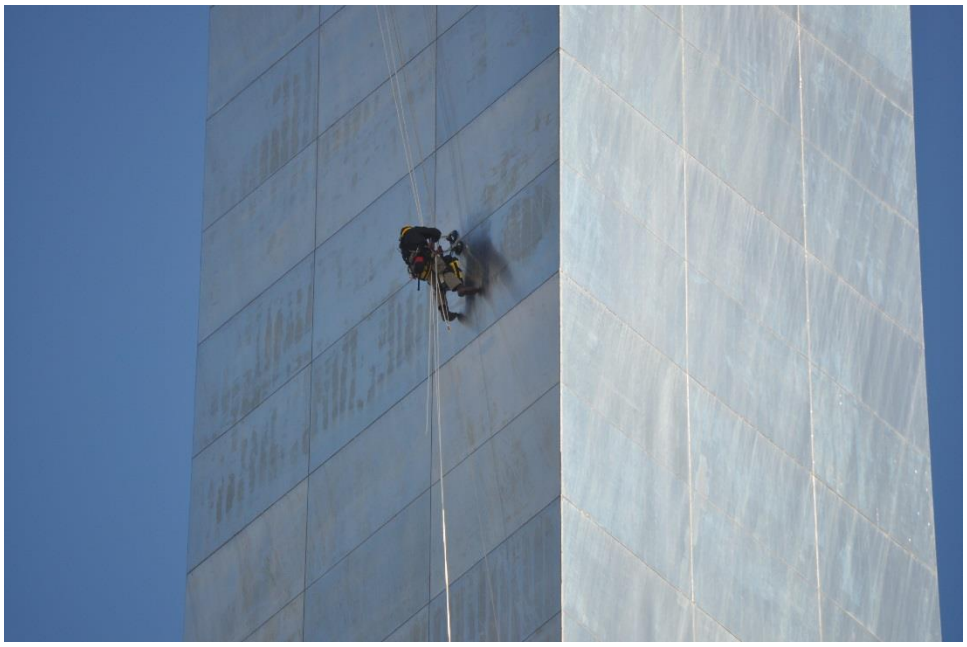
GATEWAY ARCH
Corrosion Investigation Part III

St. Louis, Missouri



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Corrosion Investigation, Part III

St. Louis, Missouri

EXECUTIVE SUMMARY

This study is a continuation of Part I and Part II of the Gateway Arch Corrosion Investigation, which were completed in May 2006 by Bahr Vermeer Haecker Architects, Ltd. (BVH) and Wiss Janney Elstner Associates, Inc. (WJE), and in September 2012 by WJE. In addition to WJE, TMR Consulting (TMR) was part of the Part III project team. The findings, conclusions, and recommendations of the Part I and Part II phases of the investigation are presented in previous reports.

The Gateway Arch (Arch) is a National Historic Landmark that is the focal point of the Jefferson National Expansion Memorial (JEFF). Commemorating the westward expansion of the nation, the Arch was designed by Eero Saarinen in response to an international competition and constructed between 1963 and 1965. The Arch has a stainless steel exterior skin, and its basic shape is an inverted weighted catenary curve with its legs as equilateral triangles in cross section. Both the height and the span are 630 feet.

Over the past two decades, National Park Service (NPS) personnel have noticed discoloration and streaking at the stainless steel exterior of the Arch. In response to these observed conditions, the project team was engaged to conduct this phased corrosion study. The scope of services for the current phase of this study included the following at the north leg:

1. Perform a close-up inspection of the stainless steel exterior skin from aerial lifts at the base.
2. Perform a close-up inspection of the stainless steel using industrial rope access (IRA) methods at a location above the concrete infill.
3. Remove weld samples for laboratory analysis.
4. Perform metallurgical analysis of weld samples and of removed deposit samples.
5. Perform cleaning trials of the stainless steel at the base and the intrados.
6. Prepare recommendations for the most appropriate treatments of the stainless steel skin to address observed discoloration and streaking, based on the investigations to date.

Based on the findings of this investigation and as further discussed below, the exterior stainless steel of the Arch is in serviceable condition, without significant structural distress or deterioration. The visual anomalies, including a variety of blemishes, deposits, and discoloration, are not causing significant corrosion or distress to the stainless steel at this time. In addition, many of these visual anomalies are from the original construction.

Findings and Conclusions

Archival Research

The JEFF archives were reviewed for relevant documents related to the fabrication, installation, and cleaning of the stainless steel exterior skin. This research revealed that throughout the fabrication and construction of the Arch, the appearance of the stainless steel panels was under discussion by the parties involved in the construction. The contractor was unable to fabricate and install pristine stainless steel panels, leading to further discussions on how to repair, refinish, and clean the panels, even while the monument was under erection. Additionally, WJE reviewed the documentary “Monument to the Dream” for additional construction and cleaning documentation included in the video footage. Noticeable damage of the finish

and staining on the stainless steel panels were visible throughout the documentary, indicating that some of the visual blemishes currently observed have existed from the time of fabrication or construction.

Access to the North Leg

WJE completed a limited investigation of the exterior stainless steel skin from September 29, 2014 to October 1, 2014, using aerial lifts at the base of the north leg, and from October 11, 2014 to October 22, 2014, using a custom IRA system along the height of the north leg. During the investigation, members of the project team visually inspected the stainless steel and welds, removed weld samples, collected deposit samples, and performed cleaning trials. The IRA system allowed access to the exterior face of the north leg for the entire height, and access to the west intrados on the north leg from approximately Station 28 to Station 35. The IRA system could be modified to access additional locations on the intrados as needed in the future, and the system could also be used to inspect the south leg.

Field Observations

The visual anomalies of the stainless steel skin can generally be classified into the following categories: 1) blemishes; 2) deposits; and 3) discoloration. Blemishes are alterations to the surface texture that create a visual anomaly under specific lighting conditions and at certain observation angles. Deposits refer to particles, such as atmospheric pollutants, on the stainless steel surface that are not part of the stainless steel. Discoloration refers to chemical alteration, such as superficial corrosion staining, to the surface of the stainless steel surface.

A variety of each type of visual anomaly was observed from the aerial lifts and by using IRA above grade. While the visual inspection completed in Part III was completed on the north leg only, the documented conditions are visible at the south leg from grade and are likely present along the height. In general, based on photographic documentation developed during the Part I and Part II studies, the stains are consistent in appearance and are not significantly worse than previously observed.

Notable conditions observed included the following:

1. Visual observations from grade:
   a. Blemishes in the stainless steel finish are a result of surface scratches that are shallower than the finish profile, and are visually apparent in a variety of patterns including vertical streaks and circles.
   b. The panels appear darker or lighter, or to have darker or lighter streaks, under specific lighting conditions and at certain observation angles.
   c. Incised graffiti and impact damage blemishes were observed on the surface at the lowest two panels. The depth of the damage ranged from superficial scratches to deep hammer indents.
   d. Surface deposits are common at many horizontal welds and tend to be dark in color. Additionally, the deposits appear to streak down the panels, originating from the horizontal welds.
   e. Heat tint was observed at some welds.
   f. Brownish-orange superficial surface corrosion staining was observed at the lowest eight panels.
   g. At the lowest two panels, red-orange corrosion staining is often associated with the incised blemishes and appeared to be the result of corrosion of iron particles embedded in the surface from the implements used to scratch the graffiti.
2. Visual observations at the extrados were generally similar to the visual observations from grade, with the following significant observations:
   a. No cracks were observed in the welds between stainless steel panels or in the stainless steel panels.
   b. At Station 6, several cracked welds were observed at the attachment of the vent slats to the frame.
   c. Surface deposits at the welds appeared to increase from the top of the Arch to the bottom.

   d. Weld spatter appeared to decrease from the top of the Arch to the bottom.
   e. Above Station 45, the out-of-plane deformation of the stainless steel panels between stiffeners, also referred to as "oil-canning," was measured to be approximately 1/8 inch at several locations.
   f. Below Station 45, the out-of-plane deformation was negligible.
3. Visual observations from Station 28 to Station 35 on the west intrados were generally similar to the visual observations from grade, with the following significant observations:
   a. At Station 35, areas of discoloration of the stainless steel panels appeared to have had a chemical applied (intentionally or unintentionally) and not completely removed, as the discoloration was adjacent to unstained areas. Similar discoloration is visible from grade at other locations on the Arch that were not accessed during this phase.
   b. The horizontal staining, parallel to the station marks, was red in hue.
   c. The vertical staining, perpendicular to the station marks, was violet in hue and appeared similar to patterns that could be attributed to water running down the face of the steel panels.
   d. At Station 35, the out-of-plane deformation of the stainless steel panels between stiffeners was noted to be negligible.
   e. No distress or corrosion was observed on the welds.

Laboratory Analysis

Laboratory analysis conducted for this study consisted of the review of silicone molds taken to observe the surface texture of the stainless steel, and analysis of the weld samples and deposit samples removed from the surface of the stainless steel.

Silicone molds were taken at several locations to observe the difference in surface relief and texture between various stainless steel finishes. Laboratory examination revealed that the vertical streaks below the welds corresponded to a difference in surface texture. The density of the surface texture applied to the stainless steel panel was greater at the areas that appeared darker.

WJE coordinated weld sample removals at the base of the north leg for laboratory analysis. Five weld samples were removed, and the stainless steel weld was repaired by A. Zahner Company (Zahner). Each sample was analyzed using light microscopy and scanning electron microscopy (SEM), with energy dispersive X-ray spectroscopy (EDS) for elemental analysis. The chemical analysis of the plate and weld material was consistent with the specified 300 series stainless steel. The welds in each sample appeared to be in serviceable condition with no surface corrosion associated with sensitization.

Gun-shot residue (GSR) sample kits were used to remove samples of the surface deposit from the stainless steel skin of the Arch. The GSR samples were taken at various locations along the height of the Arch along the north leg. In the laboratory, the samples were analyzed using SEM/EDS. The deposits were found to consist of fly ash, pollen, calcite, dolomite, and other common atmospheric pollutants.

Cleaning Trials

Cleaning trials were performed on the exterior stainless steel to evaluate the effectiveness of various cleaning systems to remove blemishes, deposits, and discoloration. The cleaning studies were completed on the east face, on the center panel at the base of the north leg, and at the intrados, which was accessed using IRA. Based on the trials, removal of the blemishes, which requires abrasive techniques, creates further visual anomalies. The surface deposits can easily be removed. Chemical cleaning is effective at removing some of the superficial corrosion staining.

Conclusions and Recommendations

The exterior stainless steel of the Arch is in serviceable condition, without significant structural distress or deterioration. The visual anomalies, including a variety of blemishes, deposits, and discoloration, are not currently an indication of significant corrosion or distress of the stainless steel, and many of these visual anomalies are from the original construction. Since the completion of Part I of the corrosion investigation, there has been no significant increase in the blemishes, deposits, or discolorations of the stainless steel. The blemishes are not likely to get worse, as they are largely the result of the original fabrication and construction. Deposits may likely increase over time as more pollutants are deposited on the surface. Some of the discolorations, such as the chloride induced corrosion, may increase over time, while other discolorations appear to be related to exposure to chemicals during construction and are not likely to increase.

The cleaning trials were successful in reducing some of the superficial corrosion staining and provided a wide range of passivation and refinishing options for the stainless steel. For cleaning treatments or long-term maintenance, a Professional Associate of the American Institute for Conservation should be engaged to ensure the proper treatment of the stainless steel. Particular care is needed with cleaning processes, as it is possible that chemically cleaning selected areas of the Arch may cause any remaining discoloration to appear more pronounced.

Cleaning treatment recommendations for each type of visual anomaly include the following:

- For blemishes (alteration of the stainless steel finish): Based on the nature of refinishing stainless steel, it is likely that any attempt to refinish the stainless steel panels could result in a more noticeable uneven appearance in the finish. Treatment of the blemishes is not recommended.
- For deposits (particles, such as atmospheric pollutants, on the stainless steel surface): At the lower portions of the Arch from Station 68 to Station 71 that can be accessed with aerial lifts, the stainless steel should be washed annually in the spring using low pressure water (less than 500 psi) to remove airborne chlorides that may be deposited on the surface. A chloride removing chemical may be added to facilitate the removal of water soluble chlorides during the washing. Above Station 68, access to the stainless steel becomes difficult, and chloride induced corrosion was not observed. As the deposits are not contributing to deterioration of the stainless steel, cleaning of these deposits above Station 68 is not considered necessary at this time.
- For discoloration (chemical alterations, such as superficial corrosion staining, on the stainless steel surface): At the base of the Arch, superficial corrosion staining has been induced by chloride exposure, and red-orange staining has occurred as a result of the corrosion of embedded iron deposits. Removal of the superficial corrosion stains is recommended to generally improve the appearance of the stainless steel. Based on the trials conducted for this study, removal of the existing incised graffiti by refinishing the stainless steel increased the difference in visual appearance and is not recommended, but removal of embedded iron near the base should be completed. Above Station 68, access to the stainless steel becomes difficult. As the discoloration is not contributing to the long term deterioration of the stainless steel, treatment of the discoloration is not considered necessary.

Additionally, recommendations unrelated to cleaning treatments include the following:

- At the vents at Station 6, the cracked welds at the louver slats on the north leg should be repaired. The louver at the south leg should be inspected close-up for cracked welds, similar to the inspection conducted at the vent at the north leg. These cracked welds are an isolated concern and do not affect the structural integrity of the Arch. The louver slats should be temporarily stabilized until the repairs can be performed.
- Future occurrences of incised graffiti should be prevented by improved security measures.

- If deicing salts are necessary near or adjacent to the Arch, non-chloride-containing deicing salts should be used.
- Over time, or with significant atmospheric or environmental changes, there is a possibility that the corrosion could become more aggressive or deposits more extensive. Annual visual monitoring of the stainless steel skin using high powered binoculars, including photographic documentation, is recommended to document visual changes to the stainless steel surface.

PROJECT BACKGROUND

Project Overview

As a partner to the National Park Service (NPS), Bi-State Development Agency (Metro) requested that Wiss, Janney, Elstner Associates, Inc. (WJE) complete a close-up inspection of the Gateway Arch (Arch) at the Jefferson National Expansion Memorial (JEFF) in St. Louis, Missouri. In addition to WJE, TMR Consulting (TMR) was part of the current project team.

This project is a continuation of a phased investigation initiated in 2005 to determine the cause(s) of apparent corrosion and staining of the stainless steel skin. The goal of Part III of the corrosion investigation is to complete the investigative portion of the project and to begin the development of treatment recommendations for the long-term preservation of the Arch.

Previous projects completed in conjunction with this project including the following:

1. Gateway Arch Corrosion Investigation Part I report, dated May 2006, prepared by Bahr Vermeer Haecker Architects, Ltd. (BVH) and WJE. The scope of services included a summary of the Arch construction, a review of pertinent archival documents, binocular survey of the exterior surface of the stainless steel skin, and recommendations for future investigation and testing.
2. Historic Structure Report, dated June 2010, prepared by BVH and WJE. The scope of services included preparation of a Historic Structure Report to compile the findings of research, investigation, analysis, and evaluation of the historic structure to date. The document is intended to function as a record document of existing conditions and as a basis for planning future preservation and maintenance of the structure.
3. Gateway Arch Corrosion Investigation Part II report, dated September 7, 2012, prepared by Koonce Pfeffer Bettis, Inc. (KPB), BVH, and WJE. The scope of services included a summary of the Arch construction, a review of pertinent archival documents, visual inspection of the exterior surface of the stainless steel skin from grade, inspection openings through the interior carbon steel to view the tube space between the carbon steel and the stainless steel, materials analysis of the carbon steel and concrete samples, field analysis of the stainless steel and weld material, implementation of long term monitoring of the interior climatic conditions, and recommendations for future work.

Project Identification

Project Name	Gateway Arch Corrosion Investigation, Part III
Project Location	Jefferson National Expansion Memorial, St. Louis, Missouri
WJE No.	2014.3432
Metro Contract No.	14-100619-DW
NPS Contract No.	PMIS 67797B
e-Tic Project No.	JEFF 366 127937

Project Goals

- Perform a close-up inspection of the stainless steel from aerial lifts at the base of the north leg.
- Perform a close-up inspection of the stainless steel using methods of industrial rope access (IRA) at a location above the concrete infill at the north leg.
- Remove weld samples for laboratory analysis.
- Perform laboratory analysis of weld samples and removed deposit samples.
- Perform cleaning mock-ups of the stainless steel at the base.
- Prepare recommendations for the most appropriate treatments for the stainless steel skin.

Project Team

Bi-State Development Agency (Metro)	Chance M. Baragary, Project Manager Diane Wright, Director of Procurement Larry Jackson, Vice-President of Procurement
National Park Service Midwest Regional Office	Al O'Bright, Historical Architect
National Park Service Jefferson National Expansion Museum (JEFF)	Tom Bradley, Superintendent Frank Mares, Deputy Superintendent Edward Dodds, Chief of Facilities Management Ann Honious, Chief of Museum Services and Interpretations Dave Caselli, Park Engineer Steve Amancio, Building Utilities Supervisor Chuck Kalert, ATS Maintenance Work Leader James Jackson, Chief of Law Enforcement Jennifer Clark, Archivist
Wiss, Janney, Elstner Associates, Inc. (WJE)	Stephen J. Kelley, Project Manager Christine Freisinger, Assistant Project Manager Joshua Freedland, Architectural Conservator Paul Krauss, Corrosion Specialist Kimberly Steiner, Chemist Dave Megerle, Rope Access Program Manager Lee Farrell, Manager of Safety Don Minner, Communications and Marketing Manager
TMR Consulting (TMR)	Catherine M. Houska, Stainless Steel Specialist

Summary of Previous Parts of the Corrosion Investigation Study

The Arch corrosion investigation has been ongoing for almost a decade, with Part I and Part II completed in 2006 and 2012, respectively. A brief summary of the findings of the previous phases is provided below for context. Refer to the previous reports for an in-depth summary of the previous work.

In 2005, BVH and WJE began working on the Part I investigation. The report for this phase was issued in May 2006. The intent of Part I was to become familiar with the design and construction of the Arch, review the ongoing suspected corrosion of the stainless steel and carbon steel with NPS personnel, and determine recommendations for further investigations. The scope of work for Part I included the following:

1. Review available documents in the JEFF archives and interview NPS personnel to become familiar with the design and construction of the Arch.
2. Observe the stainless steel from the exterior and document overall areas of corrosion or discoloration from the base of the Arch using a spotter scope.
3. Observe the carbon steel from the interior of the legs for visible corrosion and interior environmental conditions.
4. Provide recommendations for further investigations.

The recommendations developed based on the Part I study included the following:

1. Conduct additional archival research to continue to understand the design and construction of the Arch.
2. Perform close-up inspection of the exterior stainless steel to investigate the suspected corrosion and discoloration.
3. Conduct inspection openings through the carbon steel on the interior to investigate the interstitial space between the carbon steel and the stainless steel.
4. Perform laboratory analysis of the carbon steel, stainless steel, and concrete fill to confirm as-built properties.
5. Investigate environmental conditions on the interior with instrumentation and long-term monitoring.
6. Record historical and current conditions at the Arch to develop a record document for future reference.
7. Review potential future cleaning trials for the stainless steel with consideration to access to the stainless steel above grade.

In 2010, KPB, BVH, and WJE began working on Part II. The report was issued in September 2012. The intent of Part II was to continue documenting the suspected corrosion and discoloration, monitor the interior environment, and determine recommendations for further investigations. The scope of work for Part II included the following:

1. Review the JEFF archives holdings for further information on the design and construction of the Arch.
2. Review case studies of stainless steel use in other structures.
3. Document the suspected corrosion and discoloration of the stainless steel.
4. Complete the interior investigation with a series of inspection openings and material testing of removed samples.
5. Install long-term monitoring devices inside the Arch to document the interior environmental conditions.
6. Review access conditions for the exterior stainless steel.

Primary conclusions and recommendations that were developed based on the Part II study included the following:

1. Many of the observed discolorations are caused by atmospheric pollutants or by inadequate cleaning and polishing of the Arch during construction.
2. At the interior inspection openings, the interstitial space was observed to be in good condition. While signs of past moisture were observed, they were not of concern to the overall integrity of the Arch.
3. The laboratory and field analysis confirmed that the carbon steel and stainless steel met the requirements specified during construction.
4. The long-term monitoring instrumentation program indicated that during several time periods the dew point temperature was close to the steel plate temperature, indicating a propensity for condensation.
5. Recommendations included:
    a. Further investigation and testing to evaluate corrosion at the welds, contamination of the carbon steel at the welds, and the effects on the surface staining
    b. Close-up inspection and testing of the Arch using IRA to document conditions of the stainless steel above grade
    c. Continuation of the long-term monitoring program for an additional twelve month period
    d. Complete cleaning trials at the base of the Arch

Additionally, during Part II, WJE documented specific conditions on the exterior stainless steel, including the following:

1. Above Station 44, there is deformation of the stainless steel between the stiffeners and deformations at the spot welds that attach the interior stiffeners to the stainless steel.
2. Staining that appears as vertical streaks originating at the field welds is more pronounced above Station 44. Additionally, some streaks have a more distinctive brownish-orange color, some are darker, and some are more visually pronounced than others.

3. Dark discoloration occurring between stiffeners, typically above Station 44, may be caused by atmospheric pollutants on the stainless steel, by inadequate cleaning or polishing during construction, or by deformations between the stiffeners protecting this soiling from natural cleaning during water runoff.
4. Some welds were observed to have a rough finish with weld spatter present.
5. Close-up visual observations were made at the base of the Arch and at the top of the Arch from the access hatch above the observation deck and windows at the top of the Arch. In general, the staining observed could be classified as either dark grey, light grey, or red. The following types of staining and surface conditions were observed during the inspection:
   a. Light and dark vertical streaks were observed that appeared to be emanating primarily from the field welds between stations.
   b. Locations of well-adhered dark staining were visible along the welds at grade and as viewed from the access hatch.
   c. Isolated dark stains within the field of the stainless steel panels were observed at locations related to the spot welding of the stiffeners on the interior.
   d. Brownish-orange streaks below welds were observed at isolated locations. When viewed close-up, isolated brownish-orange stains were observed along the edges of field welds adjacent to the top access hatch.
   e. Red staining that appears to be tarnishing was observed at isolated locations within the field of the stainless steel panels. Tarnishing is a slight corrosion and yellowing of the surface often associated with fine particles of dirt that are incorporated in surface deposits.
   f. Red crevice corrosion was observed near grade within the field of the panels. This crevice corrosion was associated with incised graffiti.

DOCUMENT REVIEW

WJE reviewed available historic document to understand the design, fabrication, and construction of the Arch. The following review of information derived from archival research is provided as a general summary of the history of the Arch that pertains to the current phase of work. Refer to the past reports listed above for a more detailed description of archival research findings and specific archival sources.

Gateway Arch Construction

The Gateway Arch was designed as a 630 foot high weighted catenary arch with legs set 630 feet apart (Figure 1). Initiated in the Depression era, the Jefferson National Expansion Memorial (JEFF) project was first proposed as a means of rejuvenating the St. Louis riverfront and providing economic relief to the city. The memorial commemorates the vision of Thomas Jefferson and the struggles of the traders, frontiersmen, and pioneers. In 1947, 172 architects and engineers submitted designs for a memorial as part of an international competition. Upon the first review of the second stage of the competition, the jury unanimously selected Eero Saarinen as the winner. Eero Saarinen and Associates (ES&A) was the architecture firm of record, and Severud Elstad Krueger Associates of New York (SEK) was the structural engineering firm involved with the design.

The structural concept for the Arch was a collaborative effort between Eero Saarinen and his partner John Dinkeloo, and the office of SEK. Hannskarl Bandel, SEK's chief engineer, modified the inverted catenary shape for Eero Saarinen's Gateway Arch project. During the design competition, Saarinen indicated that the Arch would be a steel structure filled with concrete. However, SEK introduced orthotropic design principles in the design so that the Arch structure would be supported by its skin.

MacDonald Construction Company (MacDonald) was the general contractor, and Pittsburgh-Des Moines Steel Company (PDM) was the steel fabricator and erector.

Figure 1. Overall view of Gateway Arch looking east. (Photo by authors, 2005)

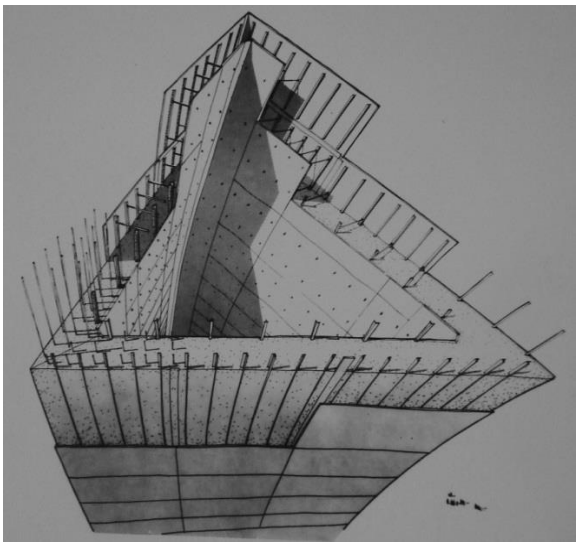

Figure 2. Equilateral cross-section of the Arch, with inner and outer skin and post-tensioned concrete core. Courtesy of Yale University Archives, Eero Saarinen Collection.

The Arch has two skins: an interior carbon steel skin and an exterior stainless steel skin. The carbon steel inner shell and stainless steel outer shell were set at slightly different weighted catenary curves and connected by stiffener plates (Figure 2). These skins are 3 feet apart at ground level and 7-3/4 inches apart above the 390 foot level. Up to a height of 300 feet, the interstitial space between the skins was filled with post-tensioned concrete. The structure is set on a concrete foundation that extends approximately 44 feet below grade.

The structure was erected using 142 prefabricated double-wall carbon steel and stainless steel stations (Figure 3). The term "station" is used to refer to specific locations on or within the Arch, numbered from Station 0 at the peak of the Arch to Station 71 at the base of each leg. Each station corresponds to the field weld installed to join adjacent segments during the construction of the Arch. PDM helped develop the construction sequence during the design phase. Because of the difficulty inherent in constructing an arched structure without centering, the legs of the Arch had to be designed to act as two cantilever structures. During construction, the legs would eventually be joined at the top and the structure would then be self-supported. The design had to consider the loadings, stresses, and structural action at the various stages, while also addressing the practicalities of construction. Finally, because the Arch was too tall for conventional cranes, the cantilevered legs had to be designed to support climbing cranes that would ride on rails attached to the outside face of each leg.

During construction, each leg needed to rely on either large tieback cables or another mechanism to hold the inward deflection to within the specified engineering tolerances until the legs were joined at the top. Therefore, the legs were designed as composite members consisting of prestressed concrete that acted together with the inner and outer skins to resist the gravity loads causing inward deflection of the legs. Additionally, a large stabilizing strut (to be removed after completion of the Arch) was installed between the legs at the height of 530 feet, which is about 100 feet from the top. This additional measure for

construction stability was deemed necessary by the contractor to ensure the stability of the cantilever legs, while simultaneously limiting the stresses on the post-tensioned concrete.

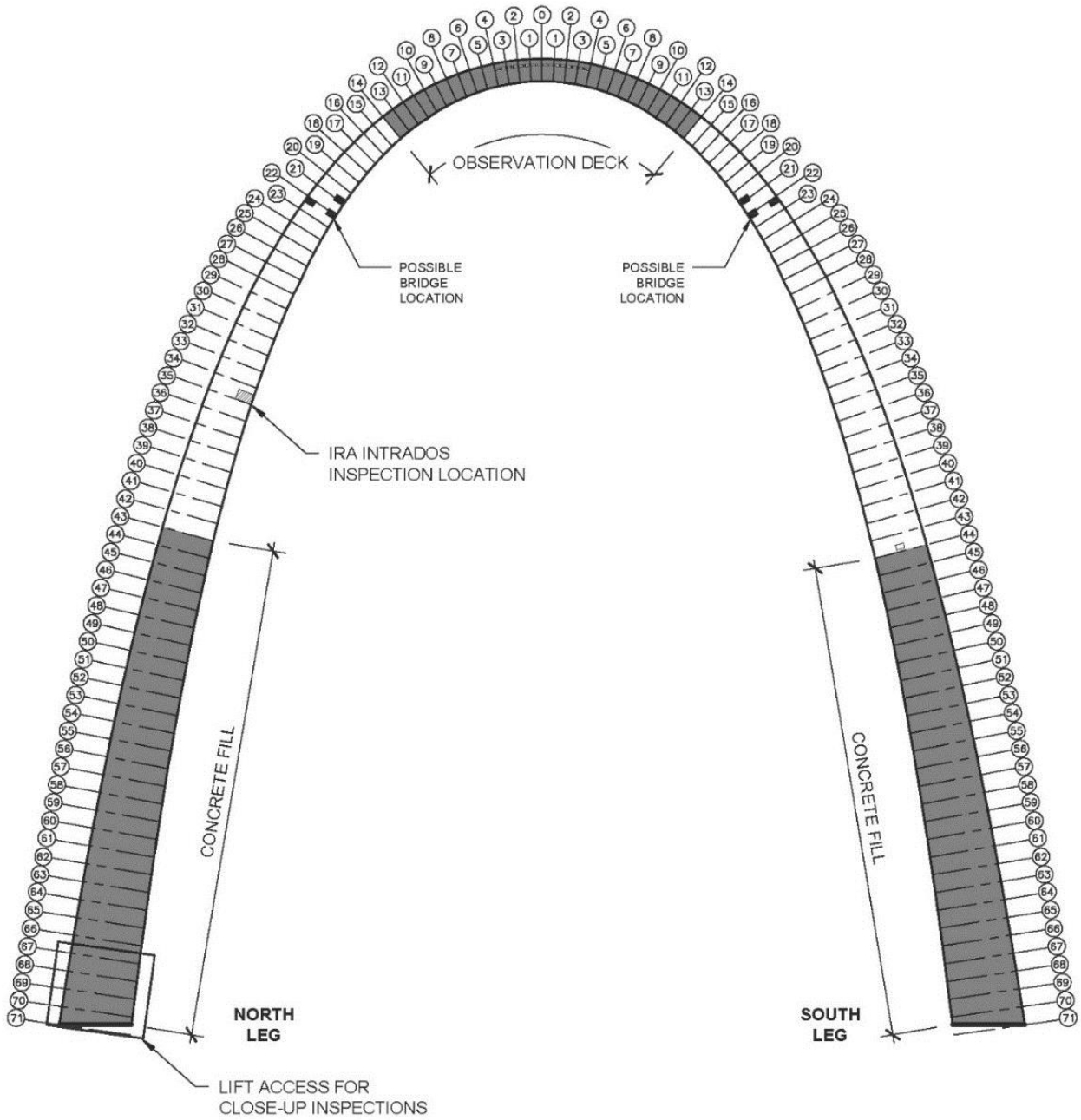

Figure 3. Schematic section through Arch showing station numbers for reference

Fabrication

PDM fabricated the Arch stations in its plants located in Pittsburgh and Warren, Pennsylvania. The stations were fabricated with 1/4 inch thick Type 304 polished stainless steel plate for the exterior skin. Nine hundred tons of polished stainless steel was used in panels varying in size from 6 feet by 18 feet, to 5-1/2

feet by 6 feet. For the interior skin, 3/8 inch thick carbon steel plate was used, except at the corners, where the steel is 1-3/4 inches thick.

While the documents describing the complete fabrication process of the stainless steel plates were not identified in the archives, the plates most likely were manufactured according to the standard practice at the time of construction. The standard practice consisted of melting, hot-rolling, cold-rolling, annealing, descaling, and pickling. Annealing dissolves chromium carbides that form in the grain boundaries of the steel. Descaling removes the thick mill scale. Pickling stainless steel involves strong oxidizing agents, such as diluted mixtures of hydrofluoric and nitric acids, to remove a thin layer of the metal from the surface of the stainless steel. After the panel edges were trimmed, the panels were subjected to a series of cold-rolling processes to obtain an accurate thickness and a smooth surface. Stresses that developed in the cold-rolling process required additional annealing and pickling. Following the final cold-rolling operation, the sheet was degreased. The stainless steel plates of the Arch were specified to have a No. 3 finish. This mechanically applied finish was created by successive passes of polishing wheels or belts across the surface.

To join the panels into the stations, gas-metal arc welding was used in the shop to butt weld both the stainless and carbon steel panels together. The fabricator built two house-sized welding fixtures: the larger for butt welding the stainless steel plates, and the smaller for butt welding the carbon steel plates and attaching angles to them. All of the shop welds on the stainless steel were reportedly completed as single pass welds to create a smooth and uniform appearance. A shielding mixture of 75 percent argon and 25 percent carbon dioxide was reportedly used. Nondestructive testing with spot X-ray was used to check the welds.

For stations below the 300 foot level at Station 45, rows of 5/16 inch stainless-steel studs were welded to the back of the stainless steel plates, and then Z-bars were fastened to the studs with carbon-steel nuts tightened with a torque wrench. High-strength steel bolts attached to the Z-bars passed through holes in the inner skin of carbon steel and were held in place by nuts that applied a compressive force to the concrete core, creating a friction bond.

Above Station 45, the inner and outer skins were to be connected together using a series of carbon steel stiffener angles, diaphragms, 1/2 inch diameter bars, and bent steel plates in a cellular type of construction, similar to aircraft design. The steel stiffener angles were spaced based on a ratio of the panel and tube width. The stiffener angles (2 inch by 2 inch by 1/4 inch) were spot welded to the back side of the exterior stainless plates with fillet welds. Spot welding was chosen to eliminate the warping that would be caused by heat if full length welds were used. A welded built-up stiffener angle, fabricated from a 2 inch by 1/2 inch steel plate and a 1/4 inch steel plate of width equal to the space between interior and exterior skins, was bolted to the interior carbon steel plates. The interior and exterior skins were further tied together with diagonal rod braces.

Erection

Construction began on June 27, 1962. Excavation for the Arch foundations required creating a pit for each leg at least 75 feet by 90 feet wide that extended to bedrock, approximately 44 feet below grade. The foundation was constructed in 5 foot increments, each of which demanded a continuous monolithic pour that took up to 23 hours and required 1,700 cubic yards of concrete. As the foundations reached 10 feet high, post-tensioning bars were installed. Installation of a second group of post-tensioning bars was started when the foundation reached 20 feet. In total, 252 vertical post-tensioning bars were set into each foundation to stabilize the structure during construction (Figure 4). The foundation was completed in February 1963.

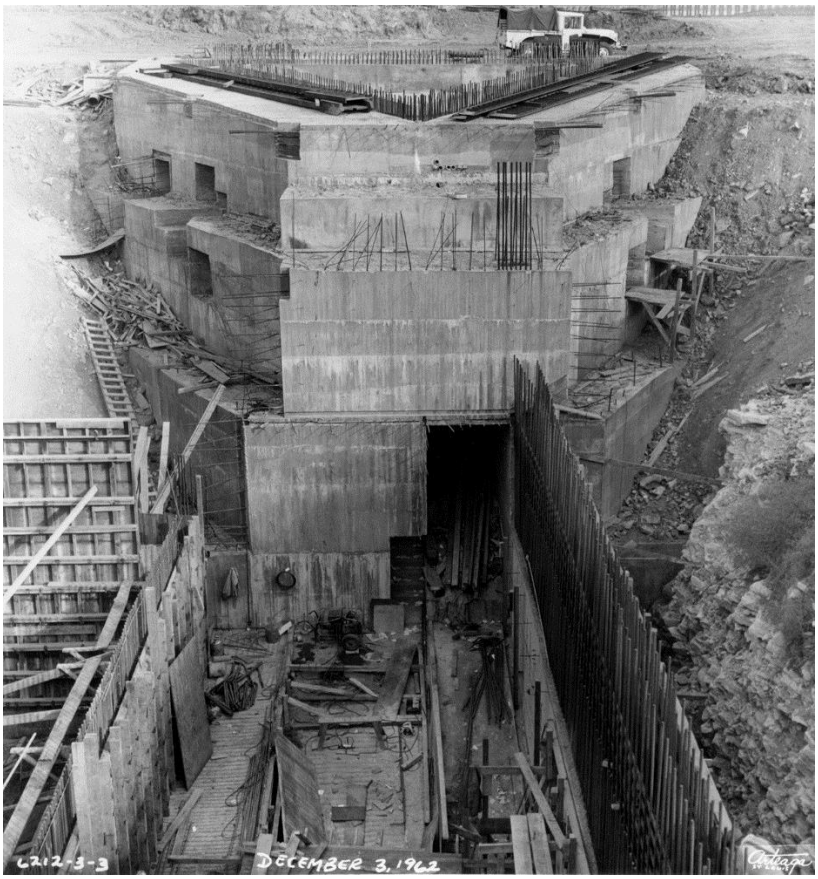

Figure 4. The north leg foundation nearing completion, December 3, 1962. Source: JEFF archives, image V106-3938.

PDM was responsible for the assembly and erection of the steel stations of the Gateway Arch. Stations 71 through 68 were shipped to the jobsite as side sections, and field-assembled on the jobsite.[1] The larger stations, at the concrete-filled portion of the Arch above Stations 71 through 68, were fabricated as three double-wall flat panels and assembled on site by installing a continuous vertical weld at each of the three corners. All stations above the concrete-filled portion (300 feet) were fabricated as three L-shaped pieces. Field welds for the upper stations were made on the faces of the panels rather than at the corners. Pick points were welded at the inside intrados corners to accommodate the creeper crane lift cables. Once the stations were assembled, they were lifted into place using the cranes.

Station 71 was placed at the base of the south leg on February 12, 1963 (Figure 5). Placement of Station 71 introduced some minor difficulties to the project. The positions of the foundation and post-tensioning bars were not in alignment with the angle of the steel station. To rectify the situation, the post-tensioning bars were slightly adjusted and bent to fit within the station, and additional reinforcing was added to compensate for the subsequent reduction in strength. On April 9, concrete was placed at Station 71.

The contractor established a systematic method and process of construction. The north and south legs of the Gateway Arch were erected simultaneously. Each station was assembled, hoisted into place, welded to the station below, filled with concrete, and then the post-tensioning process was completed. After the stations were hoisted into place and aligned, both the interior and exterior skins were tack welded into place and allowed to sit overnight while the survey team verified the height and location. In the following days, the station was secured with a continuous weld.

[1] Ken Kolkmeier, in discussion with the authors, February 2015

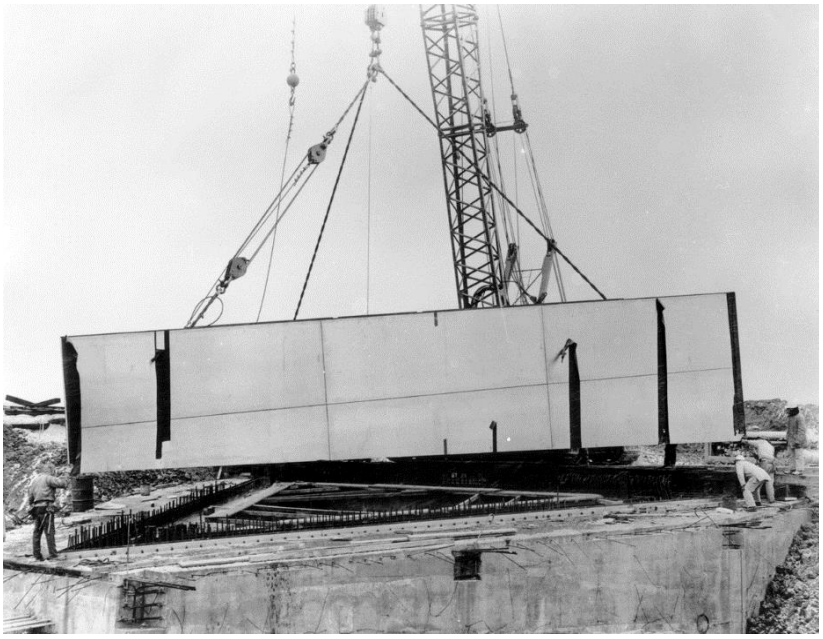

Figure 5. Placement of the first station at the south leg, February 12, 1963. Source: JEFF archives, image V106-3962.

Shielded-metal arc welding was used in a semi-automatic process to join the stainless steel joints between stations in the field. Deformation of the panels initially occurred due to heat shrinkage of the welds. The triangular stations above the 300 foot level, where the concrete was no longer placed, were cambered approximately 1-1/2 inches in 35 feet to accommodate the welding shrinkage. This welding technique, using low hydrogen electrodes, was also used to weld the inter-station joints of the carbon steel. Nondestructive testing with spot X-ray was used to check the field welds.

Because the field welding was done on a vertical surface with access from only one side, numerous weld passes and grindings were required to guarantee a complete weld. A back up bar was installed on the back side of the steel prior to setting each station to assist in the effectiveness of the welding process. The process was labor intensive and demanded skilled welders who worked in extreme heat and a confined environment. Heat tint, also referred to as weld halos, that occurred due to the field welding of the stainless steel were removed after each station was secured using electrolytic methods. Heat tint occurs in the heat affected zone when the oxide layer becomes thicker. Random samples of the welds were X-rayed to verify quality. As an architectural decision, the field welds on the exterior were not ground flush, which helped establish the pattern on the skin desired by Saarinen.

From foundation level to the 300 foot level (Station 45), the interstitial space between the inner and outer skins of both Gateway Arch legs was filled with concrete. The post-tensioning bars were stressed, at approximately 32 to 40 foot lengths, once the concrete had adequately cured.[2] The post-tensioning bars were connected by a threaded sleeve and encased in a hollow steel sleeve to allow for uniform elongation. Two hundred and fifty-two post-tensioning bars were placed in each leg and continued to the 300 foot level, where the reinforced concrete fill terminates.

In July 1963, when the Arch reached 60 feet in height, creeper cranes were built to complete the construction process (Figure 6). Each leg of the Arch had its own crane that was used for hoisting the stations and putting them in place. Dual tracks were constructed along the face of each leg of the Arch, and platforms were

[2] Ken Kolkmeier, in discussion with the authors, February 2015

assembled to support the cranes (Figure 7). As the creeper derricks proceeded up the Arch, the back legs were adjusted so that the work platforms remained level.

Figure 6. The Gateway Arch legs under construction with the creeper cranes in place, late summer 1963. Source: JEFF archives, image V106-4034.

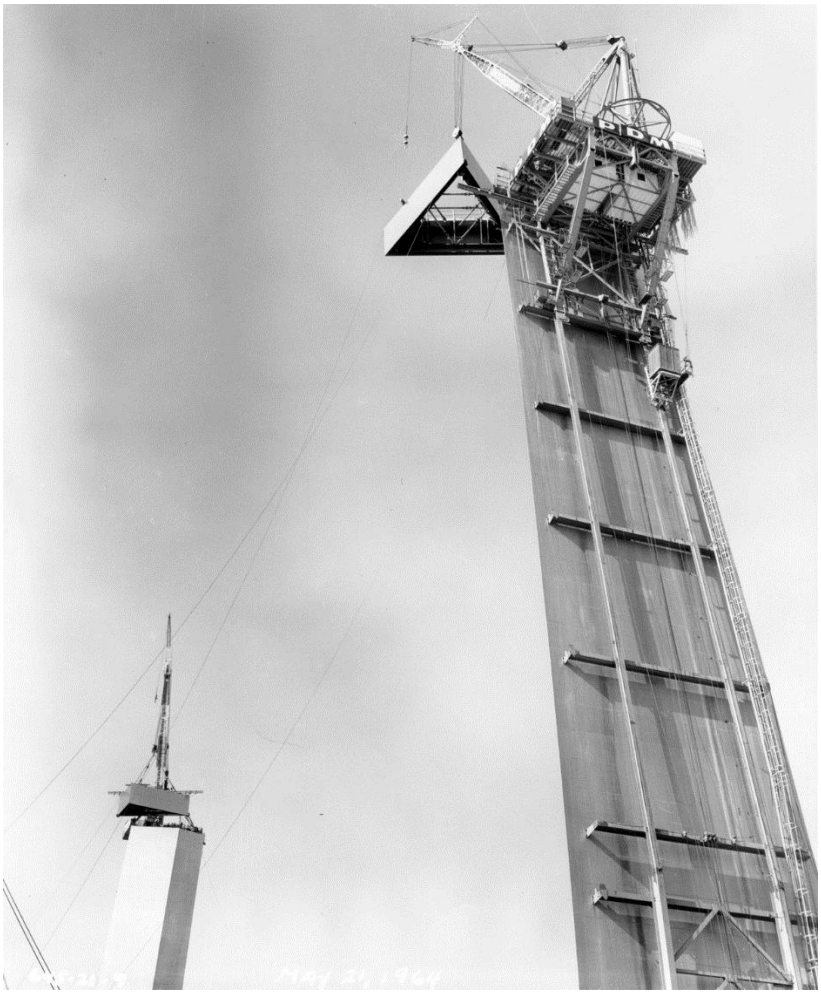

Figure 7. View of initial placement of a station of the Arch, completed from the creeper derrick crane. Source: JEFF archives, image V106-4048.

Difficulties at the Midpoint

At Station 45, approximately 300 feet high, plans called for a change in the structural assembly of the Arch. Below Station 45, the cavity between the interior and exterior steel skin was filled with concrete. At this point in the construction process, the legs were designed to lean 49 feet towards the center. Above the concrete-filled cavity, the interior and exterior skins were connected by L-shaped brackets, with the short leg spot welded to the inner skin and the long leg securing the outer skin. Upon installation of north Station 45 on September 27, 1964, it was noted that ripples in the stainless steel skin occurred every 2 feet in accordance with the locations of the stiffener angles.

Station 45 was removed on October 30, and various attempts were made to resolve the warping. The station was reinstalled on November 17, and the wall cavity at the north leg was filled with concrete in an effort to stabilize the station. South Station 45 was also filled with concrete to match the north station. Subsequent stations were installed with L-brackets as intended by the original design, and the associated ripples were accepted.

Completing the Gateway Arch

As the Arch approached 530 feet in height (Stations 22 and 23), a stabilizing strut designed to prevent excessive leaning was installed (Figure 8 and Figure 9). The legs were leaning 150 feet inward at this height, and together with the extra weight of the creeper cranes, additional support against overturning was required as part of the design. The 225 foot long, bridge-like stabilizing strut structure was assembled on the ground and hoisted into place on the morning of June 17, 1965. After the stabilizing strut was installed on the north leg and then attached to the south leg, the strut was used to jack the legs apart several inches to confirm the intended behavior of the Arch legs.[3]

Discrepancies between the height of the north and south legs were observed during the daylight hours. Throughout the day, the heat of the sun, shining more directly on the south leg, caused that leg to elongate and deflect downward 14 inches below the level of the north leg. For this reason, the Gateway Arch project team requested that the final piece be installed at night, when temperatures were consistent and the height of the legs was even. However, this approach was rejected by the City of St. Louis, and the installation of the final station was performed during daylight hours so that a public ceremony could be held at the completion of the Arch structure. The morning before the ceremony, with the application of 300 tons of pressure using hydraulic jacks between Station 1 at the north leg and Station 0 at the south leg, the topmost stations were pried 6 feet apart and aligned vertically within 3/4 of an inch.[4]

On October 28, 1965, a topping out ceremony was held when the final 8 foot wide station was inserted into the Gateway Arch (Figure 10). The ceremony was scheduled for the morning, before the south leg was heated by the sun. The local fire department sprayed the leg with cold water to keep the steel cool. The keystone station had been temporarily retrofitted with 5 inch diameter pins to help secure a quick fit with the north and south stations. As the station was lowered, the pins were inserted into place, and as the 300 ton pressure was relieved, the gap between the south leg and center station closed.[5] The legs aligned perfectly.

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[3] Ken Kolkmeier, in discussion with the authors, February 2015
[4] Ken Kolkmeier, in discussion with the authors, February 2015
[5] Ken Kolkmeier, in discussion with the authors, February 2015

Figure 8. The Arch nearing completion, with the stabilizing strut in place, September 9, 1965. Source: JEFF archives, image V106-4124.

Figure 9. View of the stabilizing strut installed during construction to resist overturning and deflection of the cantilevered legs. Source: JEFF archives, image V106-4119.

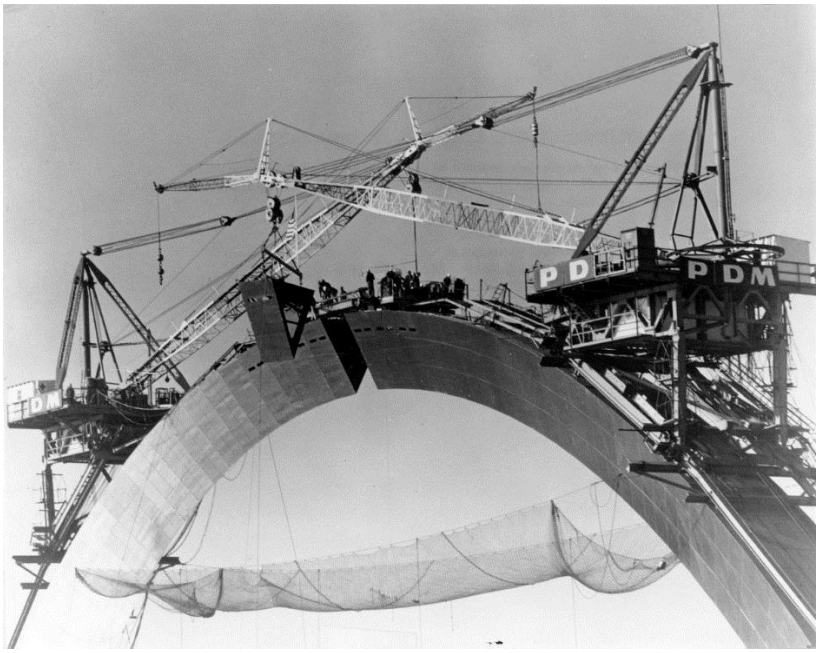

Figure 10. Installing the final station of the Arch, at the top of the north leg, October 28, 1965. Source: JEFF archives, image V106-4131.

After the keystone station of the Arch was inserted, the final cleaning, repair, and polishing could begin (Figure 11). The stainless steel panels were washed and polished by hand from the top down using the creeper cranes for access. According to the approved shop drawings, grease and dirt was removed with "Oakite #33," a proprietary chemical. The specific composition of Oakite #33 at the time of construction is unknown, but Oakite #33 remains available today. The current material safety data sheet for Oakite #33 lists phosphoric acid as the primary ingredient. Phosphoric acid was used frequently at the time of the Arch construction for cleaning stainless steel; therefore, the Oakite #33 used at the time of construction may have had similar, or the same, ingredients.

Figure 11. Cleaning the Gateway Arch and removing the creeper cranes, February 7, 1966. Source: JEFF archives, image V106-4147.

Bolt holes in the exterior skin, used during construction, were plugged with stainless steel punches salvaged from the Pittsburgh-Des Moines Steel Company manufacturing plant during fabrication. The stainless steel plugs were welded and ground smooth. The cleaning created some inconsistencies in the finish. Minor abrasions such as those caused by scaffold pads/bolts and suction cup marks were removed using a cloth impregnated with fine grit. Hand polishing did not produce the same result as the shop finish, and patched areas remained visible to the discerning eye. The locations of the stabilization struts required extensive cleaning and polishing in order to have an aesthetically pleasing appearance. The winter weather complicated the cleaning process, as water-based products turned to ice. Final preparations of the stainless steel skin continued as the creeper derricks inched their way down the Arch. In the fall of 1966, the derricks were disassembled and the cleaning of the Arch was completed. During this time, the interior of the legs were also painted red with a corrosion inhibiting coating (Figure 12).

The Arch was constructed without a means to access the stainless steel at the majority of the structure. In the years since the Arch was completed and prior to this study, the only personnel access to the stainless steel skin has been at grade, and at the access hatch at the top of the Arch.

Figure 12. Painting the interior of the Arch legs, August 4, 1966. Source: JEFF archives, image V106-4167.

Archival Research from the Jefferson National Expansion Memorial Archives

As part of the third phase of the corrosion study, archival research was conducted of the construction documents pertinent to the Arch at the JEFF archives. Specifically, WJE was interested in information about the stainless steel panels during fabrication and construction, and any relevant construction documentation. Additionally, the shop drawings, weld tests, daily reports, correspondence, and other documentation discovered as part of the Corrosion Study Part I investigation, Corrosion Study Part II investigation, and the Historic Structure Report research were reviewed for specific content relevant to the current Phase III study.

The JEFF archives provided WJE with digital scans of documents identified during our review of the archival material. These documents are listed below, organized by collection, box, and folder, with significant observations related to Part III of the corrosion investigation noted:

1. MacDonald, Box 9, Folder 1
   a. Conference Notes, dated May 2, 1962
      (1) "Before approval of a method of erection, the Contractor will submit to the Architect samples of corrective work executed on sample plates showing how bolt holes, scratches, etc. are to be repaired."
2. MacDonald, Box 9, Folder 5
   a. Letter to MacDonald from ES&A, dated September 4, 1962
      (1) ES&A and PDM tried a variety of methods to reduce the deformation on the stainless steel panels during installation of the stiffeners. The trials included "increasing the size of the copper chill bars, increasing the camber during welding operation and reducing the fillet weld from 5/16", as shown in the contract drawings, to 3/16". These alternations in the welding procedure helped to decrease the amount of deformation on the stainless steel but did not eliminate it completely."
      (2) PDM "prepared a sample stud bolt procedure for fastening the stiffener to the outer skin of the Arch. The stud bolt procedure all but eliminated the deformation on the stainless steel."
3. MacDonald, Box 9, Folder 6
   a. Conference Notes, dated October 5, 1962
   b. Shipping Statement prepared by PDM, dated October 8, 1962
   c. Letter to NPS from ES&A, dated October 12, 1962
   d. Minutes of Meeting, dated October 26, 1962
      (1) "In order that a tentative criteria for determining the acceptability of the material can be established, it was agreed on by all present that scratches of the severity of those on the rejected plates would be cause for rejections even if washing or rubbing had not been performed. Less severe scratches and blemishes, while they should be carefully avoided, would not appear to be cause for rejection if they do not exceed in number those present in the other established. It was generally agreed that no firm definitive rules can be established. Generally, when minor scratches or blemishes are such that they do not attract the eye when viewing the entire plate, and when the viewer is required to search the surface closely to detect them, then they are not to be considered cause for rejection."
      (2) "The above refers to judging of mill materials when uncrated. It was agreed that a certain amount of additional wear will take place on the plate surfaces as a result of assembly, shipping and erection. All agreed that this must be minimized, and that not until subsections are delivered, assembled, and erected can a final criteria for determining acceptability be established."
      (3) PDM "agreed to submit a detailed quality control program..."
   e. Letter to Eastern Office Division of Design and Construction (EODC) from JEFF, dated November 2, 1962 on "Trip to Pittsburgh - Des Moines Steel Company"
   f. Letter to MacDonald from ES&A, dated November 15, 1962
      (1) "Damage to the stainless steel skin during fabrication, transportation, handling, etc., must be prevented. Protective measures are not noted."
      (2) "The procedure indicates that it is not planned to apply protective covering to the stainless steel..." "We do not concur that the stainless steel can be adequately safeguarded against damage without applying a protective coating directly on the metal."
4. MacDonald, Box 9, Folder 7
   a. Letter to ES&A from MacDonald, dated December 7, 1962

(1) PDM "maintains that to date they have been unsuccessful in their attempts to find a suitable covering for the stainless steel skin."
(2) PMD "states further that they have been quite successful in preventing scratches or abrasions during manufacture and handling by the use of refined techniques and extreme care. They propose to continue as previously stated with the sheet metal covering on the extrados and with no covering attached directly to the skin."

b. Letter to PDM from MacDonald, dated December 17, 1962 with the "Welding Quality Control" submittal by PDM
(1) Radiographic inspections to be performed on the stainless steel butt welds.

5. MacDonald, Box 9, Folder 8
a. Minutes of Meeting, dated January 7, 1963
(1) "It was generally agreed that no attempt would be made to remove weld spatter on the stainless plates..." PDM "is to immediately take whatever steps necessary to reduce weld spatter."
b. Letter to ES&A from MacDonald, dated January 30, 1963, including Minutes of Meeting, dated January 25, 1963
c. Letter to MacDonald from ES&A, dated February 1, 1963

6. MacDonald, Box 9, Folder 9
a. Letter to MacDonald from ES&A, dated March 18, 1963
(1) "The stainless steel for the Gateway Arch is not being adequately protected during construction. A cable or tool has damaged the stainless steel finish significantly on the lower panel south leg, extrados side. A plastic membrane was allowed to drape over the top edge of the northeast corner north leg, spreading grease over a large area. Several scratches have occurred under the ladders leaned against the Arch, and other damage to the stainless steel surface has occurred during fabrication."
(2) "The protection, if any, provided by the manufacturer on the stainless steel material delivered and incorporated in the work is inadequate."
(3) ES&A requested the procedures to protect the stainless steel and to repair the damaged panels.
b. Minutes of Meeting, dated March 29, 1963
(1) Continued discussion of the protection of the stainless steel panels and options for repairs

7. MacDonald, Box 10, Folder 1
a. Letter to MacDonald from ES&A, dated April 8, 1963
b. Letter to NPS from ES&A, dated April 8, 1963
c. Letter to NPS from ES&A, dated April 8, 1963 (second letter of the same date as item above)
d. Minutes of Meeting, dated March 29, 1963 (second copy)
e. Letter to NPS from MacDonald, dated April 12, 1963
f. Letter to NPS from ES&A, dated April 18, 1963
g. Shop drawings to NPS from PDM, dated April 29, 1963 to include Stainless Steel Cleaning Procedure, and a letter to PDM from Eastern Stainless Steel Corporation regarding cleaning, dated April 8, 1963
(1) See WJE Appendix A for a copy of the Stainless Steel Cleaning Procedure.
(2) Notes that "Oakite 33 will dry leaving a minor streaking effect if not well rinsed or under severe dust conditions."
(3) "There are a number of excellent protective coatings that can be applied...nearly all of them present some problem either in application or removal." Discussion of various protection methods for the stainless steel panels, including a spray coating of vinyl or latex compounds, adhesive paper application, heavy grade kraft paper
h. Letter to MacDonald from ES&A, dated June 14, 1963

8. MacDonald, Box 10, Folder 2
   a. Field Memorandum Number 317 from ES&A, dated July 25, 1963
      (1) "At different occasions, sections for the Arch have arrived at the site with shipping damage. Some of this damage is where the texture of the finish has been rubbed resulting in shinny spots. The original finish will have to be restored at these spots."
      (2) Damage has occurred at sections S65, S66, N65, N66, N68 and N71.
   b. Letter to MacDonald from ES&A, dated August 12, 1963
   c. Letter to MacDonald from ES&A, dated August 23, 1963
      (1) "The stainless steel of the south rib of the Gateway Arch is streaked. Apparently the streaks are caused from water and solvent used on the Arch surfaces running down the rib."
      (2) The current procedure is deemed unacceptable, and a revised cleaning procedure is requested.
9. MacDonald, Box 10, Folder 3
   a. Letter to MacDonald from ES&A, dated September 24, 1963
      (1) "In our opinion the Arch is not now being adequately protected against scratches, high polish marks or streaking, nor do we have any indication that these problems can be adequately corrected. The back or extrados surface of the Arch is extremely dirty and streaked with mud and other materials which have fallen from the creeper crane deck. In our opinion you are not fulfilling the obligation under your contact for protection of the Arch surfaces."
   b. Letter to MacDonald from ES&A, dated October 10, 1963
      (1) "The shop inspectors at the plant of the PDM Steel Company in Warren, Pennsylvania, have reported to us that the stainless steel panels are accumulating more shop dirt, oil, and scratches from the handling procedure."
      (2) "We wish to emphasize that every precaution should be taken to handle the stainless steel plates in such a manner as not to disturb the finish on the plates bearing the shop fabrication."
   c. Letter to MacDonald from JEFF, dated October 11, 1963
   d. Letter to MacDonald from JEFF, dated October 14, 1964
10. MacDonald, Box 10, Folder 4
   a. Letter to MacDonald from JEFF Assistant Superintendent, dated November 4, 1963
      (1) Noted continued "apparent negligence in protecting the stainless steel exterior surfaces" and request for repair methods
11. MacDonald, Box 10, Folder 5
   a. Letter to EA&A from SEK Associates, dated November 19, 1963
      (1) Description of weld procedure specification, but specific information on weld filler used was provided
   b. Letter to MacDonald from PDM, dated December 5, 1963
   c. Letter to ES&A from JEFF Assistant Superintendent, dated December 17, 1963, with response from ES&A, dated December 20, 1963
      (1) JEFF is requesting that a decision be made on the protection and cleaning of the stainless steel panels. ES&A notes that the "quality control at Warren Plant has not been the best, resulting in some dirt, grease and scratches" on the stainless steel. "The results of the cleaning by 'Oakite' solution" have been "spotty." Trial test repairs have been completed to refinish the stainless steel in the field without satisfactory results.
   d. Letter from NPS from MacDonald, dated December 11, 1963, and referenced PDM letter to MacDonald, dated December 5, 1963

(1) PDM has submitted "a revised outline of procedure for protection and cleaning of the stainless steel exterior of the Arch," and is continuing to work on the trial test repairs for in field refinishing.
(2) PDM notes the following:
(a) "All handling and shipping procedures now employed by the shops will continue to be done with the upmost care, but no change in these established procedures is contemplated."
(b) "Weld haloes *[sic]*, resulting from the welding of the corner joints will be removed using our present eletrolitic *[sic]* methods."
(c) "Large accumulations of grease and dirt will be removed using a mild solution of Oakite #33, or similar solution, and minor abrasions will be repaired."
(d) "After closing operations are completed, the Arch will be washed as the creepers are lowered to the ground. Track attachments will be removed, plug welded and polished as has been demonstrated on the test plate presented..." "The same procedure will be used to repair large scratches to the stainless panels."
(e) "Minor abrasions, such as scaffold pad bruises, suction cup marks, etc., will also be removed at this time using a fine grit impregnated cloth."
(f) PDM requested witnesses on site to review the trial test repairs to the stainless steel finish.

e. Letter to JEFF Regional Director from JEFF Assistant Superintendent, dated December 18, 1963
(1) "Resident Architect Rennison proposed to test these procedures under actual field conditions. Previous attempts involving similar procedures have not produced satisfactory results in all instances. As Mr. Rennison has pointed out, a procedure that works on a test panel does not necessarily work on the actual Arch panels. In fact, abrasives used heretofore have results in noticeable changes in the texture of the stainless steel surfaces."

f. Letter to ES&A from MacDonald, dated December 18, 1963
(1) Damage to Section 60 South due to construction accident that resulted in "bends and gouges in the steel plate" that are "unrepairable." MacDonald proposes a trial field repair before sending the panel back to the shop, which could cause a delay in the schedule.

g. Letter to JEFF Superintendent from EODC, dated December 18, 1963 discussing Change Order 24

h. Letter to MacDonald from ES&A, dated December 23, 1963
(1) ES&A supports the request for independent testing of the revised welding procedure submitted by SE&A, dated November 19, 1963.

12. MacDonald, Box 11, Folder 2
a. Letter to MacDonald from ES&A, dated February 28, 1964

13. MacDonald, Box 11, Folder 3
a. Letter to MacDonald from ES&A, dated March 12, 1964
(1) "Arch Section 57 South was damaged by the Creeper Crane boom at Station 56 on the extrados side...the stainless steel plate was sharply bent...and the deflection extended over a 6 foot area."
(2) Correction of the plate was requested.

14. MacDonald, Box 11, Folder 1
a. Letter to MacDonald from JEFF Superintendent, dated January 10, 1964
(1) There has not been an agreement on the "satisfactory procedures for cleaning the stainless steel."
(2) "Protection of the Arch skin during fabrication and erection is clearly the responsibility of the Contractor."
(3) "Noted weld spattering adjacent to some welds . . . better shielding . . . is indicated."

(4) "As of now, protection [of the stainless steel] has not been good, and cleaning neglected or unsatisfactory."
(5) "We must insist that you protect the skin, and develop a satisfactory method of cleaning it as required under the terms of your contract."

b. Site visit report by ES&A, dated January 21, 1964

15. MacDonald, Box 11, Folder 4
    a. Welding Procedure for Vertical Weld submitted by MacDonald, dated April 3, 1964
        (1) Base metal noted as SS304
        (2) Filler metal classification number ER308
        (3) Metal inert gas (MIG) procedure with Argon-CO_2 20 CFH, Helium 10 CFH
    b. Letter to NPS from MacDonald, dated April 3, 1964, including letter to MacDonald from PDM, dated April 2, 1964, and "Cleaning and Protection of Polished Stainless Steel Surfaces," dated March 25, 1964
        (1) See WJE Appendix A for a copy of this letter.
        (2) Several coatings and coverings, including Permacel tapes, cloth fabric tapes, asbestos paper, and liquid plastic films were investigated for possible use to protect the stainless steel. "None have proved to be satisfactory from the standpoint of protection against nicks and scratches or from the standpoint of keeping the Arch clean."
        (3) The methods of protection being used by PDM during fabrication and erection were outlined. PDM outlined the various methods of protection utilized at the mills, in process and transportation to the site, and during erection. The methods involve keeping the stainless steel panel protected in various fashions to avoid damage to the stainless steel finish.
        (4) PDM noted that trial test repairs to a sample test panel to remove scars and blemishes was approved by the Resident Architect.
    c. Letter to NPS from MacDonald, dated April 8, 1964, including a letter to MacDonald from PDM, dated April 3, 1964 regarding a tensile test on welded steel plates
16. MacDonald, Box 11, Folder 6
    a. Letter to MacDonald from ES&A, dated June 9, 1964
        (1) " . . . Section 47 arrived . . . with scorched spots or 'halos' showing on the surfaces of the Stainless Steel Plates. These scorched spots or 'halos' are usually removed by an etching process which in this case was not properly completed."
    b. Letter to MacDonald from ES&A, dated August 24, 1962
    c. Letter to MacDonald from ES&A, dated November 15, 1962
    d. Letter to MacDonald from ES&A, dated March 18, 1963
    e. Letter to MacDonald from JEFF, dated March 22, 1963
    f. Letter to PDM from Eastern Stainless Steel Corporation, dated April 8, 1963
    g. Shop drawings to NPS from PDM, dated April 29, 1963, to include Stainless Steel Cleaning Procedure, and a letter to PDM from Eastern Stainless Steel Corporation regarding cleaning, dated April 8, 1963
    h. Field Memorandum Number 317 from ES&A, dated July 25, 1963
    i. Letter to MacDonald from ES&A, dated August 16, 1963
        (1) "There are numerous spots where tape and gum residues from shipping shields remain after the procedures followed are completed."
    j. Letter to MacDonald from ES&A, dated August 23, 1963
    k. Letter to MacDonald from ES&A, dated September 24, 1963
    l. Letter to MacDonald from ES&A, dated October 10, 1963
    m. Letter to MacDonald from JEFF, dated October 14, 1963
    n. Letter to MacDonald from JEFF, dated November 4, 1963
    o. Letter to MacDonald from PDM, dated December 5, 1963

p. Letter to NPS from MacDonald, dated December 11, 1963
q. Letter to ES&A from JEFF Assistant Superintendent, dated December 17, 1963, with response from ES&A, dated December 20, 1963
r. Letter to JEFF Regional Director from JEFF Assistant Superintendent, dated December 18, 1963
s. Letter to MacDonald from JEFF, dated January 10, 1964
t. Letter to NPS from MacDonald, dated February 3, 1964
u. Letter to MacDonald from JEFF, dated February 20, 1964
v. Meeting notes with MacDonald prepared by NPS, dated March 4, 1964
w. Letter to MacDonald from JEFF, dated March 10, 1964
x. Letter to MacDonald from JEFF, dated March 19, 1964
y. Letter to PDM from MacDonald, dated March 30, 1964
z. Letter to MacDonald from PDM, dated April 2, 1964
aa. Letter to NPS from MacDonald, dated April 3, 1964
    (1) "Submitted for approval an addendum to Section II, Paragraph #5, of our approved erection procedure entitled 'Cleaning and Protection of Polished Stainless Steel Surfaces,' Pages 1 through 4, dated March 25, 1964. (Two copies enclosed.)"
bb. Letter to MacDonald from ES&A, dated April 8, 1964
    (1) "The scaffold struck the Arch near the 75 foot level on the west side toward the extrados corner. Due to the location of the point of impact, any damage cannot be evaluated at this time. Any repairs required will be carefully and satisfactorily performed."
cc. Letter to MacDonald from JEFF, dated April 9, 1964
dd. Letter to MacDonald from JEFF, dated April 9, 1964 (second letter of the same date as item above)
ee. Letter to MacDonald from PDM, dated April 21, 1964
ff. Letter to NPS from MacDonald, dated April 28, 1964
gg. Letter to EODC from JEFF, dated May 4, 1964
hh. Letter to EODC from JEFF, dated May 19, 1964
ii. Letter to NPS from ES&A, dated May 27, 1964
jj. Letter to EODC from JEFF, dated June 16, 1964
kk. Letter to NPS from JEFF, dated July 14, 1964
ll. Letter to JEFF from NPS, dated July 16, 1964
mm. Letter to MacDonald from PDM, dated April 26, 1966
nn. Meeting Minutes, dated April 27, 1966
oo. Letter to JEFF from MacDonald, dated April 27, 1966
pp. Letter to NPS from MacDonald, dated May 3, 1966
qq. Letter to PMD from Eastern Stainless Steel Corporation, dated May 3, 1966
    (1) "Inspection at the 200 foot level on the south leg showed several rub marks on the surface... from the light movement between the neoprene-protected scaffolding and the stainless plates during construction. Attempts had been made using all known procedures to remove these marks, however, a perfect blend with the original mill finish could not be obtained... the areas vary in degree of reflectivity according to whether the day is cloudy or bright, or at what angle the sun may strike these areas."
    (2) "You cannot get a 'perfect' blend between a mill polished product and an area blended by hand tools."
rr. Letter to MacDonald from PDM, dated May 4, 1966
ss. Letter to JEFF from MacDonald, dated May 5, 1966
tt. Letter to JEFF from MacDonald, dated May 5, 1966 (second letter of the same date as item above)
uu. Letter to MacDonald from JEFF, dated May 5, 1966

vv. Job Records Memorandum by MacDonald, undated
ww. Job Records Memorandum by MacDonald, dated May 13, 1966
xx. Letter to MacDonald from PDM, dated June 30, 1966
  (1) "We have verbal acceptance of all our work on the inside of the Arch and of our work on the outside of the Arch with the exception of the blemishes and marks pointed out by the Park Service."
yy. Letter to NPS from MacDonald, dated July 13, 1966
zz. Letter to MacDonald from PDM, dated July 18, 1966
aaa. Letter to NPS from MacDonald, dated July 19, 1966
bbb. Letter to NPS from ES&A, dated July 22, 1966
  (1) See WJE Appendix A for a copy of this letter
  (2) "The contractor in erecting the Arch has caused and left abrasions and suction cup marks on the outer stainless steel skin. The specifications called for a covering to be maintained during all phases of the work over the outer surfaces during erection of the Arch."
  (3) "There are, however, marks which the Contractor could not repair on sample test panels before erection and has not been able to repair on the Arch proper. The location of these marks on the Arch has been previously provided you."
  (4) "In addition to the impairment to the surface finish of the steel plate, there are wrinkles on the Arch stainless steel surfaces beyond the flatness tolerances specified...None of the wrinkles in the plate are of structural significance. As in the case of the marks on the stainless steel surfaces, we know of no way to repair or replace the wrinkled panels, the damage is irreparable."
  (5) "We recommend that another Change Order be written relieving the Contractor of providing an Arch with surface flatness-tolerance of +/- 1/4 inch as specified and allowing abrasions and tool marks on the stainless steel plate surfaces."
ccc. Letter to MacDonald from PDM, dated August 4, 1966
ddd. Letter to PDM from MacDonald, dated August 8, 1966
eee. Letter to NPS from MacDonald, dated August 8, 1966
fff. Letter to ES&A from JEFF, dated August 16, 1966
ggg. Letter to NPS from ES&A, dated August 23, 1966
hhh. Letter to JEFF Superintendent from JEFF Project Supervisor, dated September 14, 1966
  (1) See WJE Appendix A for a copy of this letter and the survey sheets
  (2) Survey sheets of damaged stainless steel plates at the north and south legs from Station 70 to Station 54 recording "marks that were visible and objectionable to the eye from positions on the ground where the public will walk." Above Station 54, it was determined that the marks were not visible.
  (3) "The rejects include suction cup marks, marks caused by scaffolding rubbing the surface, marks caused by standards used to hold units in position on railroad cars in transportation, and various other marks from unknown causes."
iii. Letter to NPS from MacDonald, dated September 15, 1966
jjj. Letter to MacDonald from PDM, dated September 18, 1966
kkk. Letter to MacDonald from JEFF, dated September 20, 1966
  (1) "A contract credit of $367,631.20 is due to the U.S. Government for damages to the stainless steel surface on the Arch which includes, but is not necessarily limited to (1) suction cup marks, (2) marks and abrasions along scaffolding lines, (3) marks and abrasions caused by standards used to hold units in position on railroad cares while being shipped, and (4) damage to surfaces due to unknown causes."

(2) "An additional credit $86,589.00 is due the Government for reduced costs realized by PDM in not providing the protective covering for the stainless steel surfaces during fabrication and erection as required by the contract specifications."

lll. Letter to MacDonald from PDM, dated October 4, 1966
mmm. Letter to MacDonald from JEFF, dated October 18, 1966
nnn. Letter to MacDonald from PDM, dated November 7, 1966
ooo. Letter to NPS from MacDonald, dated December 19, 1966
ppp. Letter to Water Resources and Procurement from Parks and Recreation, dated January 9, 1967
qqq. Letter to JEFF from Water Resources and Procurement, dated January 19, 1967
rrr. Letter to Division of Water Resources and Procurement from Water Resources and Procurement, dated January 19, 1967
sss. Letter to Department Counsel from JEFF, dated March 2, 1967
ttt. Letter to Department of Interior from Law Offices of King and King, dated April 14, 1967
uuu. Letter to NPS from MacDonald, dated September 20, 1967, including a letter to MacDonald from PDM, dated August 17, 1967
vvv. Letter to PDM from Law Offices of King and King, dated January 30, 1969

17. MacDonald, Box 12, Folder 2
    a. Letter to NPS from MacDonald with referenced Meeting Notes, dated September 29, 1964
        (1) "Purpose of meeting: To discuss the visible deformations in the stainless steel sides of Section 45 north, now in place, and Section 45 south, now on the field assembly pad, and methods to correct them."
        (2) "...no further erection to take place until a solution is agreed upon."
    b. Memorandum to WASO DSC from JEFF, dated October 2, 1964 with referenced Excerpts from Arch Contracts
    c. Letter to NPS from ES&A, dated October 3, 1964
        (1) "The Stations 45 of the north and south legs...are not within the tolerances as indicated on drawings AR-1D which allows in the most severe case one smooth company surface curve in eight feet with a maximum 1/4" plus or minus from a flat surface."
    d. Letter to NPS from MacDonald, dated October 12, 1964
    e. Letter to MacDonald from JEFF, dated October 8, 1964
    f. Letter to NPS from MacDonald, dated October 16, 1964
    g. Letter to MacDonald from PDM, dated October 15, 1964
        (1) "It is not expected that we can completely eliminate the ripples or wrinkles which are apparent in the sides of the triangles and are a results of distortion or upset in the stainless hell over the diaphragms and stiffeners angles, due to spot welding to the stainless."
    h. Letter to MacDonald from PDM, dated October 28, 1964
        (1) "We agreed to the Park Service suggestions to install concrete in Station 45 as a way of solving present problems and getting the project moving forward again."
18. MacDonald, Box 12, Folder 7
    a. Field Memorandum Number 351 prepared by ES&A, dated March 31, 1965
        (1) "Section 32 assembly No. 2 arrived at the job site...marred by the use of some abrasive material...It will be necessary to correct the marred spots...A number of methods have proven successful when mars were removed from the sample plate submitted."
19. MacDonald, Box 12, Folder 8
    a. Letter to NPS from ES&A, dated April 21, 1965
        (1) "The original drawings, sent to the contractors for bids, only the lower eight panels of each leg were 3/8" thick stainless steel plate. Addendum No. 5 changes the thickness of these lower panels from 3/8" to 1/4"."
20. MacDonald, Box 14, Folder 6

a. Letter to NPS from MacDonald, dated April 27, 1966, including a letter to MacDonald from JEFF, dated May 5, 1966
b. Letter to MacDonald from PDM, dated April 26, 1966
   (1) "We have exhausted all methods known to us to obtain a satisfactory final finish on the stainless steel of the intrados sides of Stations 58, 59, and 60, on the South rib."
c. Letter to JEFF from MacDonald, dated May 5, 1966, including a letter to MacDonald from PDM, dated May 4, 1966
   (1) "It appears impossible to remove all marks from the stainless steel and still leave a finish completely acceptable to the Park Service."

21. MacDonald, Box 14, Folder 9
    a. Letter to MacDonald from JEFF, dated August 5, 1966
    b. Memorandum prepared by JEFF, dated July 29, 1966
    c. Letter to NPS from MacDonald, dated July 26, 1966
    d. Letter to ES&A from JEFF, dated August 16, 1966
    e. Letter to NPS from ES&A, dated July 22, 1966
22. Rennison, Box 17, Folder 26
    a. Welding Procedure Qualification Record for an inclined horizontal weld, dated May 18, 1964
    b. Welding Procedure Qualification Record for a down hand weld, dated March 20, 1961
    c. Stainless Steel Cleaning Procedure, dated April 10, 1963
       (1) See WJE Appendix A for a copy of the Stainless Steel Cleaning Procedure.
    d. Letter to PDM from Eastern Stainless Steel Corporation, dated April 8, 1963
    e. Welding Procedure Qualification Record for a down hand weld, dated December 6, 1955
    f. Welding Procedure Qualification Record for a flat and overhead weld, dated June 17, 1961
    g. PDM Report on Fractured Z Bars, dated January 9, 1963
23. Record Unit 106, Box 35, Folder 25
    a. United States Department of Interior Bureau of Reclamation summary report of a hearing on the "structural aspects of the Gateway Arch," dated February 3, 1965
24. Record Unit 106, Box 35, Folder 27
    a. "Aerodynamic Stability of Jefferson National Expansion Memorial Gateway Arch" report prepared by the U. S. Department of Commerce, dated July 1965
25. Record Unit 117, Box 18, Folder 2
    a. Letter to NPS from MacDonald, dated February 24, 1964
       (1) PDM has "advised that extensive research and experimentation has failed to reveal any alternative which will alleviate the upsetting of the polished face of the 1/4" stainless steel when welding is performed as specified."
       (2) "This condition was discussed as great length before the first sections of the Arch were fabricated and it was agreed at that time by your Professional Staff that some upsetting was inevitable."
       (3) MacDonald requests further direction on how to address the upsetting of the stainless steel at this point, or notification if they are not meeting the contract specifications.
    b. Letter to MacDonald from JEFF Superintendent, dated January 10, 1964
26. Photographs of damaged stainless steel panels taken by an unknown person during construction of the Arch (two photographs included as Figure 13 and Figure 14)

Figure 13. Damaged stainless steel panels. Source: JEFF archives, unknown photographer, unknown date.

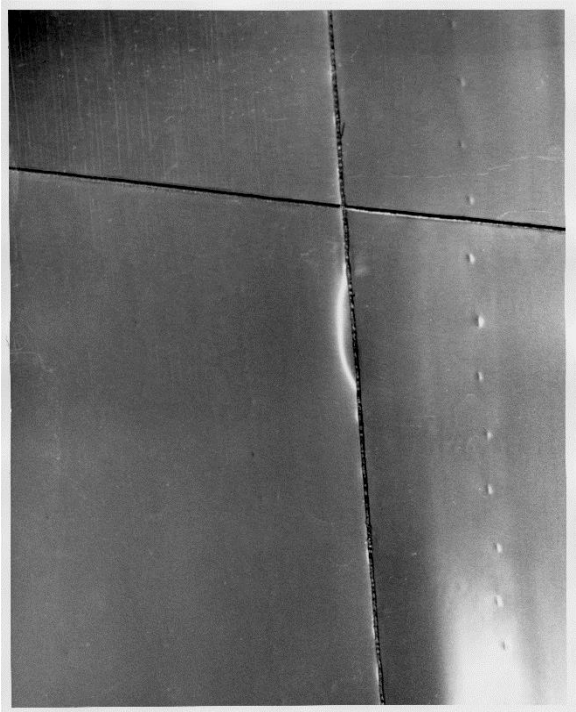

Figure 14. Damaged stainless steel panels. Source: JEFF archives, unknown photographer, unknown date.

27. Report on the Jefferson National Expansion Memorial Gateway Arch, Appendix F, prepared by the United States Department of the Interior Bureau of Reclamation, dated December 1964
28. Gateway Arch and Visitor Center Specifications and Addendum No. 1 and Addendum No. 3
    a. The stainless steel was specified to be Type 304.
    b. The electrode or filler metal wire for all welding was specified to be stainless steel type 308, 309, or 310.
    c. A 100 grit finish was originally specified which was changed by Addendum No. 1 to be a Number 3 finish.
    d. "The weld shall be 3/8" wide with a minus tolerance of 1/8". The weld shall have a maximum height above the surface of the base metal of 3/32". Above Station 53 the width of the weld may be increased, if necessary, to make adjustment for plate joints."
    e. Addendum No. 1 states that weld halos and weld flux shall be removed by means of chemical etching, employing methods and agents approved by Contracting Officer.
    f. Addendum No. 3, Question 4
        (1) "QUESTION: The heat of welding produced a heat discoloration on the fusion and EB sample welds. How was this heat discoloration removed from the samples? May we have the exact procedure that was used on the acceptable test plate?"
        (2) "ANSWER: An electrolyte or chemical solution, 50% by volume commercial Phosphoric acid in water was applied to the affected area. A low alternating electric current; 4 to 24 volts, 3 amps, was passed thru the electrolyte using arch skin as one conductor and a 1/4 inch diameter rod as the other conductor. The end of the rod was covered with a glass cloth swab. The rod was then moved over the affected discolored areas. After the weld halos were eliminated the electrolyte was then washed from the surface of the stainless steel with water.

It should be understood clearly that the procedure outlined above, in answer to the question, is not an exact contract specification to be followed by the Contractor. Moreover, it is not the only acceptable procedure for removing discoloration."

g. "4-5/7.2 Stainless Steel shall be shop cleaned to remove dust, dirt, stains and other foreign matter, employing such methods as are particularly recommended in writing by manufacturer of stainless steel employed in work and approved on trial basis by Contracting Officer. Immediately after such cleaning, protective coverings shall be restored and any and all unprotected stainless steel given adequate protection."

Review of ASTM Standard

The historic ASTM standards provides guidance for interpretation of materials and practices used, as these were the reference standards available at the time of construction.

The original design documents for the Arch refer to ASTM A167-63, *Standard Specification for Corrosion-Resisting Chromium-Nickel Steel Plate, Sheet, and Strip*, which includes the following:

1. Description of terms:
   a. "Plate - Material 3/16 inch and over in thickness and over 10 in. in width."
   b. "Sheet - Material under 3/16 in. in thickness and 24 in. and over in width. Material under 3/16 in. in thickness and in all widths with No. 3 to No. 8 finishes, inclusive."
2. Finish for Sheet
   a. "No 3 Finish - Intermediate polished finish...for use where a semi-finished polished surface is required for subsequent finishing operations following fabrication. Where sheets or articles made from it will not be subject to additional finishing or polishing operations, No. 4 finish is recommended."
   b. "No. 4 Finish - General purpose, polished finish...widely used for restaurant equipment, kitchen equipment, store fronts, dairy equipment, etc. Following initial grinding with coarser abrasives, sheets are generally finished last with abrasives approximately 120 to 150 mesh."
3. Finish for Plate
   a. "Hot-rolled, annealed or heat treated, surface cleaned and polished - Polish finish is generally No. 4 finish."
4. The chemical requirements for Type 304 stainless steel are listed as 0.08 percent carbon (max), 2.00 percent manganese (max), 0.045 percent phosphorous (max), 0.030 percent sulfur (max), 1.00 percent silicon (max), 18.00 to 20.00 percent chromium, and 8.00 to 12.00 percent nickel.

ASTM A380-54T, *Tentative Recommended Practice for Descaling and Cleaning Stainless Steel Surfaces*, provides non-mandatory recommendations for cleaning stainless steel. The standard was not referenced in the historic documents, but a review was completed to better understand common practice at the time that the Arch was constructed. The standard describes three steps for cleaning 300 series stainless steel:

1. An initial degreasing procedure using alkaline cleaners, emulsions, or solvents to remove grease, oil, and lubricants
2. Pickling using proprietary formulae, a molten alkali, salt, sulfuric acid, nitric and hydrofluoric acid baths, or electrolytic pickling to remove metallic iron, iron oxide scale, and other surface contaminants. Abrasive blasting is also described as a technique to remove surface contaminants.
3. Additional scale removal and whitening using a nitric and hydrofluoric acid bath

The standard also provides a footnote noting that passivation is recommended, either by exposing the stainless steel to an environment that promotes natural passivation, or chemically using nitric acid after the initial acid cleaning.

Currently, ASTM provides two standards that address finish and chemical requirements, which are included here as a review of current standard practice. ASTM A480-14B, *Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip*, specifies finishes as follows:

1. Definitions:
   a. "Plate - material 3/16 in. and over in thickness and over 10 in. in width"
   b. "Sheet - material under 3/16 in. thickness and 24 in. and over in width"
2. Finish for Sheet
   a. "No 3 Finish - Intermediate polished finish...a linearly textured finish that may be produced by either mechanical polishing or rolling. Average surface roughness (Ra) may generally be up to 40 micro-inches."
   b. "No. 4 Finish - General purpose polished finish...a linearly textured finish that may be produced by either mechanical polishing or rolling. Average surface roughness (Ra) may generally be up to 25 micro-inches."
   c. "There may also be overlap in measurements of surface roughness for both No. 3 and No. 4 finishes."
3. Finish for Plate
   a. "Hot-rolled or cold-rolled, and annealed or heat treated, and surface cleaned and polished - Polish finish is generally No. 4 finish."

ASTM A240-15, *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications*, specifies chemical composition, as follows:

1. The chemical requirements for Type 304 stainless steel are listed as 0.07 percent carbon (max), 2.00 percent manganese (max), 0.045 percent phosphorous (max), 0.030 percent sulfur (max), 0.75 silicon, 1.00 percent sulfur (max), 17.50 to 19.50 percent chromium, and 8.00 to 10.50 percent nickel.

Historic Information from "Monument to the Dream"

WJE reviewed the documentary "Monument to the Dream" to gain additional information on the construction of the Arch. The film was produced in 1967 by Guggenheim Productions, Inc., of Washington, D.C.

Significant observations from the film are as follows, with related screen captures of the documentary and time stamps noted in the figures:

1. During handling in the PDM fabrication shops, suction cups were used to handle the stainless steel panels (Figure 15). The suction cups left circular marks on the panels (Figure 16), although it is not clear if the marks were removable or if they were scratches in the stainless steel finish.
2. After the panels were constructed in the fabrication shops, they were transported to the jobsite on railcars (Figure 17 and Figure 18).
3. Black adhesive strips were visible on the stainless panels during lifting on site (Figure 19 and Figure 20). It is not known why or when the strips were applied to the panels. The adhesive material is unknown.
4. An unknown residue, apparently unrelated to the adhesive strips, was observed on the stainless steel panel during construction (Figure 21). The adhesive material is unknown.
5. Adhesive marketing decals were observed on the stainless steel panels (Figure 22). The adhesive material is unknown.
6. The stainless steel panels required local handling for fit-up to adjacent panels (Figure 23), before on-site field welding could be completed (Figure 24).

7. Bolts were installed on the extrados of the stations for attachment of the creeper derricks (Figure 25 and Figure 26).
8. An overall view of the Arch during construction shows a variety of finishes on the stainless steel panels (Figure 27).
9. Several overall views of the Arch during construction show streaking and staining on the stainless panels (Figure 28 to Figure 31).
10. The documentary did not describe or document the removal of the creeper derrick or the cleaning process at the end of the construction period.

Figure 15. Suction cups at PDM fabrication shop. Source: "Monument to the Dream" (03:26), courtesy Guggenheim Productions, Inc., 1967.

Figure 16. Close-up of a suction cup marking (circled) on the stainless steel. Source: "Monument to the Dream" (03:31), courtesy Guggenheim Productions, Inc., 1967.

Figure 17. Shipping the panels from the PDM fabrication plants by train to the job site. Source: "Monument to the Dream" (06:03), courtesy Guggenheim Productions, Inc., 1967.

Figure 18. View of the panels on the railcar. Source: "Monument to the Dream" (05:06), courtesy Guggenheim Productions, Inc., 1967.

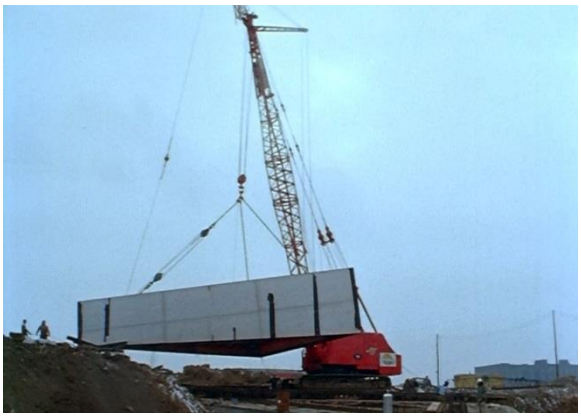

Figure 19. Lifting a section into place; note the black adhesive strips on the stainless steel. Source: "Monument to the Dream" (07:14), courtesy Guggenheim Productions, Inc., 1967.

Figure 20. Lifting a section into place; note the black adhesive strips on the stainless steel. Source: "Monument to the Dream" (07:19), courtesy Guggenheim Productions, Inc., 1967.

Figure 21. Residue on the stainless steel during construction. Source: "Monument to the Dream" (06:42), courtesy Guggenheim Productions, Inc., 1967.

Figure 22. Decal on the stainless steel during construction. Source: "Monument to the Dream" (08:03), courtesy Guggenheim Productions, Inc., 1967.

Figure 23. Fit-up between stainless steel panels. Source: "Monument to the Dream" (09:43), courtesy Guggenheim Productions, Inc., 1967.

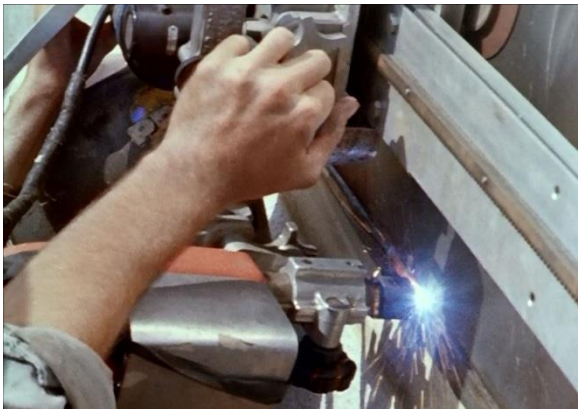

Figure 24. Field weld on site. Source: "Monument to the Dream" (10:05), courtesy Guggenheim Productions, Inc., 1967.

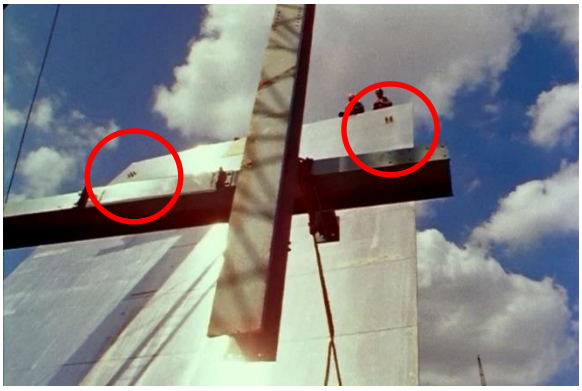

Figure 25. Creeper derrick bolts (circles) on stainless steel panels. Source: "Monument to the Dream" (13:34), courtesy Guggenheim Productions, Inc., 1967.

Figure 26. Creeper derrick attachment. Source: "Monument to the Dream" (13:50), courtesy Guggenheim Productions, Inc., 1967.

Figure 27. Overview of Arch during construction; note the variety of finishes on the stainless steel panels. Source: "Monument to the Dream" (17:43), courtesy Guggenheim Productions, Inc., 1967.

Figure 28. Streaking on the stainless steel panels during construction. Source: "Monument to the Dream" (18:32), courtesy Guggenheim Productions, Inc., 1967.

Figure 29. Streaking on the stainless steel panels during construction. Source: "Monument to the Dream" (19:28), courtesy Guggenheim Productions, Inc., 1967.

Figure 30. Water streaking on the stainless steel panels, during final station installation. Source: "Monument to the Dream" (23:08), courtesy Guggenheim Productions, Inc., 1967.

Figure 31. Streaking and debris on the stainless steel panels during construction. Source: "Monument to the Dream" (20:27), courtesy Guggenheim Productions, Inc., 1967.

ACCESS TO THE NORTH LEG

To complete the limited close-up investigation of the stainless steel, WJE project team members required access at the base of the north leg and along the height of the north leg. At the base, aerial lifts were used for access. Along the height of the leg, a custom IRA system was designed and installed. The access to the north leg was the first close-up access since construction of the Arch.

During Parts I and II of the corrosion investigation, the visual assessment indicated that the stainless steel was performing similarly at the north leg and the south leg. Based on the study completed during Part II to assess the feasibility of accessing the stainless steel, factors including weather, wind, and direct sunlight were determined to potentially affect the schedule for performing the IRA inspection. Initially, WJE had planned to complete the aerial lift access at the base of the south leg, and the IRA access at the north leg simultaneously during a single site visit in October 2014. Since the south leg received more direct sun exposure and the stainless steel temperature would be higher in direct sunlight, the IRA work was to be completed on the north leg. Additionally, based on past weather reports, it appeared that October had historically calmer weather.

During the review of the safety protocols associated with the process outline above, it became apparent that the Arch would need to be closed during this site work in order to provide a safe working environment and to protect the public. Since closing access to the Arch completely was not acceptable to the NPS, the site visit schedule was revised to perform both the IRA and the aerial lift work at the north leg, but not simultaneously.

WJE, Metro, and NPS worked together to implement a safety plan to provide a safe working environment for the team members and a safe environment for the public (Figure 32 and Figure 33). During the lift access work, a chain link fence was installed around the north leg. During the IRA access, additional safety precautions were taken, including a barricade plan, a canopy at the south leg to protect pedestrians, a command center, and several safety protocols to follow in the event of a rescue. The barricade plan defined two perimeters, including an inner chain link fence surrounding the north leg and an outer caution fence surrounding the grounds encompassing both legs and the areas between the legs. The overhead canopy allowed safe access to the Arch, allowing the public to cross within the established safety perimeter to enter the monument. Visitors also had close-up access to the base of the south leg of the Arch. The south tram remained in service to transport visitors to the observation deck.

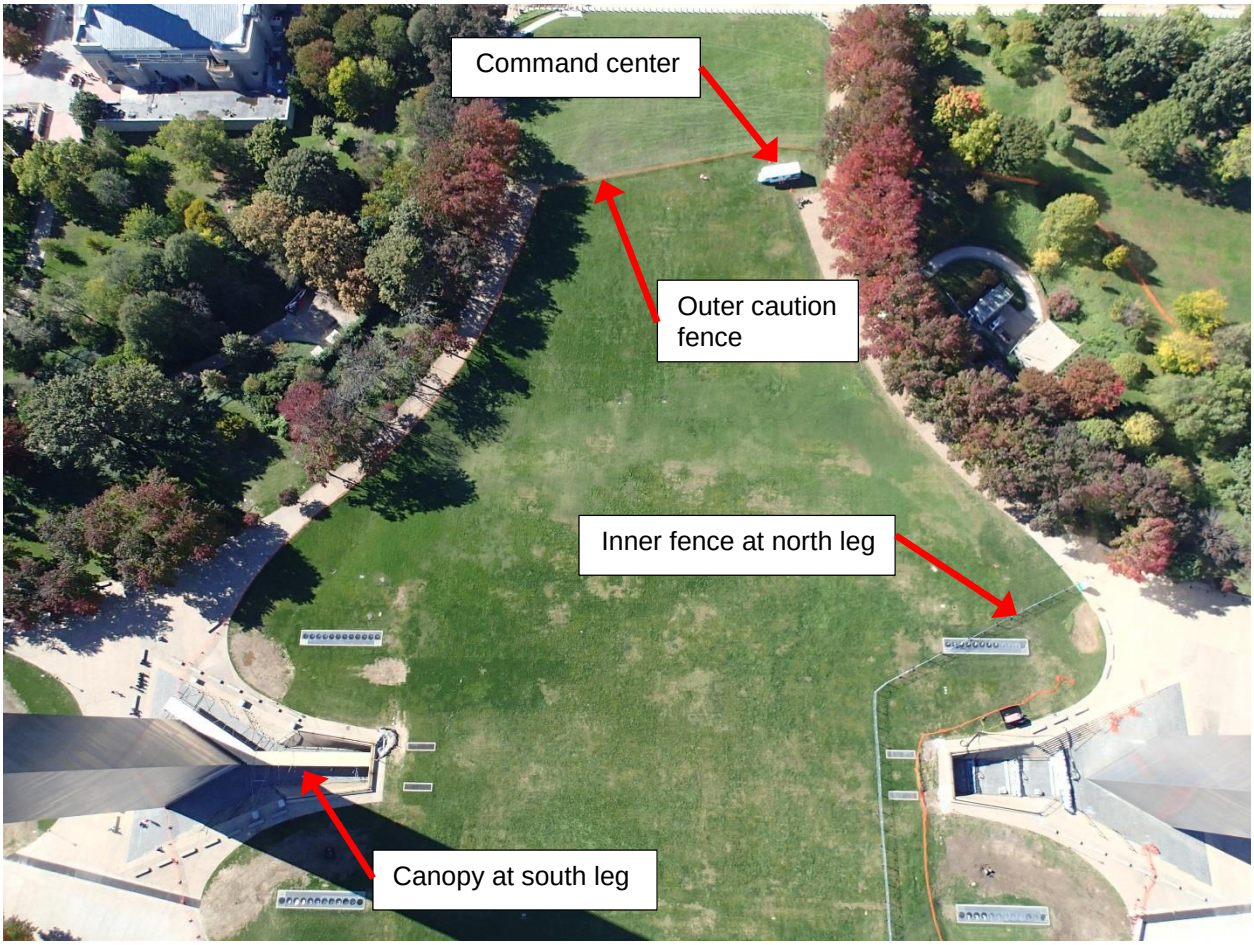

Figure 32. Overall view of the command center, barricade plan, and canopy. Photo is taken looking west. (Photo by authors, 2014)

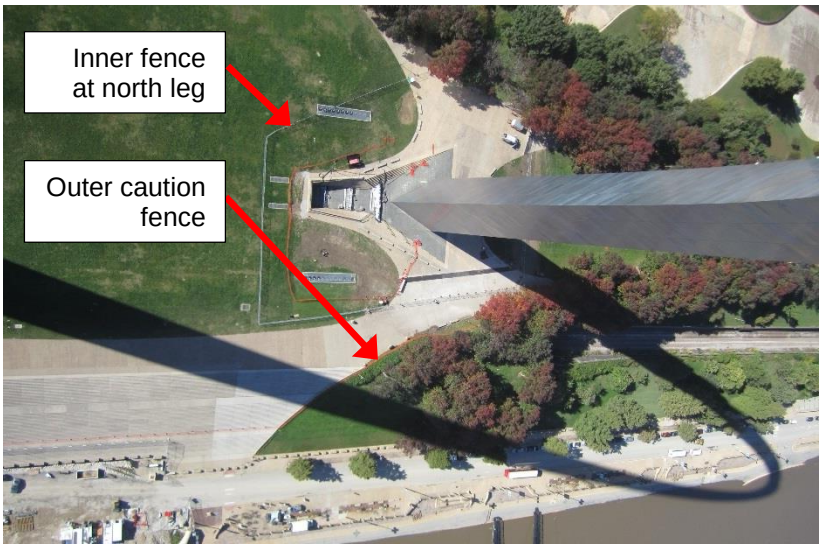

Figure 33. Inner and outer fence at the north leg. (Photo by authors, 2014)

Aerial Lift Access

WJE performed the investigation at the base of the north leg from September 29, 2014 to October 1, 2014. Two 135 foot aerials lifts provided access above grade (Figure 34). Due to the heated paving system, use of the aerial lifts was restricted to the concrete surface only. The lifts were used to gain access to the extrados to a height of approximately Station 65, and to gain access to the intrados to a height of approximately Station 66. The intent of the close-up inspection was to observe the condition of the stainless steel panels, field welds, and shop welds, and to provide access to remove weld and deposit samples.

During the site work, WJE documented the existing conditions with photographs. WJE has provided the JEFF archives with a digital copy of all photographs taken during the site work, in addition to the removed samples of the welds and the surface deposits.

Figure 34. Overall view of the north leg with the aerial lifts. (Photo by authors, 2014)

Industrial Rope Access

WJE completed the IRA portion of the investigation from October 11, 2014 to October 22, 2014. The time spent on site included installation and removal of the custom IRA system to access the extrados of the north leg and a limited portion of the west intrados of the north leg. The inspection of the extrados of the north leg was completed on October 19, 2014. The inspection of the limited portion of the west intrados of the north leg was completed on October 21, 2014.

WJE designed a custom IRA system to allow personnel to have hands-on access to the stainless steel skin without damage to the structure, or installation of permanent attachments to the stainless steel skin. The IRA system allowed access to the exterior face of the north leg for the entire height, and access to the west intrados on the north leg from approximately Station 28 to Station 35. For use in the design of the IRA system, WJE retained 3D Fusion to print a three-dimensional model of the Arch to scale (Figure 35). WJE provided the model to the JEFF archives upon completion of the field work for this study.

During the IRA work, WJE used helmet-mounted digital video recorders from various vantage points to document the existing conditions with video, in addition to still photographs taken by WJE personnel. The

digital video footage and digital photographs have been provided to the JEFF archives. See Appendix B for a summary of the helmet-mounted digital video footage provided.

Figure 35. View of the three-dimensional model used to design the custom IRA system. (Photo by authors, 2014)

The IRA system used the temporary construction of a bridle system that spanned in tension from the top of the Arch down the extrados of the north leg to the base of the arch. An overall schematic view of the IRA system is provided in Figure 36. WJE then used two-rope descent systems along the bridle system in order to reach areas of work, remove staining samples, and inspect the welds on the extrados. No intrusive or permanent connections were made to the exterior stainless steel skin or interior structural components. Metal components of the IRA system were separated from direct contact with the stainless steel skin at all times to avoid contamination of, and/or potential damage to, the stainless steel. Additionally, WJE personnel used work boots, knee pads, and other equipment that would not leave any marks on the stainless steel skin.

The primary anchor points for the bridle and the two rope systems were located at the center of the Arch observation deck. A bulkhead was constructed by NPS to secure the working half of the observation deck from the public, as the observation deck remained open during the inspection. The primary anchor point consisted of nylon anchor slings threaded through the windows on both sides of the observation deck (Figure 37) and then extended to the top of the arch (Figure 38). Window frames were protected with metal and canvas to prevent damage to the slings and interior finishes. NPS provided clear Plexiglas temporary covers to seal the windows, but otherwise allowed the windows to remain open during the IRA work.

The anchor slings for the bridle system went up and over the east and west edges of the extrados and attached to the primary anchor point consisting of a threaded rod with custom fit angles that bracketed the edges of the extrados. This configuration allowed the tensioned lines to remain intact when the hatch was closed. To separate the system from the stainless steel, the threaded rod was passed through plastic spacer discs and nylon pads were attached to the custom fit angles (Figure 39).

The bridle system below the primary anchor point was composed of two synthetic ropes (twelve strand Amsteel by Samson Rope) and a series of intermediate anchor straps (Figure 40). Amsteel was chosen for its low stretch properties, similar to wire rope, but more importantly because it would not damage the

stainless steel skin due to contact. The ropes were attached to the primary anchor point and the secondary anchor point, and were positioned to run at the approximate third points of the extrados. The intermediate anchor straps provided intermediate attachment points during installation and removal by preventing the two-rope descent systems from migrating off the extrados. The intermediate anchor straps were located at Stations 6, 10, 14, 18, 21, and 25, and were composed of synthetic straps tensioned between custom fit angles that bracketed the edges of the extrados. The secondary anchor point, located between Station 28 and Station 29, was constructed similarly to the primary anchor point (Figure 41). The west side of the secondary anchor point provided the upper connection point for the secondary tensioned line that was used to access the west face of the north leg intrados.

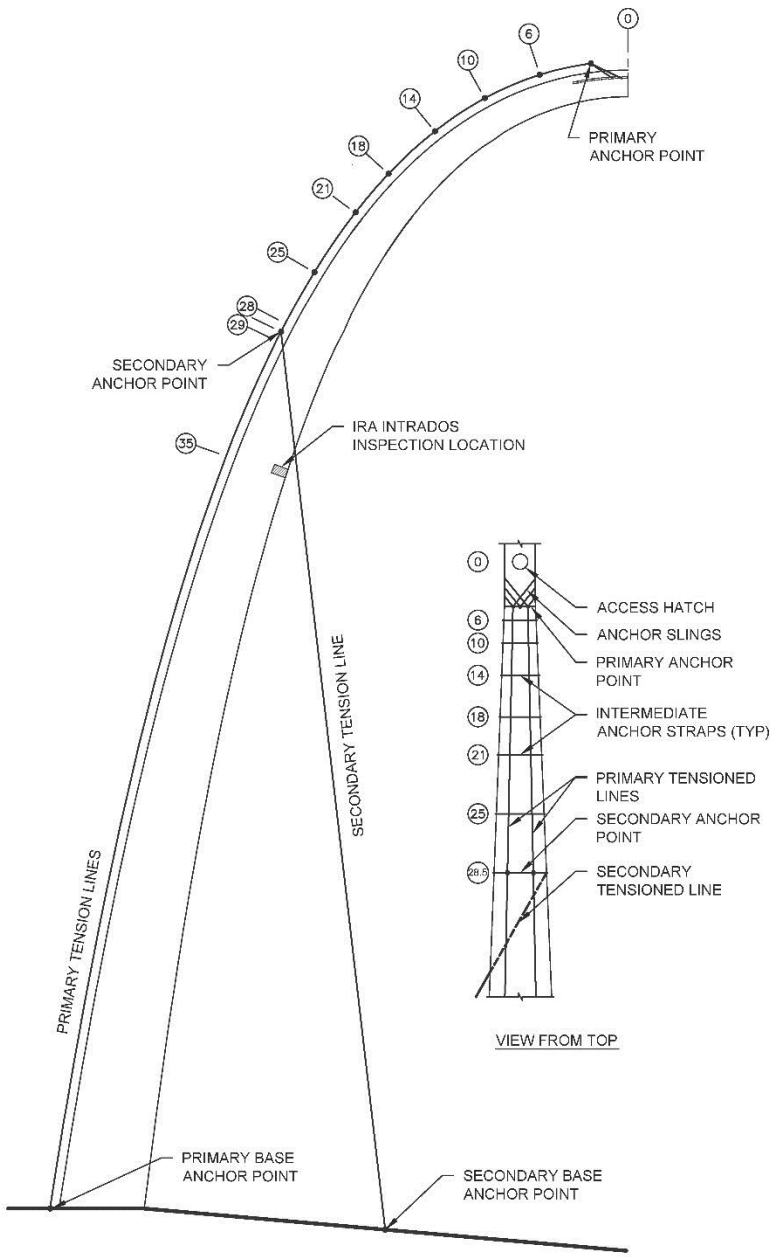

Figure 36. Schematic IRA bridle plan

Below the secondary anchor point, the bridle system consisted of two tensioned lines extending along the extrados and were tensioned between the secondary anchor point and the primary base anchor points. These primary tensioned lines consisted of two Amsteel ropes positioned at the third points of the extrados and then tensioned using chain hoists with in-line tension meters to accurately monitor and adjust the tensions in the system as necessary during the IRA work. The primary base anchor points consisted of two 5,000 pound modular concrete barriers located north of the paver system at the base of the north leg (Figure 42). These primary tensioned lines were used as guide lines for the extrados inspection to prevent uncontrolled lateral movement.

To provide a guide line along the west intrados at the north leg, a secondary tensioned line was installed between the west side of the secondary upper anchor point and the secondary base anchor point. The placement of this tensioned line allowed hands-on access to the west intrados from Station 28 to Station 35. This secondary tensioned line consisted of a single Amsteel rope. The secondary base anchor point consisted of a single 5,000 pound modular concrete barrier located east of the paver system at the base of the north leg. The system was tensioned using chain hoists with in-line tension meters to accurately monitor and adjust the tensions in the system as necessary during the IRA work.

Throughout the IRA investigation, WJE monitored the weather on site, including wind speed, wind direction, and precipitation, to ensure safe working conditions. Wind speed at the top of the Arch was measured with a weather station mounted to one of the lightning rod fixtures. If a sustained wind speed above 25 miles per hour (mph) or a gust above 30 mph was recorded, access to the stainless steel skin was halted until the weather became more favorable. The IRA investigation was halted several times due to unfavorable weather conditions, extending the time spent on site.

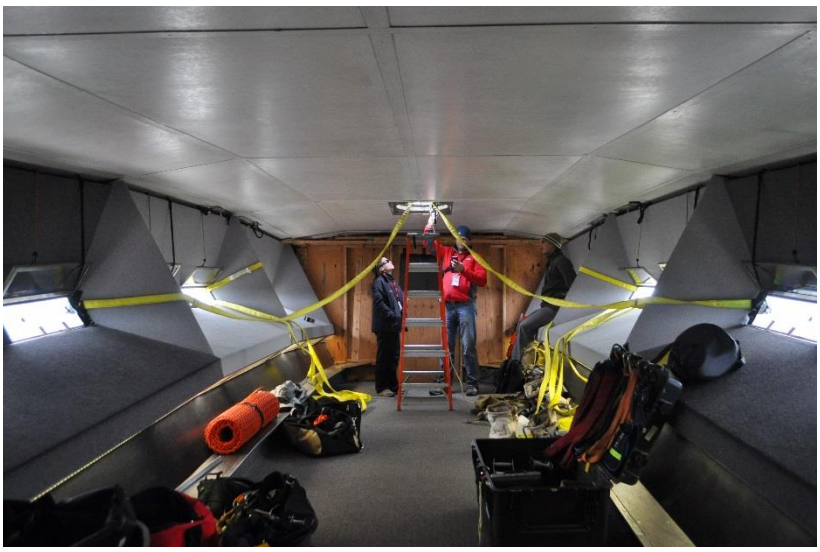

Figure 37. Primary anchor points within observation deck during installation. (Photo by authors, 2014)

Figure 38. View of the primary anchor points for the bridle system on top of the Arch. (Photo by authors, 2014)

Figure 39. Custom fit angle brackets. (Photo by authors, 2014)

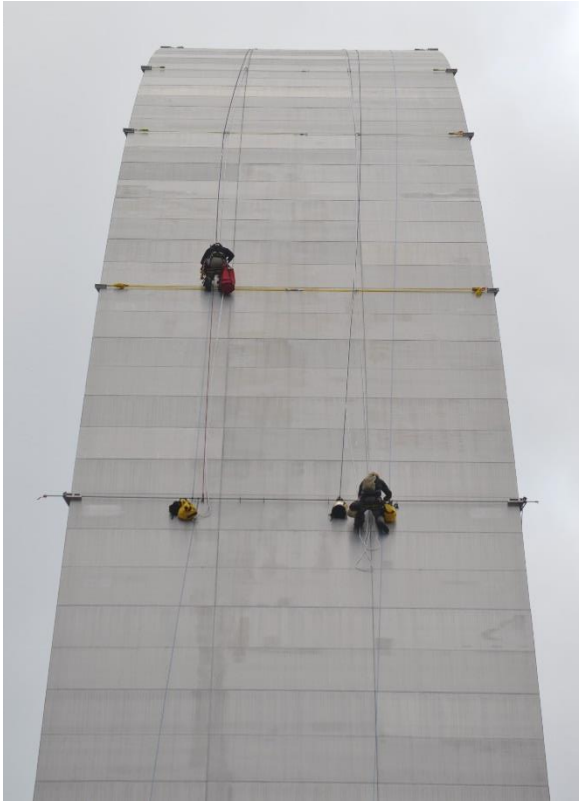

Figure 40. View of the intermediate anchor straps, bridle system and secondary anchor point. (Photo by authors, 2014)

Figure 41. View of the secondary anchor point during installation. (Photo by authors, 2014)

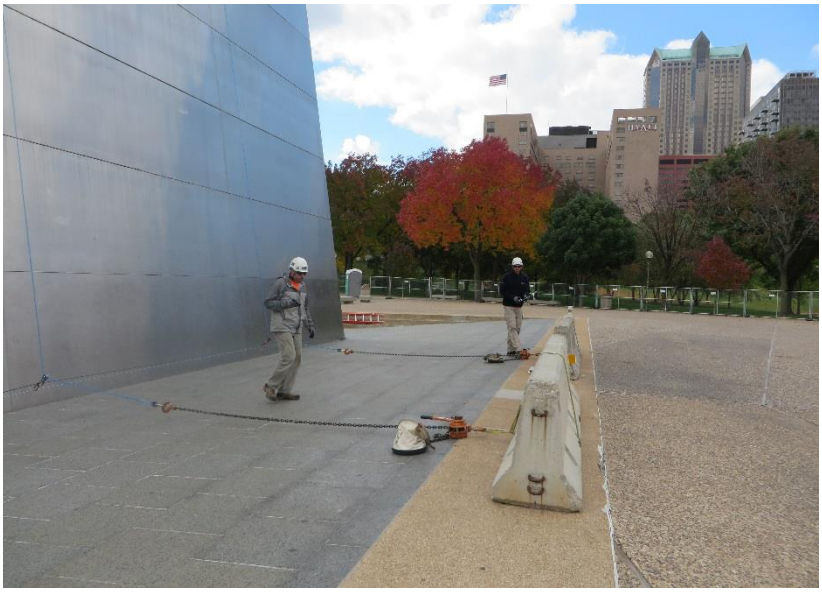

Figure 42. View of the primary base anchor points and tensioning systems. (Photo by authors, 2014)

FIELD OBSERVATIONS

The field investigation addressed a variety of visual anomalies in the appearance of the exterior stainless steel. In general, the visual anomalies of the stainless steel skin can be classified in three categories:

1. Blemishes refer to alterations to the surface texture that create a visual aberration under specific lighting conditions and at certain observation angles. (During the original construction, the NPS used the term "blemishes" to describe visual surface anomalies. The same word is used in this report for consistency.)
2. Deposits refer to particles such as atmospheric pollutants on the stainless steel surface.
3. Discoloration refers to chemical alterations, such as superficial corrosion staining, on the stainless steel surface.

While the visual anomalies can be categorized separately as noted above, they frequently overlap where observed on the Arch. Additionally, while the inspection completed in the Part III study was conducted on the north leg only, the conditions noted are visually apparent on the south leg as well. In general, based on photographic documentation during Part I and Part II, the visual anomalies are consistent, and are not significantly worse, than when observed in previous phases of the corrosion investigation.

Visual Observations from Grade

Blemishes

1. The blemishes are frequently more difficult to see at close range and frequently required assistance from someone on grade to direct the staff inspecting them close-up.
2. Some of the blemishes can only be seen under specific conditions, such as certain sun angles, light intensity, and/or viewing angles.
3. The finish on the stainless steel consisted of short lines parallel to the long edges of the panel (Figure 43).
4. Some of the panels appeared darker than adjacent panels, while other panels appeared lighter (Figure 44). The apparent relative lightness of the panels varied based on how the light struck the panels and the observation angle of the observer.

5. Microscopic examination of some blemishes revealed that the blemish often consisted of a series of surface scratches that are shallower than the finish profile. Some of these blemishes appear darker than others. Several types of these blemishes were observed, as follows:
   a. Horizontal bands with a height of approximately one-third of the panel height (Figure 44)
   b. Vertical blemishes with an approximate width of 8 to 10 inches, contained within a specific station, (Figure 45 and Figure 46)
   c. Regular shaped blemishes (Figure 47, Figure 48 and Figure 49)
   d. Circular blemish with diameter of approximately 10 or 18 inches (Figure 50)
   e. Variations of dark and light vertical streaking patterns within the surface finish (Figure 51)
   f. Large arc-shaped blemishes caused by scratches (Figure 52)
6. Rectangular blemishes on the extrados that corresponded to the creeper derrick attachment (Figure 53)
7. Brush marks adjacent to welds (Figure 54)
8. Field welds tended to be rougher with more weld spatter (Figure 55). Some field welds were irregular in shape (Figure 56). Some weld slag was also identified.
9. Welds that contained weld repairs that exhibited a shiny appearance (Figure 57 and Figure 58). These weld repairs occurred during installation to address weld gaps or porosity.
10. Minor pitting of the surface of the stainless steel was observed. The depth of the pit was negligible compared to the panel thickness.
11. Incised graffiti and impact damage blemishes, as typically observed in the two lowest panels at the base of the Arch (Figure 59). The depth of the damage ranged from superficial scratches to deep hammer indents (Figure 60). The depth of the incised graffiti was measured using a pit depth gauge (Figure 61). The incised surface graffiti was generally 1 to 5 mils (0.001 to 0.005 inch) deep. Circular (ball peen) hammer indents on the center section of the extrados (Figure 61) were approximately 6 to 11 mils deep. The deepest damage was observed at the half-moon hammer impact locations at the eastern side of the extrados, where dents were 25 to 35 mils deep. The most prominent damage on the western face near the south edge was generally near 8 to 15 mils deep.
12. The incised graffiti is frequently associated with embedded iron particles that have corroded.

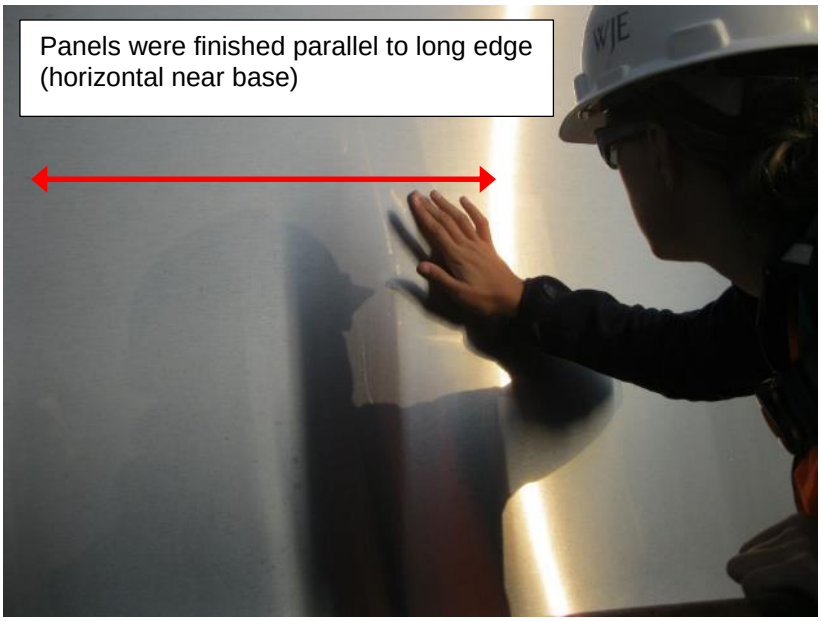

Figure 43. Examination of panel finish. (Photo by authors, 2014)

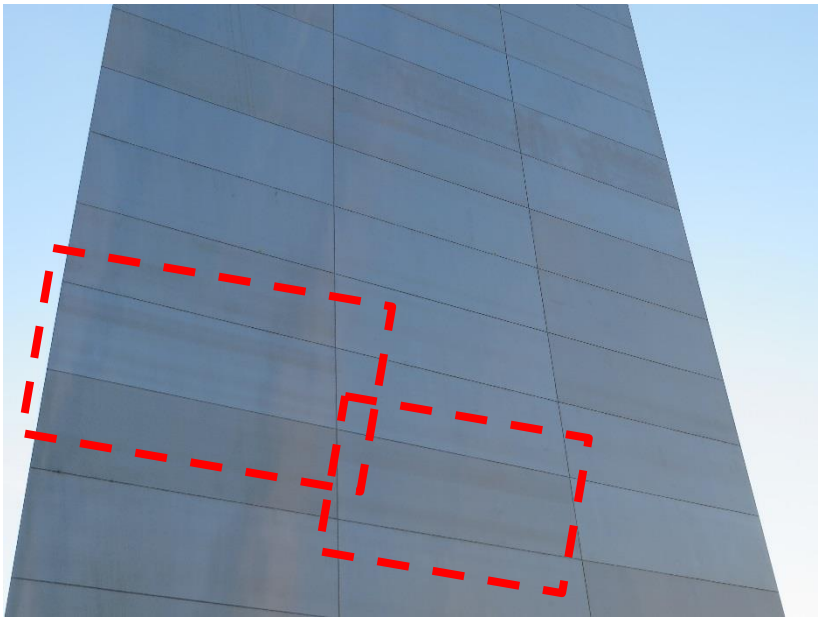

Figure 44. Large horizontal bands on the panels shown within the dashed lines. (Photo by authors, 2014)

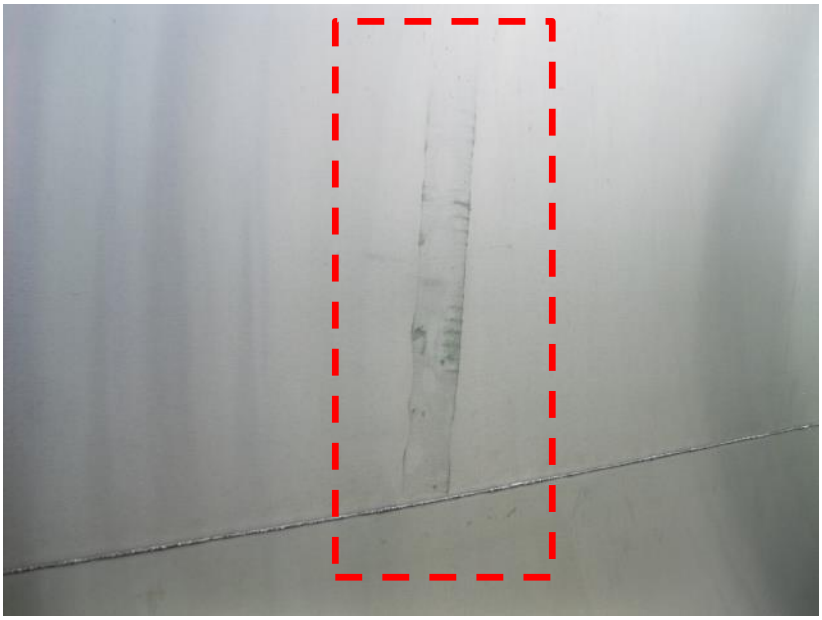

Figure 45. Vertical blemish within panel section (west face) shown within the dashed line. (Photo by authors, 2014)

Figure 46. Vertical blemish within panel. (Photo by authors, 2014)

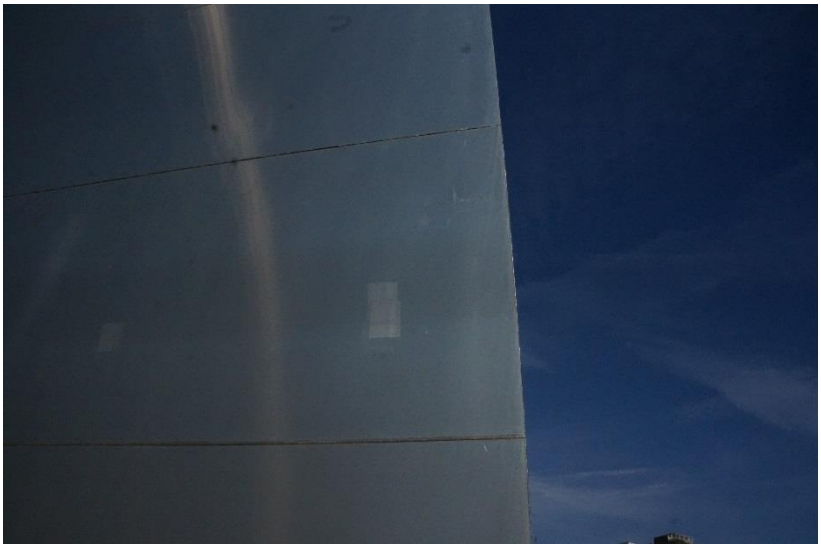

Figure 47. Overall view of blemishes. (Photo by authors, 2014)

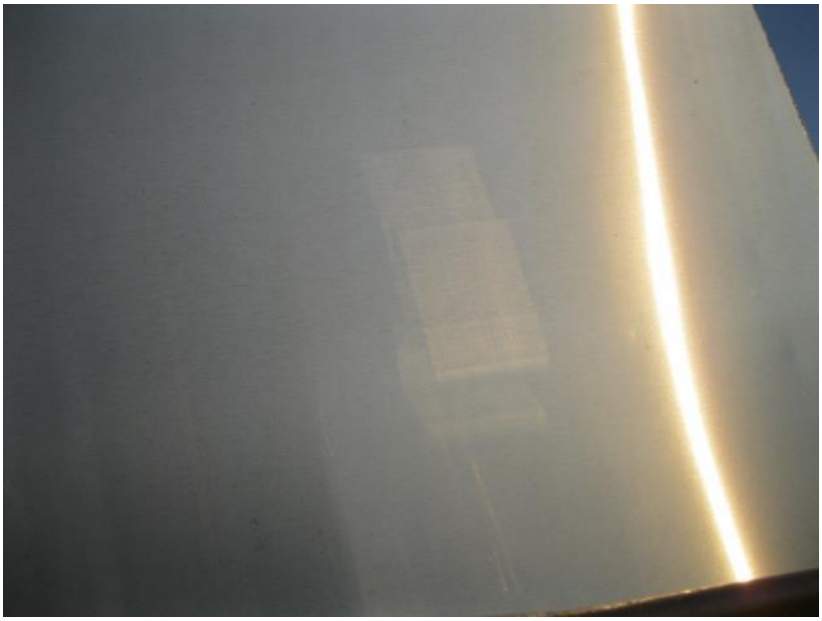

Figure 48. Blemish in panel surface associated with scratches in the surface finish. (Photo by authors, 2014)

Figure 49. Regular shaped blemish. (Photo by authors, 2014)

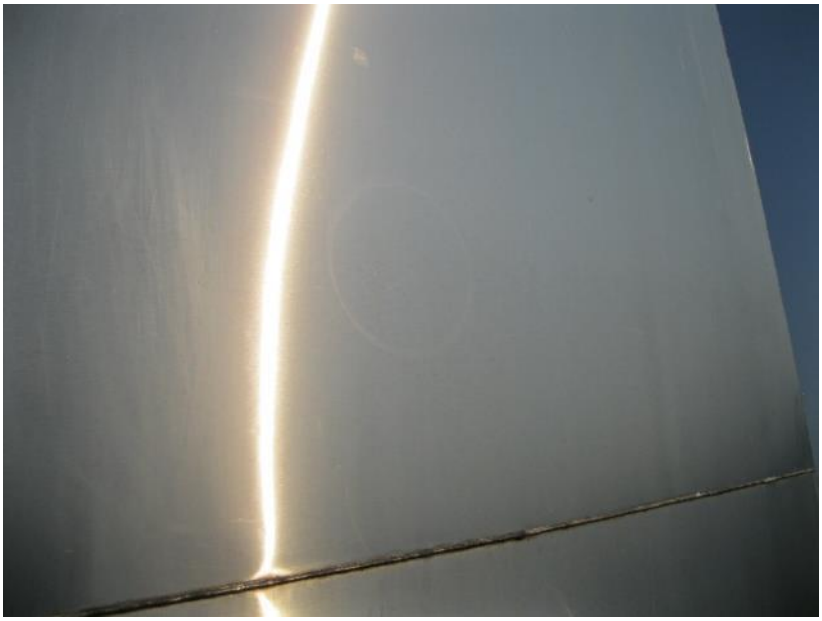

Figure 50. Large circle visible on panel surface. (Photo by authors, 2014)

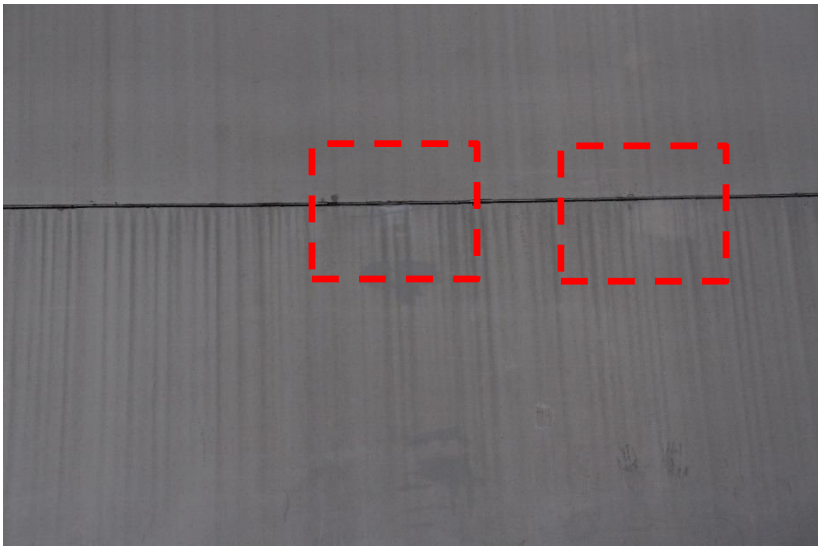

Figure 51. Variations of dark and light patterns within the surface finish. Dashed locations were part of cleaning trials described below. (Photo by authors, 2014)

Figure 52. Large arc-shaped blemishes. (Photo by authors, 2014)

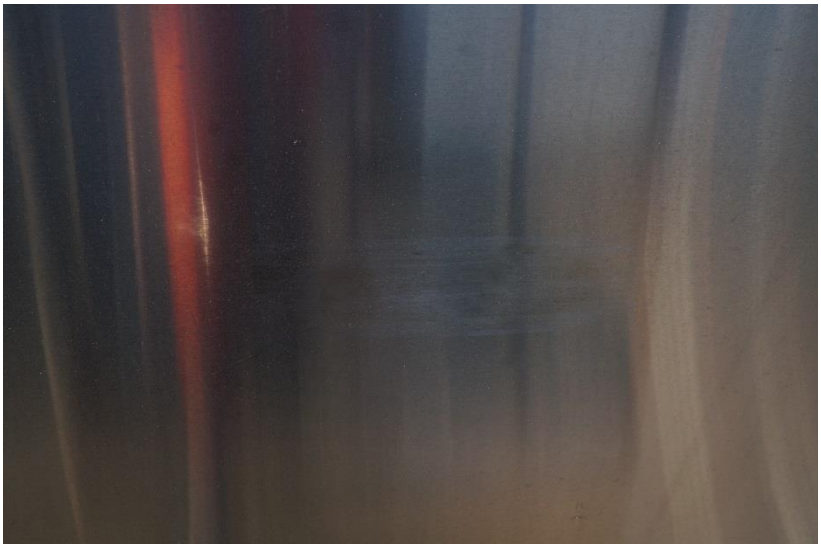

Figure 53. Blemish from field finish area after removing creeper derrick attachment. (Photo by authors, 2014)

Figure 54. Brush marks adjacent to weld. (Photo by authors, 2014)

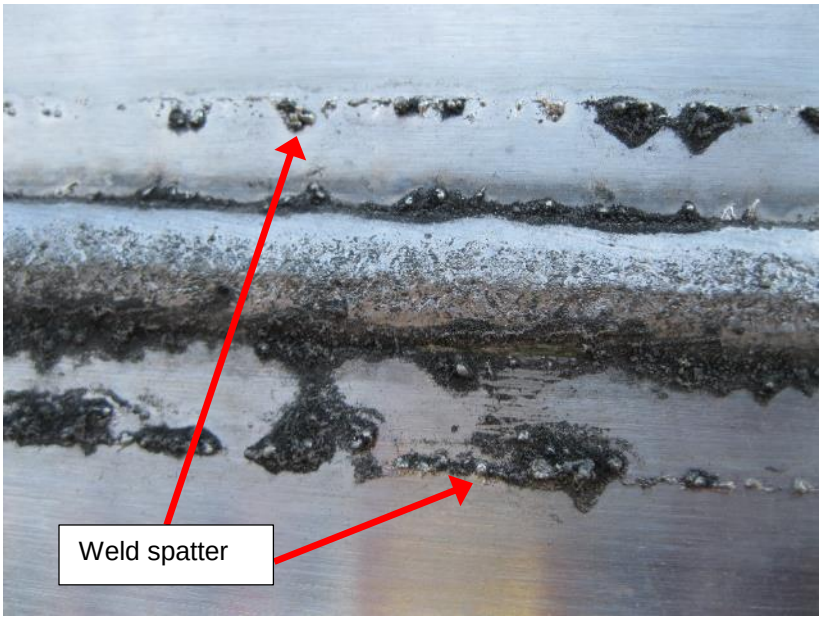

Figure 55. Typical weld spatter. (Photo by authors, 2014)

Figure 56. Irregular field weld. (Photo by authors, 2014)

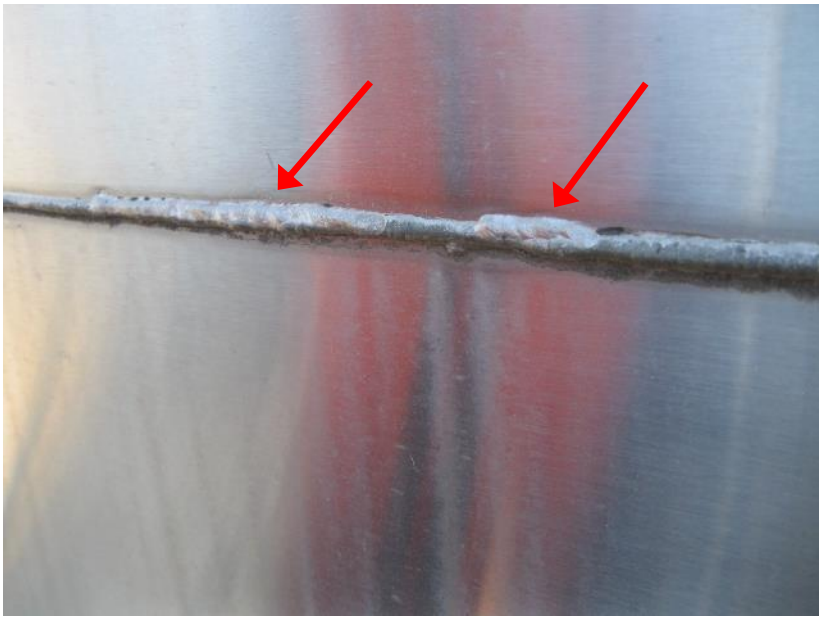

Figure 57. Weld repair along field weld. (Photo by authors, 2014)

Figure 58. Weld repair along field weld. (Photo by authors, 2014)

Figure 59. Incised graffiti at the base. (Photo by authors, 2014)

Figure 60. Impact damage (extrados). (Photo by authors, 2014)

Figure 61. Using pit depth gauge to measure depth of incised graffiti. (Photo by authors, 2014)

Deposits

1. Surface deposits were common at many welds that were horizontal to grade.
   a. The overall appearance tended to have dark vertical streaks and was more pronounced below the field welds (Figure 62 to Figure 64).
   b. Upon closer inspection, the rougher welds and weld spatter collected more surface deposits below the welds (Figure 65 to Figure 67). The heaviest deposit build-up was observed at locations with more weld spatter.

2. Irregularly shaped areas of an oily substance that collected deposits were observed (Figure 68). The deposits could be easily wiped off during the cleaning trials with a clean rag dipped in alcohol.
3. At the base of the Arch on the east face, the chloride content on the surface of the stainless steel was measured using a Chlor*Test as manufactured by Chlor*Rid International, Inc. Surface chloride content is estimated by flushing a known area with an extraction fluid, which is then checked for chloride using a titration tube reading in parts per million (ppm). A test was performed on the east face, 3 feet above grade. The chloride content was below the detection threshold (less than 1 ppm), which may be a result of low exposure or may indicate that the chloride contamination from deicing salts has been removed through rain washing.

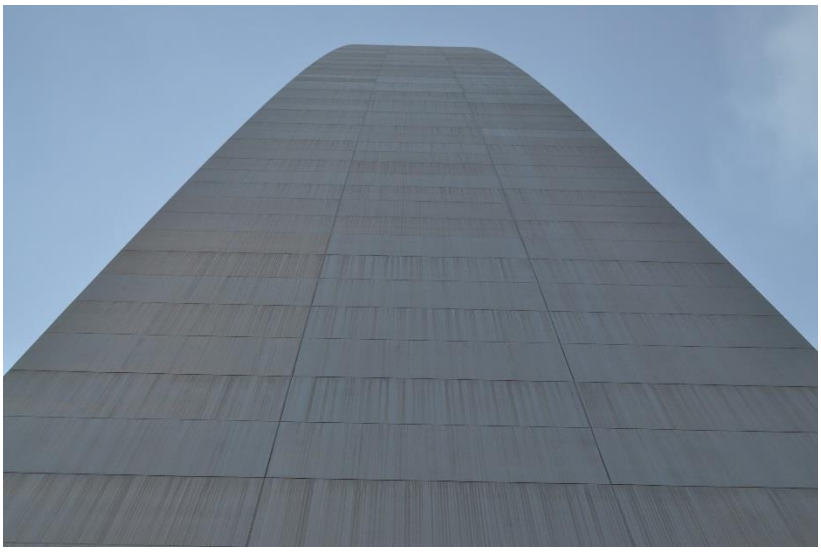

Figure 62. Deposits from run off from horizontal welds. (Photo by authors, 2014)

Figure 63. Deposits and blemishes below a field weld. (Photo by authors, 2014)

Figure 64. Deposits and blemishes below a field weld. (Photo by authors, 2014)

Figure 65. Weld spatter and dark deposits in weld area. (Photo by authors, 2014)

Figure 66. Light weld spatter with little surface deposits. (Photo by authors, 2014)

Figure 67. Heavier weld spatter with greater surface deposits. (Photo taken by authors, 2014)

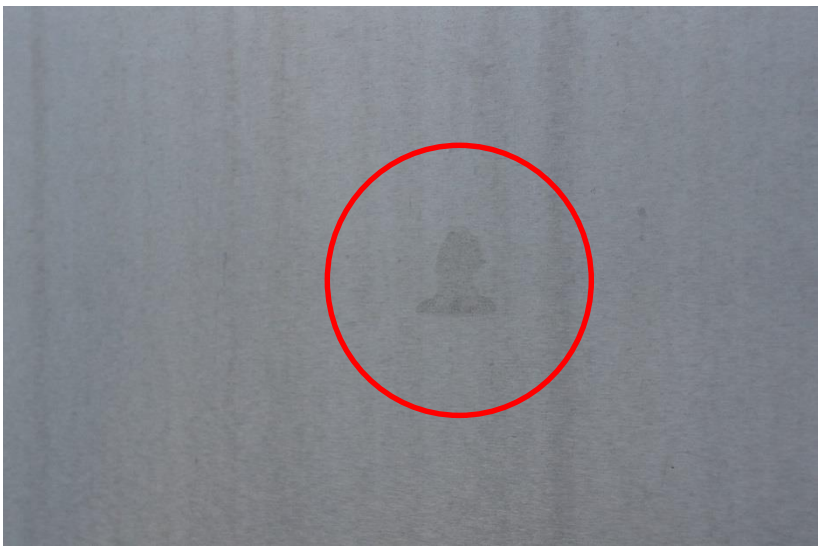

Figure 68. Irregularly shaped deposit. (Photo by authors, 2014)

Discoloration

1. Heat tint, which is a dark halo along the length of the weld, was observed at some weld locations (Figure 69).
2. There are isolated areas of red-orange corrosion from iron particle staining below weld (Figure 70).
3. Overall superficial corrosion staining with a brownish-orange color was observed at the lowest five to eight panels (Figure 71).
4. At the base of the Arch in areas of incised graffiti and impact damage blemishes, corrosion staining with a red-orange hue was observed to be associated with incised graffiti at the lowest two panels (Figure 72).

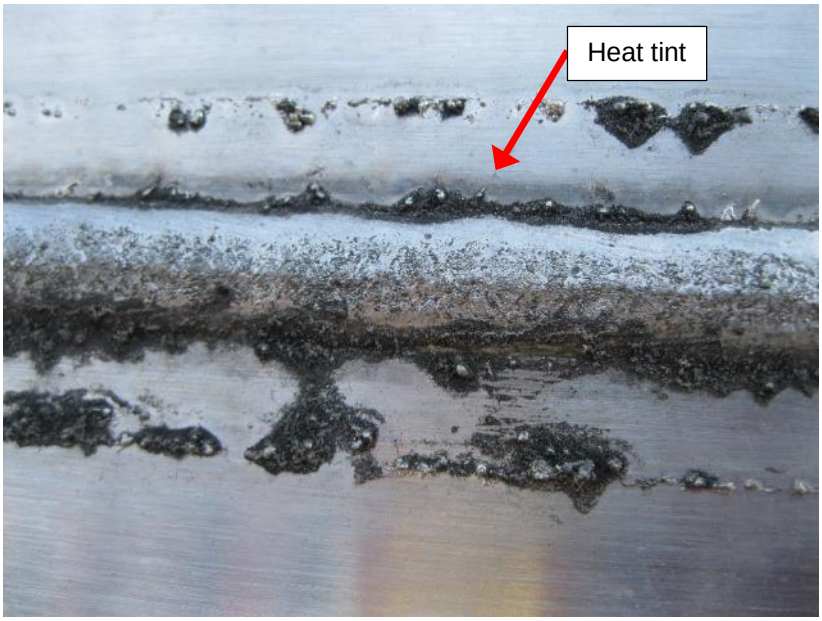

Figure 69. Heat tint at weld. The heat tint is the dark gray color that is not associated with the deposit at the weld spatter. (Photo by authors, 2014)

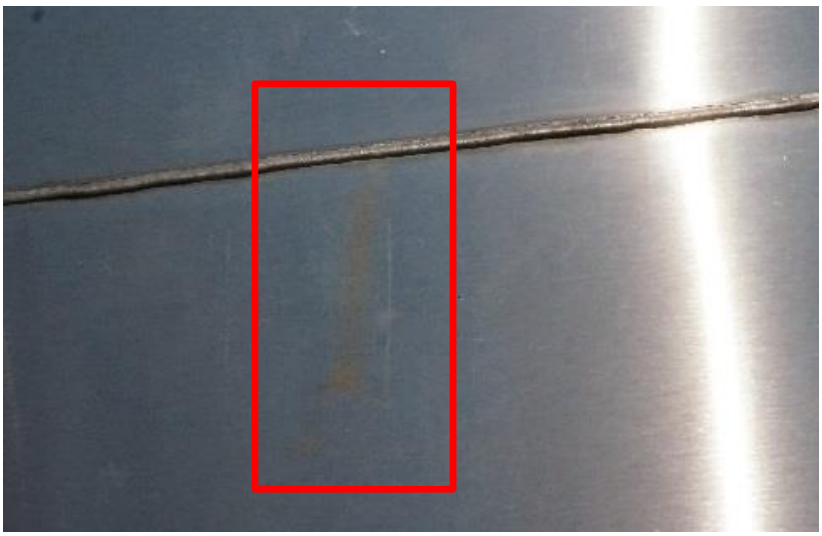

Figure 70. Red-orange corrosion staining from iron deposit below weld within the red box. (Photo by authors, 2014)

Figure 71. Overall superficial corrosion staining with a brownish-orange color at the grade up to a height of the approximately the eight panels below the red dashed line. (Photo by authors, 2014)

Figure 72. General superficial surface corrosion staining and incised graffiti. (Photo by authors, 2014)

Other Observations from Grade

Magnetism in the Welds

At several locations, a magnet that was part of a magnetic thickness gauge was used to assess the magnetism of the welds (Figure 73). The welds varied from being non-magnetic to being faintly magnetic.

Figure 73. Faintly magnetic weld. (Photo by authors, in 2014)

Surface Profile

In order to assess whether a difference in surface profile caused by the original finishing would result in a difference in appearance, the surface profile of the stainless steel panels near grade was measured using a Mahr Federal Pocket Surf Profilometer. A profilometer provides a measure of the surface finish profile (peaks and valleys) or roughness. A diamond stylus, similar to a phonograph needle, traverses a set distance on the steel surface. The instrument measures the surface texture and provides a value that describes the amount of surface variation or roughness. The arithmetic mean of all deviations from the mean line within the total measured length provides the Average Roughness, Ra (micro-inches). There are 1,000,000 micro-inches in an inch.

The surface roughness was measured both horizontally across the panel, in line with the direction of the finish, and vertically up and down along the panel, across the direction of the finish. The results provided in Table 1 for several typical stainless steel panels at the Arch show that the vertical cross-finish measurements were much rougher (more peaks and valleys) than the horizontal measurements made in line with the finish. The typical horizontal profile had an average Ra of 13 micro-inches, and the typical vertical profile had an average Ra of 30 micro-inches, showing that the surface profile in each direction is different.

Table 1. Average Surface Profile Measurements, Ra (micro-inches)

Location	Horizontal	Vertical
Extrados, west panel, above the fourth weld from the base	12.6	35.3
Extrados, west panel, above the eighth weld from the base	18.0	24.2
Extrados, west panel, below the eighth weld from the base	11.0	34.6
East intrados, north panel, seventh panel from the base	16.0	35.0
West intrados, north panel, eleventh panel from the base	11.0	16.0
West intrados, south panel, sixth panel from the base	17.0	42.0
East intrados, north panel, sixth panel from the base	6.0	21.0
West intrados, north panel, twelfth panel from the base	16.0	51.0
West intrados, south panel, seventh panel from the base	7.0	12.0
Average of Ra measurements	***13***	***30***
Range of Ra measurements in each direction	***6 – 18***	***12 – 51***

Gloss Measurements

Panels can appear relatively light or dark, depending on how daylight strikes the surface. In order to assess whether a difference in gloss caused by the original finishing has caused a difference in appearance, gloss was measured using a Rhopoint Glossmeter. The gloss meter records gloss units (GU), which is based on a scale for non-metallic coatings of 100 being near the upper end of the spectrum for a highly polished surface, and 0 being the low end of the scale for a matte surface. Highly reflective surfaces may obtain a reading of over 100 GU. Measurements were taken in both the horizontal and vertical orientation to assess if the surface finish direction affects the gloss readings. The gloss and surface profile was measured on both light and dark appearing panels. The gloss meter used measures 20 degree, 60 degree, and 85 degree gloss. Typically, gloss at a 60 degree angle is used to measure reflectance; however, for high gloss surfaces, i.e. surfaces where the 60 degree gloss is greater than 70 GU, 20 degree gloss values are typically used. If the 60 degree gloss is less than 10 GU, than typically 85 degree gloss values are used. Select 60 degree and 20 degree measurements are summarized in Table 2 and Table 3. See Appendix C for a complete summary of the gloss meter readings.

The measured gloss was variable between locations for both types of panels, and no clear distinction in the gloss between the light and dark appearing panels was noted. The panels with the darker appearance tended to have a finer, less rough surface texture in both the horizontal and vertical directions. Smoother panel finishes may reflect less light than panels with rougher surfaces, making them appear slightly darker. Rougher panels have more facets, such as in a diamond ring, which reflect more light and make them look lighter.

Table 2. Gloss and Surface Profile Readings for Panels with Lighter Visual Appearance

Panel Location	Horizontal Scan		Vertical Scan	
	GLOSS20 (GU)	Profile, Ra (micro-inches)	GLOSS60 (GU)	Profile, Ra (micro-inches)
East intrados of north leg, north panel, seventh from base	83.4	16	23.6	35
West intrados of north leg, north panel, eleventh from base	132.8	11	41.2	16
West intrados of north leg, south panel, sixth from base	101.1	17	27.7	42
Average	***106***	***15***	***31***	***31***

Table 3. Gloss and Surface Profile Readings for Panels with Darker Visual Appearance

Panel Location	Horizontal Scan		Vertical Scan	
	GLOSS20 (GU)	Profile, Ra (micro-inches)	GLOSS60 (GU)	Profile, Ra (micro-inches)
East intrados of north leg, north panel, sixth from base	81.4	6	27.2	21
West intrados of north leg, north panel, twelfth from base	154.4	16	19.8	51
West intrados of north leg, south panel, seventh from base	110.5	7	51.1	12
Average	***115***	***10***	***33***	***28***

XRF Analysis

In order to analyze the chemical composition of the stainless steel and weld material, the surface of the steel was evaluated using a handheld X-ray fluorescence (XRF) device. Handheld XRF is a technique that allows non-destructive elemental analysis of materials. The surface to be analyzed is irradiated with X-rays, resulting in the production of fluorescent X-rays, which are characteristic of the elements present. The data can be interpreted to indicate which elements are present and the relative amounts of these elements. All samples, including the weld, generally conformed to 300 series stainless steel. Detailed XRF data was provided in Part II report for the corrosion investigation.

Visual Observations at the Extrados

During the extrados inspection performed on October 19, 2014, WJE completed a visual inspection of the stainless steel panels and welds on the extrados of the north leg. See Appendix D for a complete list of observations and photographs. Surface details were documented with a digital camera attached to a field microscope.

Visual observations at the extrados were generally similar to the visual observations from grade, with the following significant observations:

1. At the vent at Station 6:
    a. Approximately half of the forty-two louver slats were observed with cracked welds, some of which were partially cracked at the attachment of the louver slats to the frame (Figure 74). There is one loose slat which was found to be the source of the tapping noise that can be heard from inside the observation deck during high winds (Figure 75).
    b. Red-orange corrosion staining was visible between the slats (Figure 76). GSR Sample 14 was collected.
    c. A black deposit was visible at the top of the vent (Figure 77). GSR Sample 13 was collected.
2. At Station 14, a repair at a previous creeper derrick attachment was observed (Figure 78 and Figure 79). No distress was observed.
3. At Station 20, a typical weld profile was documented (Figure 80), and a gouge with a depth of approximately 1/32 inch was observed in the stainless steel panel (Figure 81). No corrosion was observed in the gouge.
4. At Station 24, a typical weld was found to be faintly magnetic (Figure 82 and Figure 83).
5. At Station 31:
    a. A blemish was observed in the finish of the stainless steel panel (Figure 84 and Figure 85).
    b. Typical black deposits were visible at welds. GSR Sample 4 was collected.
6. At Station 35, a dent was observed in the stainless steel panel. The dent was measured to have plan dimensions of approximately 24 inches horizontally by two panels vertically, and a depth of 1/2 inch (Figure 86 and Figure 87).
7. At Station 36, a blemish was observed in the finish of the stainless steel panel (Figure 88 and Figure 89).
8. At Station 43 and Station 49, heat tint was observed at welds (Figure 90 and Figure 91). One of the welds was faintly magnetic.
9. At Station 50, typical black deposits were visible at welds. GSR Sample 15 was collected.
10. Above Station 45, the out-of-plane deformation (oil canning) of the stainless steel panels between stiffeners was measured to be approximately 1/8 inch at several locations.
11. Below Station 45, the out-of-plane deformation was negligible.
12. Typical observations:
    a. No cracks were observed in the welds or stainless steel panels.
    b. Welds were confirmed to be generally non-magnetic.
    c. Black deposits at the welds appeared to increase from the top of the Arch to the bottom.
    d. Weld spatter appeared to decrease from the top of the Arch to the bottom.

Figure 74. Overall view of vent at Station 6. (Photo by authors, 2014)

Figure 75. Cracked weld at loose louver slat. (Photo by authors, 2014)

Figure 76. Red-orange corrosion staining visible between the louver slats. (Photo by authors, 2014)

Figure 77. Black deposits visible at the top of the vent. (Photo by authors, 2014)

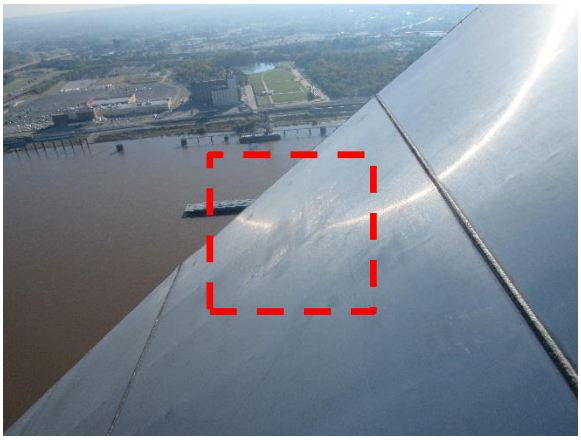

Figure 78. Overall view of repaired stainless steel at an existing creeper derrick attachment. (Photo by authors, 2014)

Figure 79. Closer view of repaired stainless steel at an existing creeper derrick attachment. (Photo by authors, 2014)

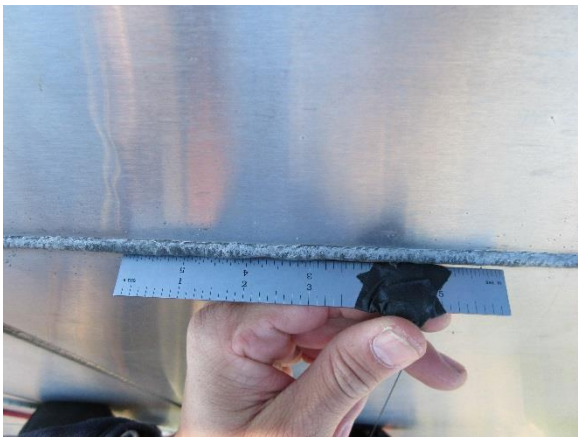

Figure 80. Overall view of typical weld profile. (Photo by authors, 2014)

Figure 81. Gouge with a depth of approximately 1/32 inch gauge at stainless steel panel at Station 20. (Photo by authors, 2014)

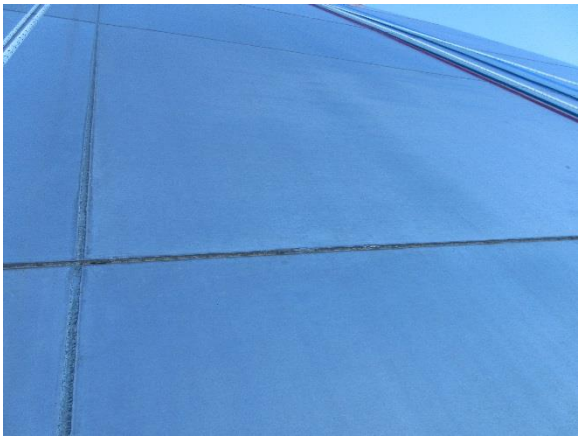

Figure 82. Typical weld repair. (Photo by authors, 2014)

Figure 83. Close up of typical weld repair. (Photo by authors, 2014)

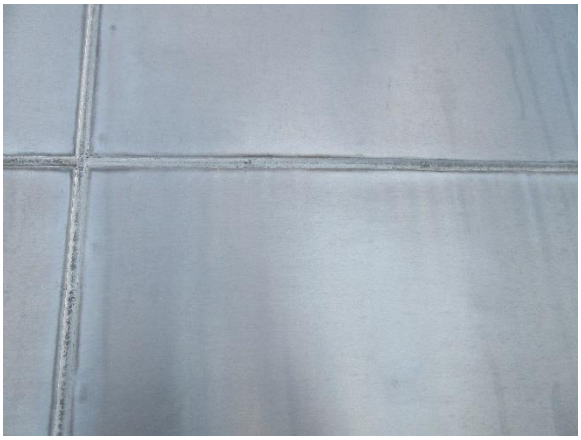

Figure 84. Variation in stainless steel finish at Station 31. (Photo by authors, 2014)

Figure 85. Close-up of the variation in the stainless steel finish. (Photo by authors, 2014)

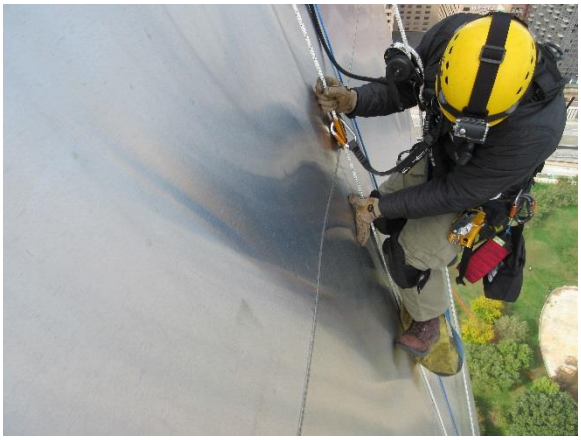

Figure 86. Dent observed at Station 35. (Photo by authors, 2014)

Figure 87. Close up of dent with a ruler at the location of maximum deformation. (Photo by authors, 2014)

Figure 88. Variation in stainless steel finish at Station 36. (Photo by authors, 2014)

Figure 89. Close-up of the variation in the stainless steel finish. (Photo by authors, 2014)

Figure 90. Heat tint observed just above and below weld at Station 43. (Photo by authors, 2014)

Figure 91. Close up of heat tint that may have been partially cleaned. (Photo by authors, 2014)

Additionally, while WJE had access to the top of the Arch, the welds at the top of the Arch were inspected for cracks, and a chloride test was completed.

1. At one weld location northwest of the access hatch, a portion of the weld is irregular (Figure 92 and Figure 93). No distress or deterioration was observed at the weld locations. No cracked welds were observed.
2. The chloride content on the surface of the Arch west face was measured using a Chlor*Test kit. The test location was accessed from a window. The chloride content was below the detection threshold (less than 1 ppm).

Figure 92. Overall view of weld with irregular weld (circle). (Photo by authors, 2014)

Figure 93. Close up of irregular weld with no crack observed. (Photo by authors, 2014)

Visual Observations at the Intrados

During the IRA access on the west intrados of the north leg, WJE completed a close-up visual inspection of the stainless steel from Station 28 to Station 35 (Figure 94 and Figure 95). See Appendix E for a complete list of the photographs.

Visual observations at the intrados were generally similar to the visual observations from grade, with the following significant observations:

1. Overall photos of the stainless steel at Station 35 are provided as Figure 96 through Figure 101. General observations included:
   a. The discoloration was located in an area which appeared to have had a chemical applied (intentionally or unintentionally) and of not being removed, as it was at adjacent unstained areas.
   b. Staining, parallel to station marks, was red in hue.
   c. Staining, perpendicular to station marks, was violet in hue.
   d. Vertical streaking appeared similar to patterns that could be attributed to water running down the face of the steel panels. The vertical streaking was visible from grade (Figure 96).
2. At Station 35, the out-of-plane deformation (oil canning) of the stainless steel panels between stiffeners was noted to be negligible.
3. No distress or corrosion was observed at welds.
4. Minimal black deposits were observed on the welds in this area of the Arch (Figure 102 and Figure 103).

Figure 94. Location of intrados inspection at Station 35. (Photo by authors, 2014)

Figure 95. View of Station 35. The rectangle shows the area shown in Figure 97. (Photo by authors, 2014)

Figure 96. Vertical streaking visible from grade at Station 35 (rectangle). (Photo by authors, 2014)

Figure 97. Close-up view of hands-on inspection location. See Figure 95 for an overall view of Station 35. (Photo by authors, 2014)

Figure 98. Overall view of stainless steel at Station 35. (Photo by authors, 2014)

Figure 99. Overall view of stainless steel at Station 35. (Photo by authors, 2014)

Figure 100. Overall view of discoloration of stainless steel at Station 35. (Photo by authors, 2014)

Figure 101. Overall view of discoloration of stainless steel at Station 35. (Photo by authors, 2014)

Figure 102. Overall view of stainless steel above Station 35 without visible discoloration. (Photo by authors, 2014)

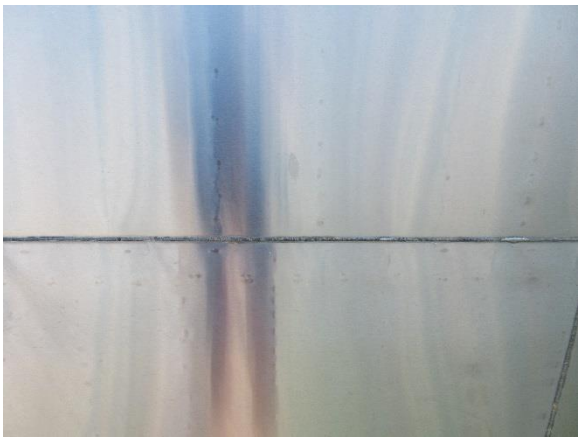

Figure 103. Close up of stainless steel above Station 35 without visible discoloration. (Photo by authors, 2014)

LABORATORY ANALYSIS

Silicone Molds

The differences in surface relief and texture between various areas of the Arch were subtle. In order to examine surfaces in microtexture using laboratory microscopy without removing historic fabric from the structure, physical molds of the stainless steel surface and representative welds were created using the RepliSet system. RepliSet is a silicone mold-making material that replicates ultra-fine details as small as 0.1 micros, and is an accepted texture replicating system in accordance with ASTM E1351, *Standard Practice for Production and Evaluation of Field Metallographic Replicas*.

WJE prepared molds of the Gateway Arch skin from the aerial lift and using industrial rope access at the intrados and the top of the Arch, as summarized in Table 4. In the laboratory, the silicone molds were examined using reflected light microscopy at up to 125x with controlled lighting.

Laboratory examination revealed that the vertical streaks below the welds corresponded to a difference in surface texture. This difference in surface texture appeared as if the finish lines in the horizontal direction overlapped, as shown in Figure 108 schematically. The density of the applied surface texture to the stainless steel panel was greater at the areas which appeared darker. The increased amount of texture may also collect dirt preferentially to some minor extent; however, when the surface was wiped with a solvent, the darkness remained visible. This overlapping of the finish occurred during the original polishing of the stainless steel plates during fabrication.

Table 4. Silicone Molds

Sample	Location
1	Location of blemish consisting of dark and light vertical streaking patterns within the surface finish on extrados from the lift at Station 69 (similar to Figure 51) (Figure 107)
2	Location of blemish at stainless steel below weld on intrados at Station 35 (Figure 104)
3	Shop weld at top of Arch near access hatch (Figure 105)
4	Field weld at top of Arch near access hatch (Figure 106)
5	Typical surface at top of Arch near access hatch

Figure 104. Close-up view of hands-on inspection location noting location of silicone mold. See Figure 95 for an overall view of Station 35. (Photo by authors, 2014)

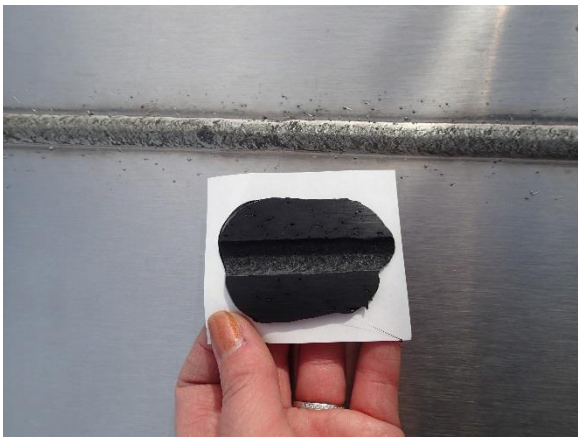

Figure 105. Silicone mold at typical shop weld at top of Arch. (Photo by authors, 2014)

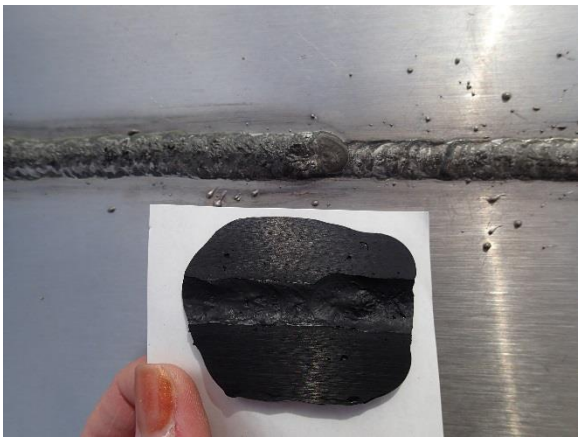

Figure 106. Silicone mold at typical field weld at top of Arch. (Photo by authors, 2014)

Figure 107. Silicone mold at stainless steel panel. Area above red line shows overlapping finish lines. (Photo by authors, 2014)

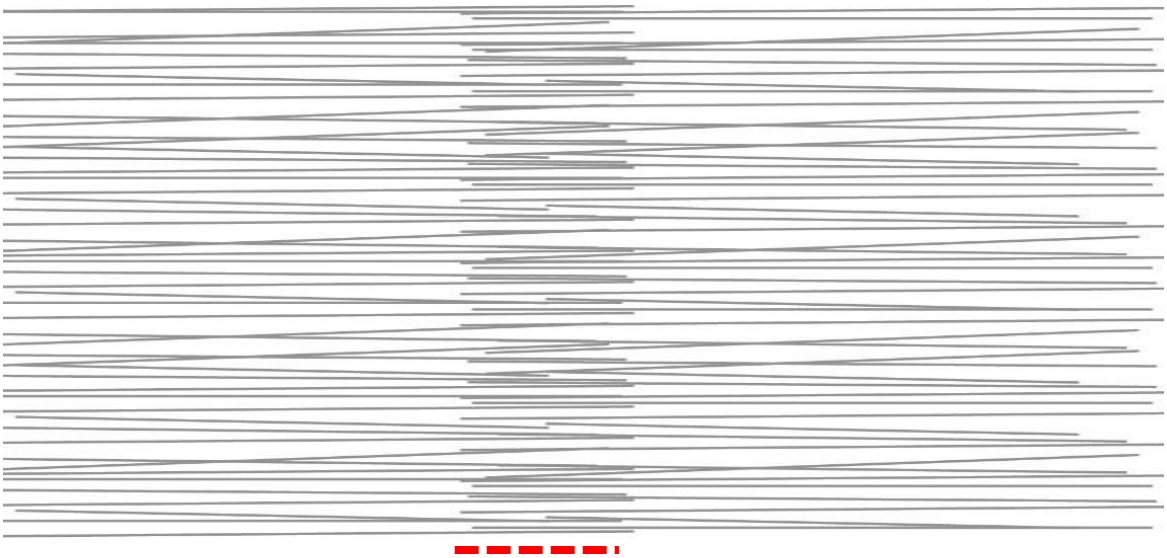

Figure 108. Schematic sketch of overlapping finishing lines in the stainless steel. Area above red line shows overlapping finish lines. (Sketch by authors, 2015).

Weld Samples

Description of Weld Sample Removal

To confirm the stainless steel plate material, weld filler metal, and quality of the welds at limited locations, several weld samples were removed from the Arch. The weld samples were taken through the 1/4 inch stainless steel at five locations that were accessible from the aerial lifts at the north leg. Field welds and shop welds were sampled, as different welding processes were used in the field and in the shop.

WJE coordinated the weld sample removals with A. Zahner Company (Zahner), an engineering design consultancy and fabrication shop located in Kansas City, Missouri. The removed weld samples were approximately 3/4 inch in diameter. Sample removal locations were repaired with stainless steel plugs. The weld sample size was intended to reduce the profile of the plugs and mitigate the appearance of the plugs from grade. The samples were removed during the site visit of September 29, 2014 to October 1, 2014. Kevin Hidy and Kerry Butler of Zahner, both certified stainless steel welders, completed the sample removal and repairs.

Prior to the on-site weld sample removal, Zahner prepared off-structure trial mock-ups of the weld sample plugs for NPS and WJE to review and approve (Figure 109 and Figure 110). The weld mock-ups and removed weld samples were given to the JEFF archives at the end of the project.

The weld sample removal process consisted of the following procedure:

1. WJE and TMR located five weld samples locations. Weld sample locations were selected at welds that had been determined to be faintly magnetic. See Table 5 for an overview of the weld sample locations. See Figure 111 through Figure 114 for the weld sample locations at the north leg.
2. A template plate was used to guide the coring saw, as the stainless steel precluded the use of a magnetic drill, and the pilot bit on the coring saw was removed to allow the complete 3/4 inch diameter weld sample to be obtained in the field. A 3/8 inch thick stainless steel template plate with a pre-drilled hole was tack welded to the existing welds. The template was then used to guide the carbide tip coring saw to remove the weld samples.
3. The template with the pre-drilled hole and the weld sample were removed. The tack welds used to secure the template were then removed and ground smooth, leaving no visible damage to the substrate.
4. The hole in the existing weld was cleaned and prepared. A stainless steel plug of 304 alloy was then installed using the tungsten inert gas (TIG) arc welding process and a filler rod of 316 alloy, which provides slightly better corrosion resistance at the weld. The welding unit was grounded to the Arch using a copper plate held against the stainless steel with a suction cup. See Figure 115 for a photo of the weld sample after the plug was installed. The mill certification for the stainless steel plug is provided in Appendix F.
5. The welds and stainless steel in the vicinity of the weld sample were passivated with WonderGel Stainless Steel Pickling Gel, manufactured by Bradford Derustit. The WonderGel also removed the heat tint in the vicinity of the weld sample.

Table 5. Weld Sample Locations

Sample Designation	Location on North Leg	Comment on Sample
W-1	West intrados, ninth weld from base, north panel	Field weld
W-2	West intrados, tenth weld from base, center panel	Shop weld
W-3	West intrados, sixth weld from base, north panel, east of W-4	Field weld
W-4	West intrados, sixth weld from base, north panel, west of W-3	Field weld
W-5	Extrados, eighth weld from base, east panel	Field weld

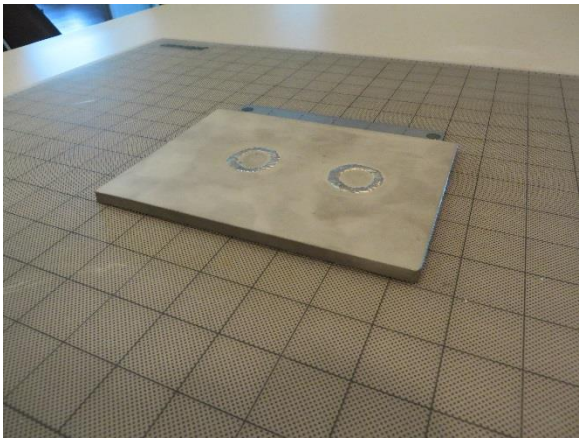

Figure 109. Weld mock-up prepared by Zahner. (Photo by authors, 2014)

Figure 110. Weld mock-up prepared by Zahner. (Photo by authors, 2014)

Figure 111. Overall view of west intrados on the north leg. Area shown in red square is overall view of Figure 112. (Photo by authors, 2014)

Figure 112. Weld sample locations W-1 through W-4. (Photo by authors, 2014)

Figure 113. Overall view of the north leg extrados, indicating weld sample location W-5. (Photo by authors, 2014)

Figure 114. Overall view of Zahner representatives at W-5. (Photo by authors, 2014)

Figure 115. Overall view of a weld sample location after the plug was installed. (Photo by authors, 2014)

Weld Sample Measurements

The stainless steel plate at all removed weld samples was 1/4 inch thick. The width and profile height of the welds in the removed samples and the silicone molds were measured. The measurements are summarized in Table 6. The welds were specified to be 1/4 to 3/8 inch wide and 3/32 inch high. Typically, the welds measured were slightly larger than specified at both the samples and molds.

Table 6. Weld Measurements

Sample	Width (inch)	Profile Height (inch)
W-1	9/16	1/8
W-2	5/16	3/32
W-3	1/2	1/8
W-4	3/8	1/8
W-5	5/16	1/8
1 - mold	7/16	1/16
2 - mold	1/2	1/8
3 - mold	5/16	1/8
4 - mold	7/16	3/32

Weld Sample Preparation

Each weld sample was analyzed using light microscopy, as well as SEM/EDS, for elemental analysis. After each weld sample was examined by TMR, the weld sample was sectioned using a water-cooled abrasive cutting wheel. The metallographic sections were mounted in epoxy and the cross section polished using progressively finer abrasives. A portion of the polished surface was then masked to expose a limited area for electrolytic etching. Etching was performed using an oxalic acid solution and a current density of approximately 1 amp per square centimeter for a period of 90 seconds. Using optical light microscopy, each section was examined in the etched condition. The section number corresponds to the weld sample number; for example, section 1 is from weld section W-1.

In order to analyze the samples, TMR worked with the R. J. Lee Group, who performed SEM/EDS analysis of select samples working with TMR. WJE also performed SEM/EDS analysis of the samples. Findings of the SEM/EDS analysis are discussed below.

Light Microscopy

Each weld sample was analyzed using light microscopy. Photographs of the sample location in situ and the as-received sample condition before preparation are included in Appendix G; select photographs are also provided in Figure 116 through Figure 132.

Significant findings from the optical light microscopy of the sections are as follows:

1. The welds in each sample were full penetration (Figure 120 and Figure 121).
2. Varying amounts of weld porosity were noted in all of the sectioned welds (Figure 122). The largest weld metal void was noted in Sample 4, with a diameter of approximately 0.04 inch (Figure 123). Sample 5 contained a void with an approximate diameter of 0.024 inch (Figure 124).
3. Varying degrees of sensitization were found in the grain boundaries in the heat affected zone of all five samples when they were examined in the etched condition. The band of sensitized grains on Sample 2 was located approximately 0.045 inch from the edge of the weld (Figure 125 and Figure 126). All samples had some minor weld imperfections, and the plate adjoining all of the welds examined had been sensitized. There was no micro-cracking associated with the sensitization. No sensitization related corrosion was observed.
4. A shallow weld undercut was noted at the inside surface of the plate in Sample 3 (Figure 127). No cracking or corrosion was observed in association with this condition.
5. Slag contamination was observed at the weld in Sample 5 (Figure 128 and Figure 129).
6. Magnesium sulfide inclusions in the stainless steel plate were observed in Samples 1 and 3 (Figure 130 through Figure 132).

Figure 116. Weld Sample 1 (shop weld), prior to removal. (Photo by authors, 2014)

Figure 117. Weld Sample 1 (shop weld), as-received condition. (Photo by authors, 2014)

Figure 118. Weld Sample 3 (field weld), prior to removal. (Photo by authors, 2014)

Figure 119. Weld Sample 3 (field weld), as-received condition. (Photo by authors, 2014)

Figure 120. Macrograph cross-section of weld Sample 1 in the etched condition. (Photo by authors, 2014)

Figure 121. Macrograph cross-section of weld Sample 2 in the etched condition. (Photo by authors, 2014)

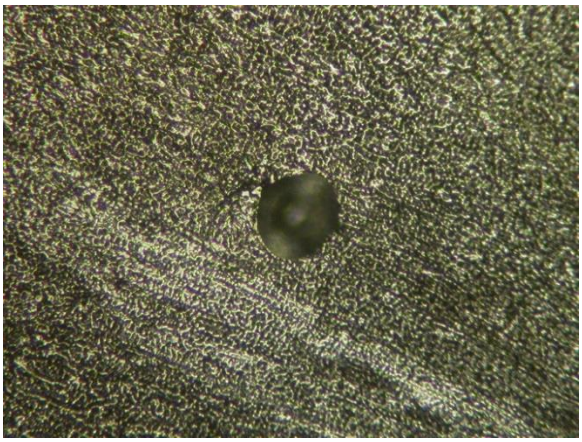

Figure 122. Micrograph of weld Sample 2, etched condition, weld porosity, approximate diameter 0.004 inch. (Photo by authors, 2014)

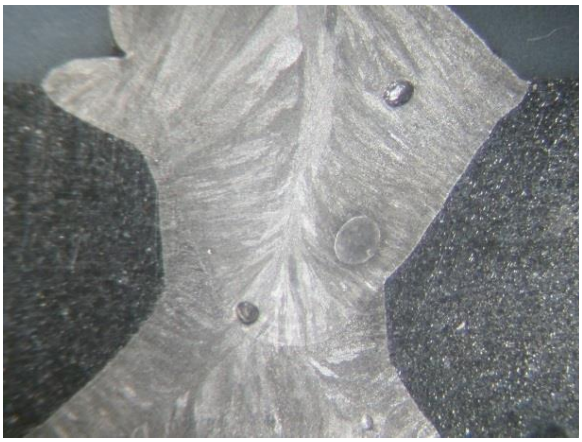

Figure 123. Macrograph cross-section of weld Sample 4 in the etched condition showing porosity. (Photo by authors, 2014)

Figure 124. Macrograph cross-section of weld Sample 5 in the etched condition showing porosity. (Photo by authors, 2014)

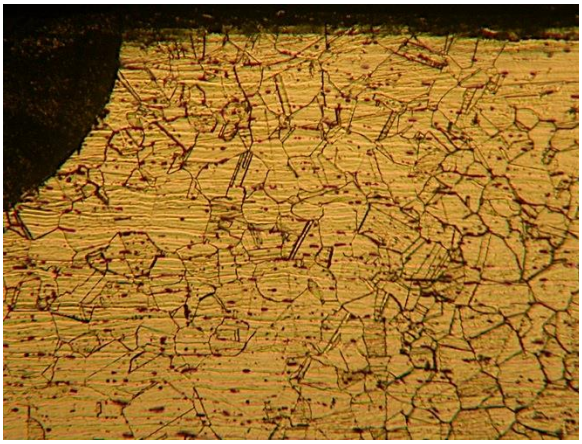

Figure 125. Micrograph of weld Sample 2, etched condition, showing weld metal (top left corner), a band of grains that are not sensitized (center), and a band of sensitized grains (right) (122x). (Photo by authors, 2014)

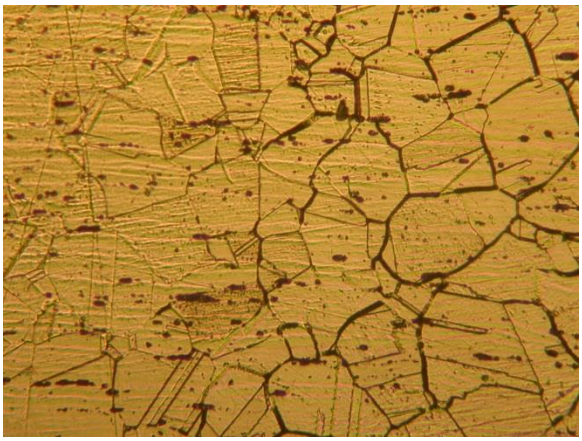

Figure 126. Micrograph of weld Sample 2, etched condition, showing sensitized grains (right) and grains that are not sensitized (left) (256x). (Photo by authors, 2014)

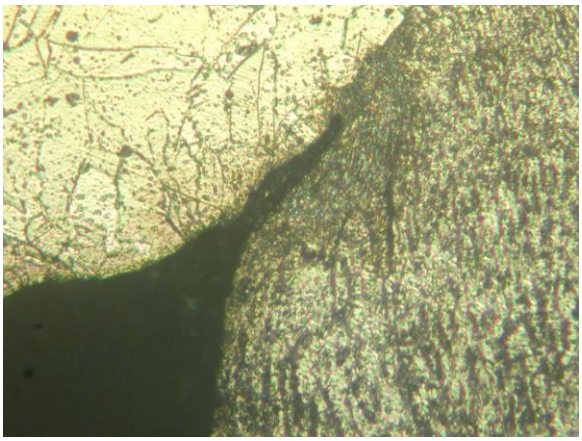

Figure 127. Micrograph of Sample 3, etched condition, showing shallow undercut where the weld metal and base metal meet, inside surface of the plate (517x). (Photo by authors, 2014)

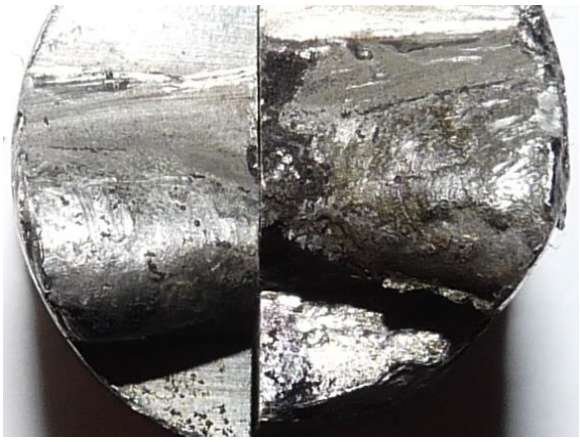

Figure 128. Sample 5 after sectioning, and a corresponding micrograph (Figure 129) of section 5 at the weld crown showing weld slag contamination on the surface. (Photo by authors, 2014)

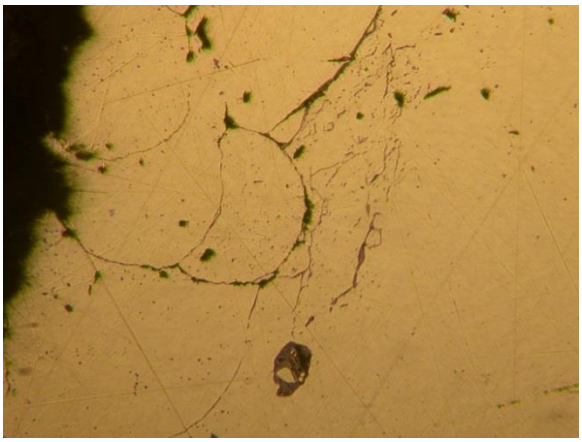

Figure 129. Weld slag contamination on the weld surface and subsurface of Sample 5(256x). (Photo by authors, 2014)

Figure 130. Micrograph of plate inclusion, Sample 1, as-polished condition (517x). (Photo by authors, 2014)

Figure 131. Micrograph of manganese sulfide stringers in the plate, Sample 1, as-polished condition (256x). (Photo by authors, 2014)

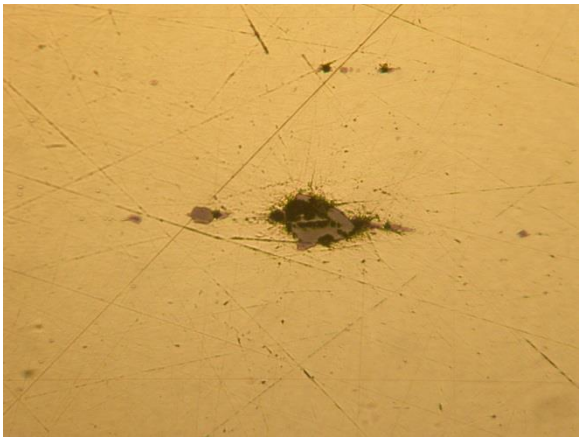

Figure 132. Micrograph, Sample 3, plate inclusion, as-polished condition (256x). (Photo by authors, 2014)

SEM/EDS Analysis

Each weld sample was analyzed using SEM/EDS. The results of the analysis are provided in Table 7 and in more detail in Appendix G. The analysis of Samples 1 and 5 was conducted by R. J. Lee Group, working with TMR. WJE performed analysis of larger areas of all samples to confirm the results. Representative photomicrographs and EDS spectra are provided in Figure 133 through Figure 136.

Significant findings are as follows:

1. The primary elements within the stainless steel plate material and weld material were compared to the ASTM A167-63, *Standard Specification for Corrosion-Resisting Chromium-Nickel Steel Plate, Sheet, and Strip*, and to a variety of stainless steel materials. Based on this comparison:
   a. The chemical analysis of the plate material was consistent with the specified 300 series stainless steel.
   b. The chemical analysis of the weld material was consistent with the specified 300 series stainless steel.
2. The presence of manganese sulfides was noted in the base metal of Sample 1 (Figure 137).

3. All samples also had some surface weld slag (Figure 138).
4. Subsurface contamination was noted in the weld metal near the weld crown of Sample 5 (Figure 139).

Table 7. SEM/EDS Chemistry Analysis

Sample	Description	SEM/EDS Data for Primary Elements (Mass %)				
		Si	Cr	Mn	Fe	Ni
ASTM Specification	ASTM A167-63 Type 304	1.0	18.00-20.00	2.0	remaining	8.0-12.0
ASTM Specification	ASTM A167-63 Type 308	1.0	19.00-21.00	2.0	remaining	10.0-12.0
ASTM Specification	ASTM A167-63 Type 309	1.0	22.00-24.00	2.0	remaining	12.0-15.0
ASTM Specification	ASTM A167-63 Type 310	1.5	24.00-26.00	2.0	remaining	19.0-22.0
1	Stainless plate	0.4	17.2	1.8	65.7	8.8
1	Weld	0.4	17.6	1.8	61.9	8.4
2	Stainless plate	0.4	17.8	2.0	65.3	8.4
2	Weld	0.5	17.8	2.0	62.9	8.3
3	Stainless plate	0.6	18.1	2.3	64.5	8.5
3	Weld	0.4	17.2	2.1	59.8	8.0
4	Stainless plate	0.4	17.8	1.7	65.1	8.7
4	Weld 1	0.4	16.8	1.5	56.5	7.6
4	Weld 2	0.4	16.6	1.5	55.7	7.6
4	Weld 3	0.4	17.4	1.5	60.7	8.0
5	Stainless plate	0.4	17.5	1.6	65.8	8.5
5	Weld	0.4	17.8	1.7	61.3	8.3

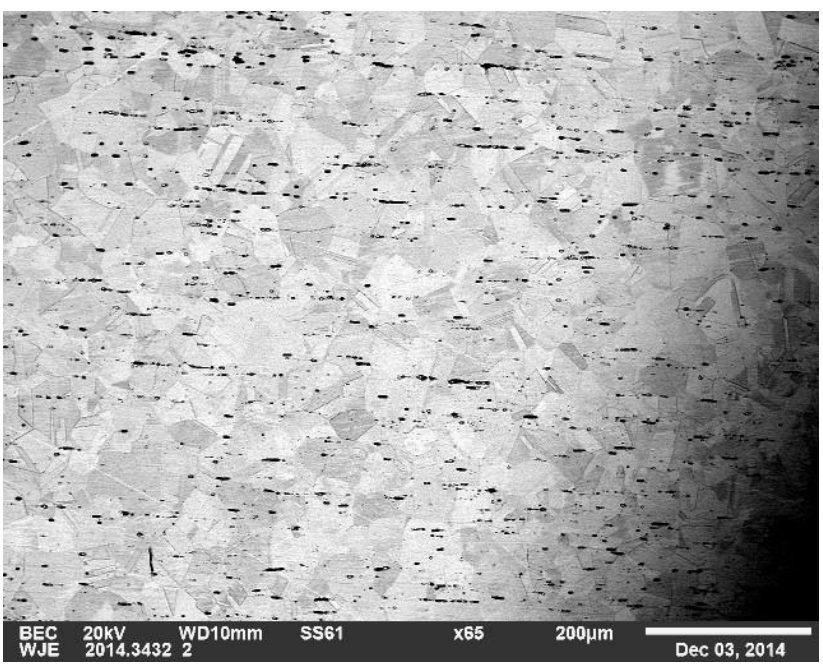

Figure 133. Polished sample of stainless steel plate, Sample 2. (Photo by authors, 2014)

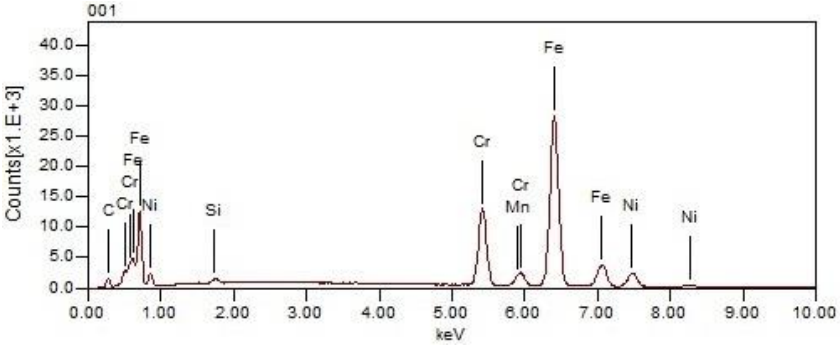

Figure 134. EDS spectra of stainless steel plate, Sample 2 (Spectra by authors, 2014).

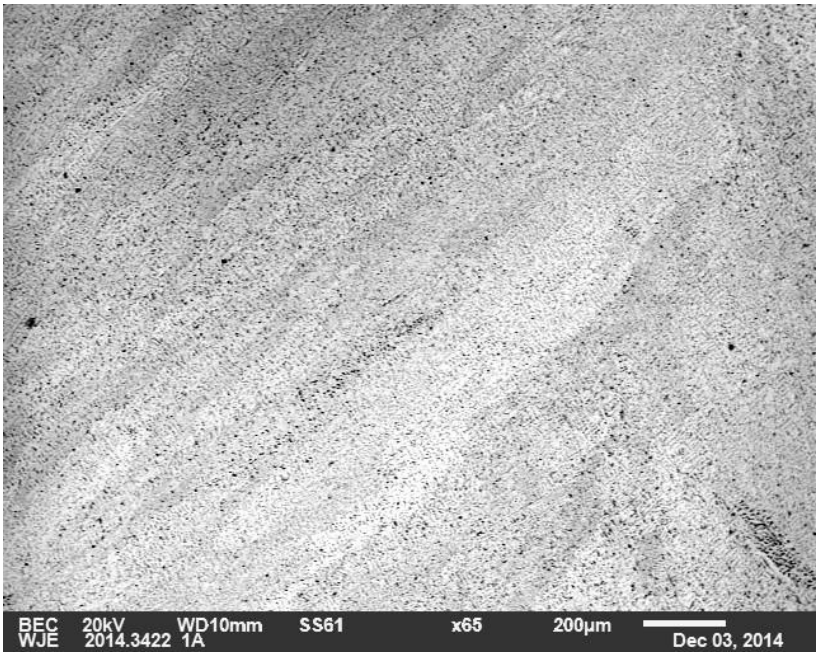

Figure 135. Polished sample of stainless steel weld Sample 1. (Photo by authors, 2014)

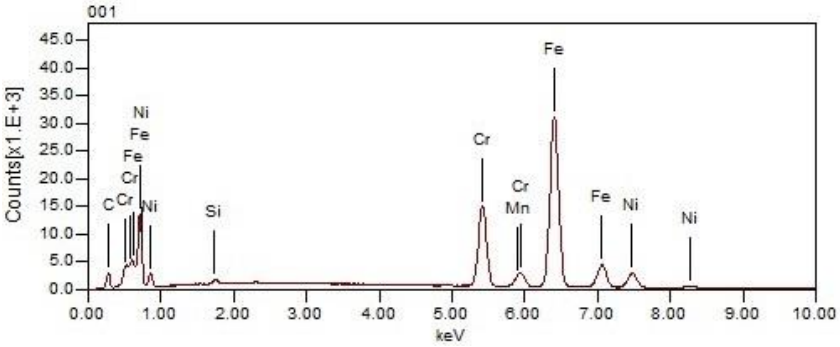

Figure 136. EDS spectra of stainless steel weld Sample 1 (Spectra by authors, 2014).

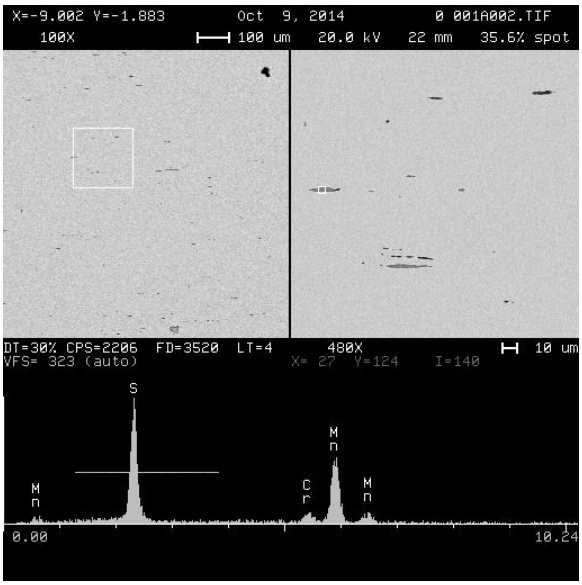

Figure 137. SEM images and EDS scan confirming the presence of manganese sulfide stringers (Sample 1). (Photo by authors, 2014)

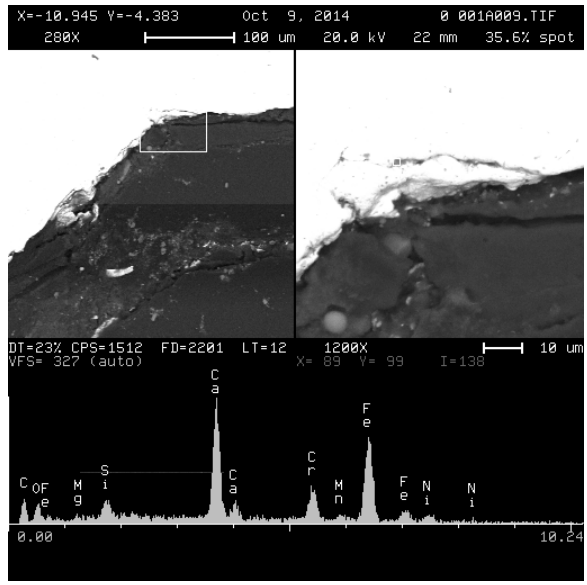

Figure 138. SEM images and EDS scan showing some surface weld slag (Ca and Si) (Sample 1). (Photo by authors, 2014)

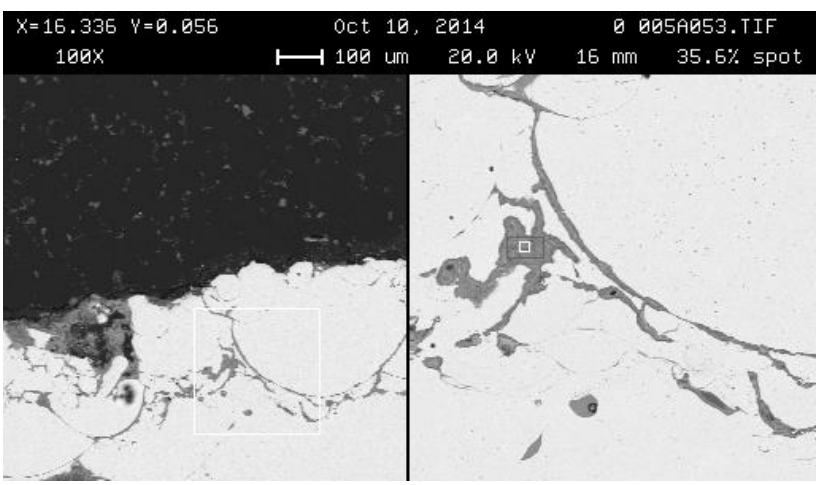

Figure 139. SEM, weld slag inclusion area at different magnifications (Sample 5). (Photo by authors, 2014)

SEM/EDS Analysis of Removed Deposits

Gunshot residue sample (GSR) kits were used to remove samples of the surface deposits from the stainless steel skin of the Arch. The GSR kits contain an adhesive that allows the collection of surface deposits non-destructively, without causing damage to the stainless steel. The GSR adhesive can typically remove finer particles for laboratory analysis than other non-destructive techniques. The adhesive can then be placed directly into a scanning electron microscope for SEM/EDS microscopic and compositional analysis. Two different size sample kits were used: 1) circular 0.5 inch diameter metal stubs with an applied adhesive (Figure 140), and 2) surface sampling strips with adhesive applied to a plastic sheet measuring approximately 2 by 3-1/4 inches (Figure 141).

The samples were taken at various locations along the height of the north leg from a variety of access points. A summary of the sample numbers, locations, and descriptions of the deposits being sampled is provided in Table 8. The B series samples were collected during the inspection from the aerial lift. The C series samples were collected during IRA access. Select sample locations are shown in Figure 142 through Figure 145.

The R. J. Lee Group performed the SEM/EDS of the samples for interpretation by TMR. WJE analyzed all samples and reviewed the R. J. Lee Group findings for confirmation. The complete analysis of the residue samples is provided in Appendix H. The analysis identified carbon, oxygen aluminum, silicon, potassium, calcium, iron, and manganese. In addition, small amounts of copper, zinc, and titanium were also identified.

Based on the morphology and chemical analysis in the SEM/EDS analysis, the deposits were largely identified as carbon rich material such as spores and pollen. In addition, industrial particulates including fly ash, ferrochrome oxide, iron and steel slag, iron, copper, copper zinc lead and titanium were found on every sample. In addition, common mineral deposits including clays, silica, dolomite, calcite, and magnesia alumina silicate were present. Representative SEM photomicrographs and EDS spectra are provided in Figure 146 through Figure 149. These deposits are common airborne particulates that are either natural or may be a result of atmospheric pollutants from industrial plants.

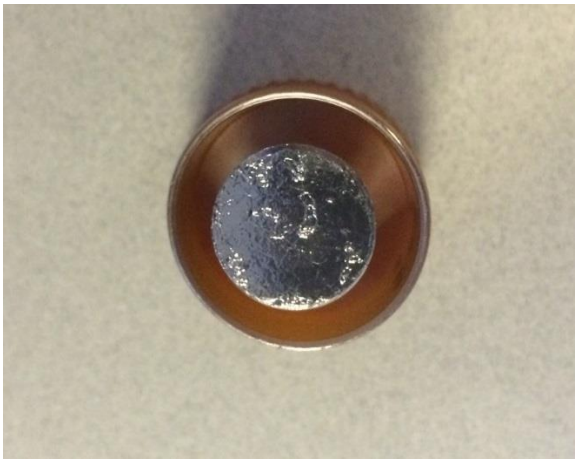

Figure 140. GSR metal stub sample collection. (Photo by authors, 2015.)

Figure 141. GSR surface sampling strips. (Photo by authors, 2015.)

Table 8. Surface Deposit Samples

Sample	Location	Sample Type	Description of Deposit Sampled
1B	Station 70, extrados	Strip	Grey and black particles concentrated on weld spatter
2B	Station 69, extrados (Figure 145)	Strip	Dark deposits on surface with distinct small grey, black, and brown areas
3B	Station 68, extrados	Strip	Area has both dark and white deposits and superficial corrosion staining
4B	Station 31, extrados	Strip	Area has both dark and white deposits and surface discoloration areas and a rainbow effect in area

Sample	Location	Sample Type	Description of Deposit Sampled
5B	Station 67, intrados	Strip	Surface sample from an area with what appears to be superficial corrosion staining of the stainless steel
6B	Unknown location accessed from aerial lift at base	Strip	Surface sample from an area with what appears to be superficial corrosion staining of the stainless steel
7B	Station 69, extrados	Strip	Dark parallel vertical marks on the panel sections
5C	Station 35, intrados	Strip	Dark residue
6C	Station 35, intrados	Strip	No residue
13C	Louver at Station 6, extrados	Stub	Reddish deposit
14C	Station 6, extrados	Stub	Black deposit
15C	Station 49, extrados	Stub	Black deposit
1C	Station 35, intrados (Figure 142 to Figure 144)	Strip	Dark residue. Residue did not transfer to strip. Typical location of stainless steel below weld on
3C	Station 35, intrados (Figure 142)	Strip	Superficial corrosion staining location of stainless steel below weld on intrados
4C	Station 31, extrados	Strip	Dark residue
5C	Station 35, intrados (Figure 142)	Strip	Dark surface deposits at horizontal weld
6C	Station 35, intrados	Strip	Typical location without visible deposits

Figure 142. Overall location of deposit sampling using GSR kits. See Figure 95 for an overall view of Station 35. (Photo by authors, 2014.)

Figure 143. Location of discoloration on intrados at Station 35. (Photo by authors, 2014.)

Figure 144. Photomicrograph of discoloration at residue Sample 1. (Photo by authors, 2014.)

Figure 145. Sample 2B collection location, which appeared to have the same type of deposits as Sample 2A. (Photo by authors, 2014.)

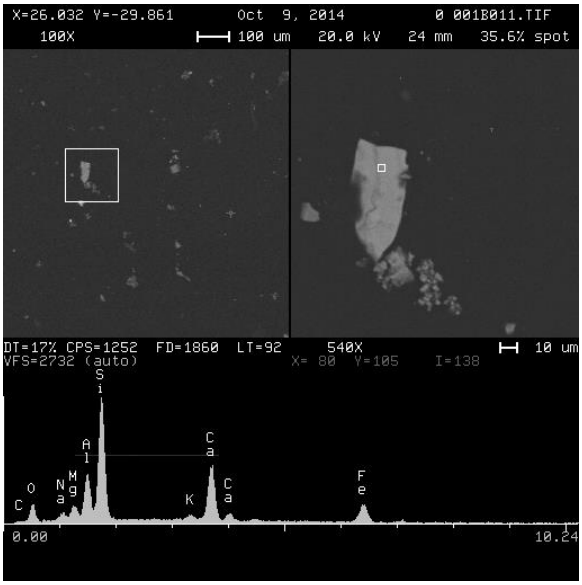

Figure 146. SEM/EDS of deposits removed showing clay particle. (Photo by authors, 2014.)

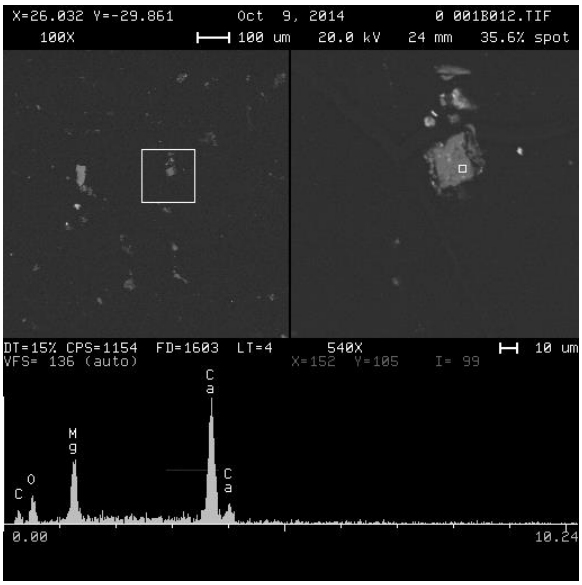

Figure 147. SEM/EDS analysis showing calcite and dolomite particles removed from Arch. (Photo by authors, 2014.)

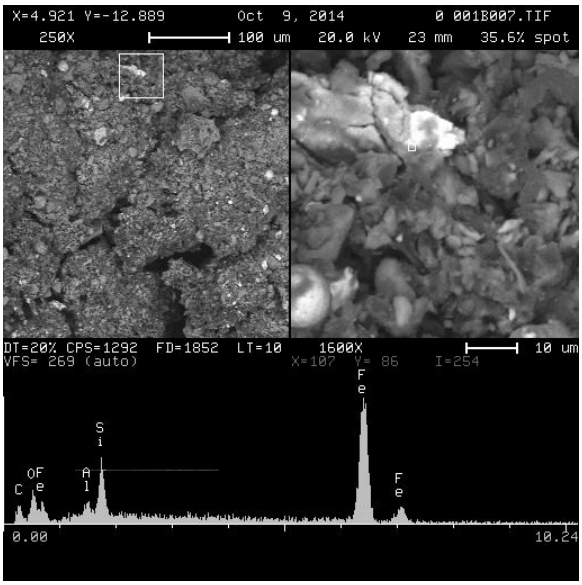

Figure 148. SEM/EDS analysis of deposits removed showing clays and corrosion products. (Photo by authors, 2014.)

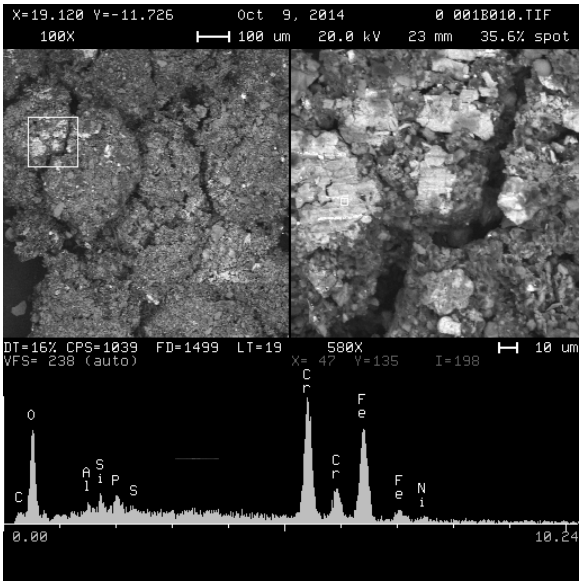

Figure 149. SEM/EDS analysis of deposit showing corrosion products. (Photo by authors, 2014.)

CLEANING TRIALS

Cleaning trials were performed to evaluate the effectiveness of various cleaning systems to remove blemishes, deposits, and discoloration. WJE selected cleaning techniques for testing based on an understanding of existing conditions and our experience on previous projects. Solvents and mild detergents were selected to remove deposits; weak acids were used to remove discoloration; and surface refinishing

techniques were tested to remove blemishes. The cleaning trial locations, a general description of the cleaning systems tested, and observations are summarized below and in Table 9:

1. A series of cleaning trials were completed at the base of the north leg on the east face, center panel, at locations of significant blemishes. These blemishes included incised graffiti and mechanical scraping, possibly by equipment used for snow removal, as well as significant discoloration due to surface corrosion (Figure 150). The 2 foot wide trials areas were separated by masking tape to create control areas between the cleaning test areas after the masking tape was removed. The trial areas were labeled A through K.
2. A cleaning trial, which was labeled L, was performed on the extrados of the north leg at the second weld from the base on the west panel, at a location of dark vertical streaks (Figure 151 and Figure 152).
3. A cleaning trial, which was labeled M, was performed at a severe incised graffiti location on the west face of the north leg (Figure 153 and Figure 154).
4. In addition, several trials, labeled 1 through 6, were performed from IRA at the discolored area on the intrados at Station 35 (Figure 155 to Figure 158).

Cleaning systems that were tested included solvents, detergents, degreasers, weak acids, and abrasive techniques. The cleaning chemicals are described in Table 10. Due to safety concerns, the chemical cleaners utilized from IRA were limited to the mildest systems. Based on the results of cleaning trials performed at the base, and field observations indicating that subtle differences in surface texture could create visual anomalies, no cleaning systems that could alter the surface profile of the stainless steel were conducted at Station 35.

Prior to cleaning the trial locations at the base, the stainless steel was cleaned with a solvent wipe to remove organic residue such as oils, waxes, lotions, etc. The surfaces were wiped with a clean cotton cloth dipped in xylene, followed by a clean cotton cloth dipped in ethanol. Following the application of the cleaning system, the surfaces were all rinsed with water and wiped with ethanol and a clean cotton rag. The paste cleaners (Bar Keeper's Friend and Zudd) were mixed with water and applied as a paste slurry. Micro-crystalline wax and lanolin coatings were tried on small areas of cleaned samples.

Appendix I provides photographs of the cleaning trials and the individual test areas.

Significant findings for the cleaning trials are as follows (completed cleaning study areas are shown in Figure 150):

1. Visually, the cleaning systems used at trial areas G and J had very little to no effect in improving the surface appearance.
2. The cleaning systems used at trial areas B and E resulted in minor improvement to the surface appearance, but the improvement was considered limited.
3. The cleaning systems used at trial areas A, A2, C, C2, F, and H noticeably improved the surface appearance.
4. The cleaning at trial area K dramatically changed the surface appearance but resulted in a very coarse and rough surface that was significantly different than the original surface finish.
5. The cleaning at trial area M dramatically changed the surface appearance, but resulted in a very coarse and rough surface that did not acceptably simulate the original surface finish (Figure 153 and Figure 154).
6. The surface profile was measured in both the horizontal and vertical directions after cleaning trials A through K were completed. The results are summarized in Table 11.
7. During all the trials at the intrados at Station 35 (Figure 155 through Figure 158), light atmospheric deposits were removed, although the removals were too slight to be visually noticeable from grade when viewed with the spotter scope. The discoloration became noticeably less visible when all the

samples were wiped with isopropanol; however, the discoloration became visible again as the surface dried.

8. The chemical cleaners alone did not change the surface profile, but when combined with the abrasive pads, some alteration to the surface profile was noted. The Norton Ultra Fine pad caused the most significant change to the surface profile.
9. While initially Trials L, N, and O appeared to remove the dark streaks while the surface was wet, the streaks reappeared when the surface dried.
10. Trial P successfully removed the oily deposit.
11. The wax resulted in minimal visual change to the stainless steel, while the lanolin created a darker and glossier appearance with a slight orange tint (Figure 159 and Figure 160).

Table 9. Summary of Cleaning Trials

Section	Description	Observations
A	Bar Keeper's Friend	Noticeable removal of superficial corrosion staining
A2	Bar Keeper's Friend Avesta 630	Noticeable removal of superficial corrosion staining
B	E-nox Clean	Minor removal of superficial corrosion staining
C	Norton Woven Clean and Abrasive Ultra Fine Pad	Noticeable removal of superficial corrosion staining
C2	Norton Woven Clean and Abrasive Ultra Fine Pad Avesta 630	Noticeable removal of superficial corrosion staining
D	Solvent cleaning only	Minor removal of deposits
D2	Resurfaced using abrasive paper 60 grit, 80 grit, 180 grit, and finished with 320 grit	Removal of discoloration and significant alteration to the surface finish
E	Zudd	Minor removal of superficial corrosion staining
F	Avesta Cleaner 401 Avesta Passivator 630	Noticeable removal of superficial corrosion staining
G	Avesta Passivator 630	Removed light surface deposits
H	Bar Keepers Norton Woven Clean and Abrasive Ultra Fine Pad	Noticeable removal of superficial corrosion staining
J	Scotchbrite Light Duty Cleaning Pad (white)	Removed light surface deposits
K	Stainless steel brush	Removal of superficial corrosion staining and significant alteration to the surface finish
L	Avesta Cleaner 401	Removal of light surface deposits. Minor removal of superficial corrosion staining.
M	Resurfaced using abrasive paper 60 grit, 80 grit, 180 grit, and finished with 320 grit	Removal of discoloration and significant alteration to the surface finish
N	Avesta Cleaner 401	Removal of light surface deposits. Minor removal of superficial corrosion staining.
O	Avesta Cleaner 401	Removal of light surface deposits. Minor removal of superficial corrosion staining.
P	Isopropanol	Removed deposit
1	Solvent wipe only	Very light surface deposits removed. While wet with alcohol, soiling not visible, but reappeared when surface dried.
2	Triton X100 with finishing sponge	No visible deposits removed. While wet, soiling not visible, but reemerged when surface dried.

Section	Description	Observations
3	Simple Green with finishing sponge	No visible deposits removed. While wet, soiling not visible, but reemerged when surface dried.
4	Scotchbrite Light Duty Cleaning Pad (white)	No visible deposits removed
5	Norton Woven Clean and Abrasive Ultra Fine Pad	No visible deposits removed
6	Norton Woven Final Shine Abrasive Micro Fine Pad	No visible deposits removed

Table 10. Description of Cleaners

Cleaning Product	Description	Active Ingredients and pH
Xylene	Non-polar solvent	
Ethanol	Polar solvent	
Triton X100	Surfactant (mild detergent)	pH 9.7
Simple Green All-Purpose Cleaner	Slightly alkaline detergent	Ethoxylated alcohol Sodium citrate Teatrasodium N,N-bis(carboxymethyl)-L-glutamate Sodium carbonate Citric Acid Isothiazolinone mixture Fragrance Colorant pH 9.0
Enox UNO SF	Alkaline detergent	Alkaline degreaser with a pH of <12, no hazardous ingredient listed on MSDS
Enox Clean	Acidic cleaner	Phosphoric acid (10-30%) Linear alkyl benzene sulphonate (1 - 5%) pH 1.5
Avesta Cleaner 401	Acidic cleaner	Phosphoric acid (10 to 20 percent) Hexafluorosilicic Ac (0.1 to 0.9 percent) Alcohol (3 to 5 percent) pH 0.6
Avesta FinishOne Passivator 630	Hydrogen peroxide	Hydrogen peroxide (2 to 4.5 percent) pH 7
Bar Keeper's Friend Cleaner and Polisher	Acidic cleaner with mild abrasive powder	Oxalic acid (5 to 10 percent) pH 1.5 to 2.5
Zud Heavy Duty Cleanser (Powder)	Acidic cleaner with mild abrasive powder	Oxalic acid (5 to 10 percent) Crystalline silica (70 to 80 percent) Pumice (10 to 20 percent) pH 1.5 to 2.5

Table 11. Surface Profile Measurements of the Cleaning Trials

Test Location	Orientation	Average Ra	Maximum Ra	Minimum Ra	Comments
Average	Horizontal	13	18.0	6.0	Untreated
	Vertical	30	51.0	12.0	Untreated
A	Horizontal	26.0	40	16	Increased horizontal profile
	Vertical	22.3	25	18	May decrease vertical profile
A2	Horizontal	15.3	24	11	Tended to increase horizontal profile

Test Location	Orientation	Average Ra	Maximum Ra	Minimum Ra	Comments
	Vertical	26.8	34	22	May decrease vertical profile
B	Horizontal	9.8	12	7	Possible slight reduction in horizontal profile
	Vertical	18.8	22	14	Possible slight reduction in vertical profile
C	Horizontal	12.0	20	7	Tended to increase horizontal profile
	Vertical	22.5	30	19	No significant effect on vertical profile
C2	Horizontal	24.6	52	10	Increased horizontal profile
	Vertical	26.0	31	21	No significant effect on vertical profile
D	Horizontal	10.8	14	8	No effect on profile
	Vertical	33.7	75	17	No effect on profile
E	Horizontal	15.0	27	7	No effect on profile
	Vertical	26.0	28	22	No effect on profile
F	Horizontal	18.5	29	9	Tended to increase horizontal profile
	Vertical	27.5	46	17	No significant effect on vertical profile
G	Horizontal	18.0	40	9	Tended to increase horizontal profile
	Vertical	19.3	22	17	Possible slight reduction in vertical profile
H	Horizontal	23.5	37	16	Increased horizontal profile
	Vertical	27.6	46	21	No significant effect on vertical profile
J	Horizontal	11.3	15	8	No effect on profile
	Vertical	19.8	26	15	No effect on profile
K	Horizontal	20.0	27	14	Increased horizontal profile
	Vertical	39.4	49	31	Increased vertical profile

Figure 150. Cleaning study test areas. (Photo by authors, 2014.)

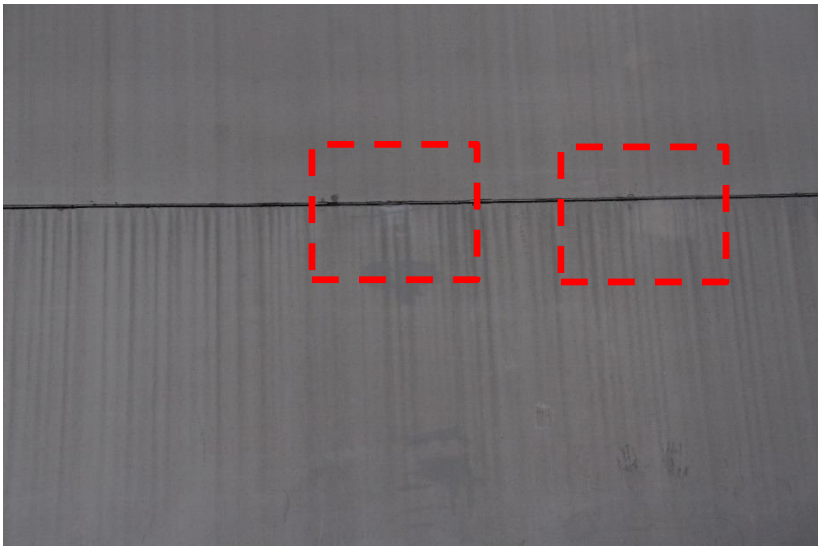

Figure 151. Variations of dark and light patterns within the surface finish. Dashed locations show cleaning Trial L. (Photo by authors, 2014.)

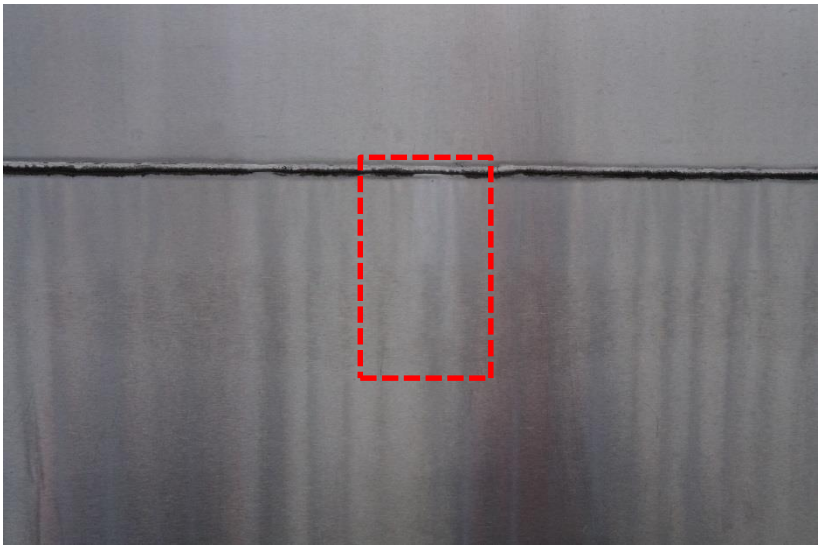

Figure 152. Detail of cleaning trial on extrados at Station 70. (Photo by authors, 2014.)

Figure 153. Cleaning Trial M before. (Photo by authors, 2014.)

Figure 154. Cleaning Trial M after. (Photo by authors, 2014.)

Figure 155. Overall location of cleaning samples at intrados. See Figure 95 for an overall view of Station 35. (Photo by authors, 2014.)

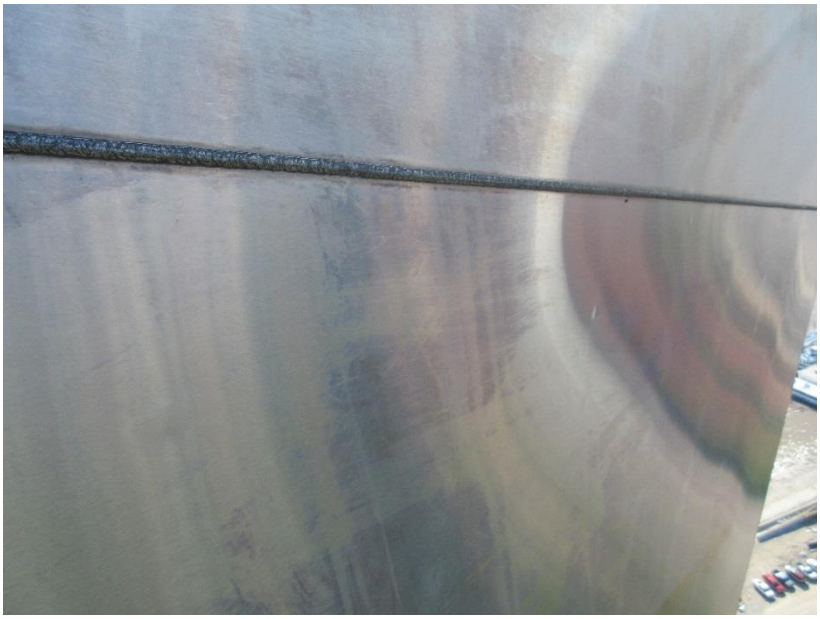

Figure 156. Overall of location of cleaning Trials 2 through 4 before cleaning. (Photo by authors, 2014.)

Figure 157. Photomicrograph before cleaning at trial areas 2 through 4. (Photo by authors, 2014.)

Figure 158. Photomicrograph before cleaning at trial areas 2 through 4. (Photo by authors, 2014.)

Figure 159. Wax and lanolin trials before

Figure 160. Wax and lanolin trials after

DISCUSSION AND CONCLUSIONS

The Arch was an unprecedented structure at the time of its construction, especially for its use of stainless steel as the exterior surface. Additionally, the magnitude of its fabrication and construction was a new frontier for structures at the time. The stainless steel and welds have performed well over time. Visual anomalies present in the stainless steel today are related to a variety of different causes over the life of the panels, from fabrication to atmospheric exposure. Assuming that the atmospheric and environmental conditions remain the same, with proper maintenance the condition of the stainless steel and welds will not pose a risk to the monument.

Original Design and Construction

Based on the review of archival documents, correspondence related to construction of the Arch, and the documentary "Monument to the Dream," many of the visual anomalies observed during the field inspection can be attributed to construction. Archival research revealed that throughout the fabrication and construction of the Arch, the appearance of the stainless steel panels was under discussion between the parties involved in the construction. The contractor was unable to fabricate and install pristine stainless steel panels, leading to further discussion of how to repair, refinish, and clean the panels, even while the monument was under erection.

During construction, survey sheets of damaged stainless steel plates at the north and south legs from Station 70 to Station 54 were prepared that recorded "marks that were visible and objectionable to the eye from positions on the ground where the public will walk." Above Station 54, it was determined that the marks were not visible.

Confirmation of Specified Materials

Based on the archival research conducted for this study, the original stainless steel plate material was specified to be stainless steel Type 304 in accordance with ASTM A167-63, *Corrosion-Resisting Chromium-Nickel Steel Plate, Sheet, and Strip*, which was the standard in effect at the time of construction. The weld material was specified to be 300 series stainless steel. In general, the chemical constituents of Type 304 stainless steel as given in ASTM A167-63 are very similar to those cited in the current standard ASTM A240-15, *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and General Applications*, with the historic standard allowing a slightly higher range for chromium and nickel. At the time of the Arch's construction, material chemical analysis

often took several days to complete, so steel mills typically included more chromium and nickel than the minimum specification requirements in order to obtain the desired properties of the stainless steel and avoid possible rejection of the steel based on the chemical requirements. The original mill or weld filler metal chemical certifications for the stainless steel used in the Arch were not identified in the JEFF archives or in the files of the original producers of the stainless steel (currently ATI Allegheny Ludlum and Outokumpu).

During our investigation, chemical analysis of the stainless steel and weld metal was conducted using XRF and SEM/EDS. These techniques measure only a very small surface area of the material. While these techniques are considered sufficient to provide a general classification of materials, the results may show minor variations from the standard chemical constituents of the materials. Some of the analyzed samples showed slightly less chromium and nickel, and slightly more manganese, than the requirements established by ASTM A167-63; however, based on the analytical techniques used during our investigation, these differences are not considered significant, and findings indicate that the materials used in the construction of the Arch were generally within the specified range. The chemical analysis of the plate material was consistent with the specified Type 304 stainless steel. The chemical analysis of the weld material was consistent with 300 series stainless steel.

The construction of the Arch predates the use of an argon oxygen decarbonization furnace, which was first introduced to stainless steel mills in the United States in the mid-1970s. Argon oxygen decarbonization furnaces are more efficient than previous furnaces at removing impurities, including sulfur and carbon, from stainless steel. During our investigation, the SEM/EDS analysis identified impurities in the stainless steel samples from the Arch. While the sulfides from a higher level of impurities may affect the corrosion resistance of the stainless steel, based on our observations during the investigation, there is no noticeable corrosion of the stainless steel related to these impurities.

Shop Welds and Field Welds

Based on a review of archival documentation during bidding, a sample of welded stainless steel was provided to contractors. No cleaning technique was specified to remove heat tint. During the bidding process, an answer to a bidder's question identified a low alternating current and phosphoric acid as the method to be used to remove heat tint as present on the sample. Based on the archival documents (letter from NPS from MacDonald, dated December 11, 1963, and referenced PDM letter to MacDonald, dated December 5, 1963), while the steel fabricator indicated that heat tint was to be removed using "electrolitic *[sic]* methods," the letter did not give specific procedures, but the process during construction may have been similar to the procedure provided during the bidding process noted in Addendum No. 3.

Welding procedures for a variety of welds were reviewed in the archives. The procedures used metal inert gas (MIG) welding with different argon-CO_2 helium cover mixtures for different joint orientation. Additionally, the procedures indicated that weld clean-up was to be with a wire brush and that weld halos (heat tint) were to be removed using electrolytic methods. The procedures also noted that Oakite #33 was used to clean and degrease the surface prior to welding. The procedures reference American Welding Society (AWS) code and American Society for Mechanical Engineers (ASME) code.

The welds were typically finished with a stainless steel wire brush after cleaning. The shiny appearance of some welds is a result of electrolytic cleaning without using a wire brush subsequently. The lack of finishing the weld using a wire brush does not present a durability concern. These welds serve as physical documentation of the construction challenges of the Arch, and it is not recommended to brush these welds.

In general, the heat tint was largely removed from the stainless steel plate, although it remained minimally visible. While heat tint was observed at welds on the Arch, the heat tint has not contributed to long term

corrosion of the stainless steel skin. Heat tint does not increase over time and is only an aesthetic issue. We do not recommend removing heat tint, as it serves as a physical documentation of the construction of the Arch.

Faint magnetism indicates sensitization in the stainless steel. Sensitization is the precipitation of chromium carbide at grain boundaries of stainless steel and is associated with a depletion of chromium that is often a result of excessive heating during the welding process. With chromium depletion, areas of sensitization will have reduced corrosion resistance. The field observations identified faint magnetism at isolated weld locations. Based on the review of archival documentation, multiple weld passes were often required during construction, especially at the base of the Arch, and have led to excessive heating and sensitization in the stainless steel. Laboratory microscopy of the removed samples confirmed sensitization of the plate adjacent to the welds; however, based on our observations during the investigation, the environment has not been severe enough for the stainless steel plate to corrode at sensitized areas.

Passivation During Construction

When stainless steel is used in construction, the final cleaning process, including passivation, is critical to the long term protection of the steel against corrosion. Passivating stainless steel is the chemical process that removes free iron, iron scale, and other impurities, and facilitates the creation of a passive film that provides protection of the stainless steel from corrosion. If not chemically treated, a natural passive film will form on stainless steel in an oxygen-containing environment.

Based on the review of archival documentation, the specific procedures used during construction for final cleaning and passivating are unclear. The specifications provided general guidance regarding final cleaning and called for shop cleaning and protection during construction. The passivating procedure used for the stainless steel at the Arch is not documented in available archival materials. Based on the archival review, the stainless steel was cleaned at the conclusion of construction with Oakite #33, a weak acid cleaner.

At the time of construction, ASTM A380-54T, *Tentative Recommended Practice for Descaling and Cleaning Stainless Steel Surfaces*, identifies both chemical passivation using nitric acid, and natural passivating by placing the stainless steel in an environment that promotes passivation. Phosphoric acid is not specifically identified as a passivator in ASTM A380-54T, even though it facilitates the formation of a passive film on stainless steel. Phosphoric acid is the active ingredient in the current formulation of Oakite #33. Oakite #33 would have cleaned the stainless steel, which would have helped to remove surface deposits as well as surface impurities, such as sulfur or free iron on the surface, and facilitated the formation of a passive film which has protected the stainless steel from noticeable corrosion. Removal of the deposits and impurities would have increased the corrosion resistance of the stainless steel.

Stainless Steel Finish

A Number 3 finish of the stainless steel in accordance with ASTM A167-63 was specified in Addendum No. 3 of the original construction documents. While the standard only references a Number 3 finish for stainless steel sheet (less than 3/8 inch thick) and not stainless steel plate, which was used for the Arch, (greater than or equal to 3/8 inch thick), our understanding of the intent was an intermediate, polished finish consistent with the Number 3 finish for stainless steel sheet. A Number 4 finish is the next level of finish and is more highly polished than a Number 3 finish.

The finish definitions of the historic ASTM A167-63 standard and the current ASTM A480-14B standard for stainless steel are generally consistent. Currently, the Stainless Steel Industry of North America describes a Number 3 finish as a finish with short parallel lines, polished with 100 to 120 grit abrasive, and

a surface roughness of Ra 40 micro-inches or less. A Number 4 finish is typically a Number 3 finish, polished with a finer, 120 to 320 grit abrasive, with a surface roughness of Ra 25 micro-inches or less. Both of these descriptions are in alignment with ASTM A480-14B. Based on the surface profile measurements of the stainless steel at the Arch, which had an average Ra of 21.5 micro-inches, the finish of the stainless steel is consistent with a Number 4 finish rather than a Number 3 finish. The differences in overall appearance of the panels may in part be a difference in the finish as a result of fabrication issues, such as uneven wear on sanding belts.

Blemishes are associated with a difference in the surface finish or texture of the stainless steel. Blemishes observed in Part III were noted at the time of construction to a great extent and are documented throughout the JEFF archives. During our investigation, close-up inspection of the blemishes revealed extremely fine differences in the surface of the stainless steel, primarily consisting of scratches or other minor damage to the finish. The scratches were typically shallower in profile than the dominant finish on the panels. The blemishes were typically more difficult to identify when close to the stainless steel and were more visible in certain lighting conditions and when viewed at certain angles. Since no access has previously been made above grade, the blemishes above the lowest stations are likely a result of the original fabrication and construction.

The blemishes originated from a range of causes including:

- Original fabrication, resulting in increased density of the finished surface at certain areas, which has created dark vertical streaks and was identified using the silicone molds
- Damage during shipping, such as minor scratches caused by shipping straps, which appear as vertical streaks on the surface
- Refinishing in the field during construction, at areas such as the creeper crane track attachments on the extrados

As observed from grade and close-up, some of the panels generally appeared darker or lighter than adjacent panels under specific lighting conditions and at certain observation angles. Rougher surfaces appear lighter because the reflected light is more scattered, while smoother surfaces may appear darker; however, no differences in the surface texture or gloss were measured between these panels and no difference was measured in the surface texture. Furthermore, the apparent relative hue of the panels changed as lighting conditions and the visual angle changed. The perceived visual difference is likely a result of a difference in direction of the finish (left to right versus right to left), rather than any differences in the surface texture. Based on the checkerboard appearance of the panels on the Arch, the panels were not oriented in the same direction during fabrication. The difference in polishing direction does not present a long term durability concern.

Silicone molds were taken at several locations to observe the difference in surface relief and texture between various stainless steel finishes. Laboratory examination revealed that the vertical streaks below the welds corresponded to a difference in the surface texture. The density of the applied surface texture of the stainless steel panel was greater at the areas that appeared darker.

The visual observations identified several anomalies in the stainless steel that were a result of the construction process. Blemishes from handling the stainless steel panels include circular scratch patterns, likely from suction cups used to move the panels, and vertical scratch patterns, likely from tie-downs used during shipping. Weld spatter was observed and appeared to decrease from the top of the Arch to the bottom. At Station 35, discoloration was observed in a localized area that appeared to have had a liquid applied (intentionally or unintentionally) and not removed, as it was at adjacent unstained areas. Similar discoloration is visible from grade at other locations on the Arch that were not accessed close-up during

this study. On the extrados above Station 45, the out-of-plane deformation of the stainless steel panels between stiffeners was measured to be approximately 1/8 inch at several locations. At the intrados between Station 28 and Station 35, the out-of-plane deformation of the stainless steel panels between stiffeners was noted to be negligible. These conditions create visual anomalies but are not considered significant to the long-term performance of the arch.

Performance of Stainless Steel and Cleaning Effects

The visual anomalies observed from grade have been classified by WJE into three categories: blemishes, deposits, and discolorations. These visual anomalies can be categorized separately, but often overlap on the stainless steel. While the majority of the blemishes are a result of the construction process as discussed above, the incised graffiti and impact damage at the base are a result of vandalism after construction. The sources of deposits and discolorations, which are visual anomalies that occurred after construction of the Arch, are discussed below.

WJE completed a series of cleaning trials at the base of the north leg to evaluate the effectiveness of various cleaning systems at removing blemishes, deposits, and discoloration. For any cleaning project, the gentlest cleaning method that is effective should be selected, in keeping with the *Secretary of Interior's Standards for the Treatment of Historic Buildings*. The cleaning system or systems to be used must be appropriate for the substrate and conditions to be addressed. Improper cleaning can damage materials by causing discoloration, etching, or superficial corrosion staining. WJE selected cleaning techniques based on an understanding of existing conditions and our experience on previous projects. Cleaning techniques that provided a range of active chemicals were tested. The techniques selected for cleaning trials may be classified in four categories: 1) mild detergents; 2) solvents; 3) weak acids; and 4) surface refinishing techniques. Each trial included solvents to remove oils and organic residues. Some techniques combined weak acids and surface finishing techniques. In general, detergents and solvents were tested to remove surface deposits; weak acids were tested to remove superficial corrosion staining; and surface refinishing techniques were tested to remove blemishes. The techniques were combined when the stainless steel at the sample area had several visual anomalies.

At the base of the Arch, incised graffiti and impact damage have created significant blemishes. Several of the cleaning trials partially reduced the visual appearance of the blemishes; however, the most effective trials required refinishing the stainless steel. While the refinishing trials largely resulted in similar profiles to the stainless steel as were present before the trials were conducted, a visual difference between the trial areas and the original finish remained. While the visual difference could likely be reduced with additional field trials to more closely match the appearance of the original finish─potentially including the use of power tools since the original finish consists of relatively short polishing marks─it would be extremely difficult to match the original finish of the stainless steel exactly. The field refinishing samples conducted at the time of construction remain visible as blemishes.

Chemical or electrochemical cleaning could be used to remove embedded iron in the stainless steel skin at locations of incised graffiti. Removing the superficial corrosion staining reduces the appearance of the incised graffiti, as further discussed below. To prevent future damage to the Arch, and especially because the graffiti is very difficult to address with treatments, improved security measures are recommended to prevent the occurrence of graffiti. While a film-forming coating could be considered and may discourage some incised graffiti, after consultation with the NPS, no trial of a coating was performed since this treatment would noticeably change the visual appearance of the stainless steel and would require frequent maintenance.

Micro-crystalline wax and lanolin coatings were tried on small areas. The wax resulted in minimal visual change to the stainless steel, while the lanolin created a more noticeable visual change. Due to the frequent maintenance required for reapplication of these coatings and the fact that the stainless steel has proven to be durable without these coatings, the application of these coatings is not recommended.

Dark deposits were observed at various locations on the Arch. Areas with a rougher surface have collected deposits preferentially. These rougher surface areas include blemishes─irregularities in the stainless steel finish, as observed in the silicon molds, field welds, and weld spatter adjacent to the welds. The deposits appear to increase the visibility of the rougher surfaces. In addition, weather patterns, such as prevailing winds, and the geometry of the Arch, have created run-down patterns of precipitation that have created dark areas.

Samples of deposits taken using GSR kits at various locations along the height of the north leg of the Arch were analyzed in the laboratory using SEM/EDS. Elemental analysis indicated that the deposits consist of common atmospheric pollutants including fly ash, calcite, dolomite, silica, pollen, and spores. These deposits are typically loosely adhered and can be removed using very mild cleaning procedures, such as a solvent or detergent wipe, that were used in the cleaning trials. While the surface deposits may be considered visually objectionable, no evidence was observed to suggest that these deposits are accelerating deterioration of the stainless steel. If removed, the deposits will likely reappear, although the rate at which they will reappear is unknown. It should also be noted that the Clean Air Act of 1963, a federal regulation to monitor and generally reduce air pollution, with major amendments in 1970, 1977, and 1990, has resulted in a general decrease in pollutant levels as monitored in the St. Louis area (http://www.epa.gov/airdata/ date accessed February 14, 2015). It is likely that the extent of deposits visible on the surface has slowly increased as the Arch ages; however, general reduction in industrial pollutants as a result of increased clean air standards, and a reduction of nearby industry, will reduce the rate of additional deposit accumulation over time.

Discoloration of the stainless steel surface refers to a chemical alteration of the stainless steel that causes a visual difference, such as superficial corrosion staining. There were no indications during this investigation that the superficial surface corrosion has resulted in significant section loss of the stainless steel or is a structural concern. In the future, if there are significant atmospheric or environmental changes in the St. Louis area, there is a possibility that the corrosion could become more aggressive or deposits more extensive.

One of the more pronounced discolorations observed is the brownish-orange superficial corrosion staining near the base of the Arch, which is likely a result of chloride surface contamination related to prior use of deicing salts. It is likely that chloride deicers used near the base, prior to the installation of the snow melt system, circa 1985, contributed to this type of corrosion. In addition, airborne deicing salts from nearby roads and sidewalks may also have contributed to the chloride contamination. This corrosion was observed at the lowest eight panels. Chloride contamination of stainless steel accelerates surface corrosion, creating a brownish-orange corrosion product. During the investigation completed in both Part II and the current phase of this study, chloride deposits on the stainless steel were measured at the base and near the top of the Arch. In all measurements, chloride deposits were minimal. The low chloride deposits may in part be a result of the time of year in which the measurements were taken (fall), well after the deicing season in St. Louis, and precipitation may have washed some of the chlorides from the surface. The low chloride levels may also be a result of less frequent exposure to deicing salts since the installation of the snow melt system at the base.

In the cleaning trials conducted for this study, chemical cleaning using weak acids, such as Avesta Cleaner 401 or Bar Keeper's Friend, were successful in removing the chloride induced corrosion staining. Routine gentle cleaning using mild, chloride reducing cleaners will likely be sufficient to remove chloride contamination at the base of the Arch that would have the potential to accelerate surface corrosion.

Additionally at the base of the Arch, the isolated red-orange corrosion observed at the lowest two panels is related to the corrosion of deposits of steel left in the surface as a result of the incised graffiti. The embedded iron can only be removed with refinishing or pickling. Pickling stainless steel involves strong oxidizing agents, such as diluted mixtures of hydrofluoric and nitric acids, to remove a thin layer of metal from the surface of the stainless steel, and can dull the finish of the stainless steel. Based on the cleaning treatments evaluated during the trials, oxalic and phosphoric acid cleaners remove the surface corrosion, but nitric acid and hydrofluoric pickling acids will be necessary to remove the embedded iron. Since pickling acids will likely dull the finish, this should be done carefully using small brushes only at the embedded iron. If the treatment does not fully remove the iron particles or if additional incised graffiti deposits more particles, the treatment may have to be repeated if corrosion reappears.

Heat tint, also referred to as weld halos, was observed at some welds. Heat tint is a visual anomaly and does not contribute to the deterioration of stainless steel. To remove the heat tint, electrolytic cleaning methods could be evaluated but were not included as part of this project. Removal of heat tint is not recommended as it serves as a physical documentation of the construction process.

The discoloration observed at Station 35 of the intrados, which was also observed at several locations on the Arch, appears to be related to the final cleaning of the surface at the time of construction. No distress related to the discoloration at the intrados was observed. Given safety concerns during the IRA portion of the study, cleaning trials of the discoloration observed on the intrados with the weak acidic cleaners used in the trials near the base of the Arch were not possible. It is possible that those cleaning systems would be partially successful in removing the discoloration. It is also possible that chemically cleaning selected areas of the Arch may make any discoloration appear more pronounced on areas that are not cleaned.

Welds

During the visual inspection of the north leg, no cracked welds were observed between the stainless steel panels. Cracked welds were observed at the louver slats at Station 6. The cause of the cracks in the welds and the time at which the cracks occurred are unknown.

Increased weld spatter near the top is likely a result of less visibility or increased difficulty as a result of the angles and access at the time of construction. The increased weld spatter does not present a long term durability concern.

Custom IRA System

The custom IRA system allowed WJE project team members to have hands-on access to the stainless steel skin without damage to the structure. The IRA system allowed access to the exterior face of the north leg for the entire height, and access to the west intrados on the north leg from approximately Station 28 to Station 35. The IRA system could be modified to access additional locations on the intrados as needed in the future, and the system could also be used to inspect the south leg.

RECOMMENDATIONS

The exterior stainless steel of the Arch is in serviceable condition, without significant structural distress or deterioration. The visual anomalies, including a variety of blemishes, deposits, and discoloration, are not

an indication of significant corrosion or distress of the stainless steel at this time, and many of these visual anomalies are from the original construction.

The cleaning trials were successful in reducing some of the superficial corrosion staining, and provided a wide range of passivation and refinishing options for the stainless steel. For cleaning treatments or long-term maintenance, a Professional Associate of the American Institute for Conservation should be engaged to ensure the proper treatment of the stainless steel. Particular care is needed with cleaning processes, as it is possible that chemically cleaning selected areas of the Arch may make any remaining discoloration appear more pronounced.

Cleaning treatment recommendations for each type of visual anomaly are as follows:

1. For blemishes (an alteration to the stainless steel finish): Based on the nature of refinishing stainless steel, it is likely that any attempt to refinish the stainless steel panels could result in a more noticeable uneven appearance in the finish. In addition, while unintended, the blemishes are a result of the construction and are part of the history of construction of the Arch. Treatment of the blemishes is not recommended.
2. For deposits (particles, such as atmospheric pollutants, on the stainless steel surface):
   a. At lower portions of the Arch from Station 68 to Station 71 that can be accessed with aerial lifts, the stainless steel should be washed annually in the spring to remove airborne chlorides that may be deposited on the surface. Washing should be completed with pressure washing at up to 500 psi pressure with hot water (120 degrees Fahrenheit). A specialty cleaner designed to improve the efficiency of removing chlorides from metals, such as Chlor*Rid manufactured by Chlor*Rid International, may be used in the wash water. If the cleaning is not done, additional chloride induced corrosion may form.
   b. Above Station 68, access to the stainless steel becomes difficult. As the observed deposits are not contributing to deterioration of the stainless steel, removal of these deposits is not considered necessary at this time.
3. For discoloration (chemical alterations, such as superficial corrosion staining, on the stainless steel surface):
   a. At the base of the Arch, superficial corrosion staining has been induced by chloride exposure and red-orange staining has occurred as a result of the corrosion of embedded iron deposits. Removal of the superficial corrosion stains is recommended to generally improve the appearance of the stainless steel. Based on trials conducted for this study, removal of the existing incised graffiti by refinishing the stainless steel increased the difference in visual appearance, and is not recommended.
      (1) To remove the chloride induced superficial corrosion and the superficial corrosion staining at the incised graffiti, a cleaning treatment could be implemented with a weak acid cleaner, such as Bar Keeper's Friend or Avesta 401, using an very fine abrasive pad; the method would need to be precisely defined based on additional trials. Based on the cleaning trials performed as part of this study, this process does not significantly alter the finish of the stainless steel. Refinishing the stainless steel, including at areas of graffiti, would remove much of the shallow graffiti; however, refinishing the stainless steel is not recommended because it would be extremely difficult to match the original finish of the stainless steel. In addition, the refinishing process would involve more extensive intervention than the cleaning treatments discussed above.
      (2) At locations of incised graffiti, the cleaning treatment recommended above will remove the superficial corrosion staining. The appearance of the stainless steel will be improved by removing the superficial corrosion staining. The cleaning may remove some of the red-orange staining resulting from the corrosion of the embedded ferrous metal, but the staining may

reappear if the embedded steel is not fully removed. The cleaning process may need to be repeated in the future as the remaining embedded steel corrodes, causing additional staining. The surface should be monitored to determine the appropriate intervals for cleaning.

(3) Removal of embedded iron using pickling paste or electrolytic cleaning should be considered in very isolated areas and using a very controlled process. Pickling isolated areas may dull the surface locally and should be conducted as a trial prior to implementation.

(4) In addition to the cleaning recommended above to remove the localized discoloration currently present on the stainless steel, consideration should be given to a long-term maintenance plan for the stainless steel at the base.

b. Above Station 68, access to the stainless steel becomes difficult. As the discoloration is not contributing to the long term deterioration of the stainless steel, treatment of the discoloration is not considered necessary.

c. Observed heat tint is part of the original fabrication and is not contributing to the long term deterioration of the stainless steel. Treatment of the discoloration would involve electrolytic cleaning and is not considered necessary.

Recommendations unrelated to cleaning treatments are as follows:

1. At the vents at Station 6, the cracked welds at the louver slats on the north leg should be repaired. The vent at the south leg should be inspected close-up for cracked welds, similar to the inspection conducted at the vent at the north leg. This inspection will require IRA, as the vent is inaccessible from the observation deck for inspection. We understand that JEFF has initiated a project statement for this repair. The louver slats should be temporarily stabilized until the repairs can be performed.
2. Future incised graffiti should be prevented by improved security measures.
3. If deicing salts are necessary near or adjacent to the Arch, non-chloride-containing deicing salts, such as calcium magnesium acetate, should be used. Due to the likely more limited use of deicing salts near the base since the installation of the heated snow melt system, the rate of chloride induced corrosion on the stainless steel of the Arch should be slower.
4. Park maintenance staff should be trained to safely perform routine maintenance, such as removing stickers and tape from vandalism, so as to not cause damage to the stainless steel. In addition, measures should be implemented to train the staff in preventing mechanical damage during routine maintenance involving ladders and snow removal equipment.
5. Annual visual monitoring of the stainless steel skin using high powered binoculars or spotter scopes, including photographic documentation, is recommended to document visual changes in the stainless steel. Annual monitoring close-up of the incised graffiti and scratches at the base should also be performed. These changes should be compared against previous documentation and evaluated for significance.
6. To understand the structural behavior of the Arch in depth, in terms of thermal stresses and/or lateral deflection at the observation deck, a finite element analysis could be performed.

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WJE | ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

APPENDIX A -
ARCHIVAL RESEARCH DOCUMENTS

MacDONALD CONSTRUCTION COMPANY
1310 South Grand Avenue
St. Louis, Missouri

SHOP DRAWINGS:

FOR: (Item of Work) STRUCTURAL

FROM: (Subcontractor) PITT DES MOINES

TO: NATIONAL PARK SERVICE
#11 North 4th Street
St. Louis 2, Missouri
ATTN: Supt. J.N.E.M.

DATE: 29 APRIL 1963

PROJECT : Gateway Arch & Visitors' Center, Jefferson National Expansion Memorial
St. Louis, Missouri
#14-10-0232-462

The Following Sepias / Brochures ✓ / Drawings Are Submitted:

TO: Architect-Engineer

FOR: ☑ Approval and Return
☐ Correction
☐ Resubmittal

No.	Drawing No.	Title	Latest Date
1		STAINLESS STEEL CLEANING PROCEDURE	
1	COPY	EASTERN STAINLESS STEEL CORP LETTER (4-8-63)	

PLEASE RETURN APPROVED OR CORRECTED:

☐ Transparency
☐ Brochures
☐ Drawing

TO: MacDONALD CONSTRUCTION COMPANY
299 Chestnut Street
St. Louis 2, Missouri

J C Wright
MacDONALD CONSTRUCTION CO.

EASTERN STAINLESS STEEL CORPORATION

BALTIMORE 3, MARYLAND

TELEPHONE
ATWATER 8-2000

TELETYPE
ESSEX 283 OR 376

April 8, 1963

Mr. George L. Bader, Director of Purchasing,
Pittsburgh-Des Moines Steel Company,
3436 Neville Island,
Pittsburgh 25, Pennsylvania

Dear George:

John Schweizer has asked me to write you relative to the Mill's recommendation regarding a protective covering of some kind for the stainless steel surfaces on the Memorial Arch during fabrication, transportation and erection.

As you perhaps know, there are a number of excellent protective coatings that can be applied to stainless to prevent damage during handling and fabrication, but nearly all of them present some problem either in application or removal. These objections and pitfalls I am sure you want to avoid.

Probably the easiest for application would be a spray coating of one of the vinyl or latex compounds. However, the difficulty here is that exposure to heat or pressure has a tendency to harden these compounds so that they are extremely difficult to remove.

An adhesive paper application is fairly easy but, here again, the adhesive compound has a tendency to self vulcanize, particularly at temperatures above 60° Fahrenheit and if this occurred the stripping of the paper from the finished part can be difficult and time consuming. Also, the adhesive compounds are subject to aging and few of the manufacturers will guarantee them for easy strippability after six months service.

If protective coating is absolutely necessary, it is our opinion that probably a heavy grade of kraft paper applied with paperhanger's paste is probably one of the best and cheapest means of providing protection. The cost of the material is low and it can be removed with warm water, or with a simple steamer similar to that used for removing wallpaper from a home wall.

Mr. George L. Bader,
Pittsburgh-Des Moines Steel Company

April 8, 1963

None of these protective coatings are particularly fool-proof and I would hope that you would be able to find ways and means of handling these sections of the archway during fabrication, transportation and erection so that scratching and damage could be avoided rather than trying to protect against it by some adhesive film.

If I can be of any further help to you in connection with this problem, I would be pleased to have you call me.

Most cordially yours,

EASTERN STAINLESS STEEL CORPORATION

Richard C. Cunningham
esg

Richard C. Cunningham
Vice President in Charge of Sales

RCC:esg
cc: Mr. J. B. Schweizer,
Industrial/Buffalo

STAINLESS STEEL CLEANING PROCEDURE April 10, 1963

1. Provide area for washing which is well equipped with water supply and so designed to carry off excess drainage during washing operations.

2. Apply Oakite 33 to S.S. surface using foamizer unit by Oakite Products, Inc. over entire surface of one wall section.

3. Agitate with soft brush over entire surface. Only one man should be used for this operation so that some small amount of time will be allowed for the Oakite to set and work on hard to remove rust and discoloration spots.

   Severe rust spots and discoloration, localized, will require a double application of Oakite 33. Second application can be made at time of the brushing or agitation operation.

4. Hose rinse.

5. A small quantity of Oakite 74L should be kept at the job site. Oakite 33 will dry leaving a minor streaking effect if not well rinsed or under severe dust conditions.

   If it become necessary to do a quick wash with Oakite 74L, the application can be made with the same foamizer unit used to apply the 33.

   The 74L would be applied after rinsing the 33 and hose rinsed without agitation.

MACDONALD CONSTRUCTION COMPANY

General Contractors

April 3, 1964

OFFICES IN PRINCIPAL CITIES

EXECUTIVE OFFICE
1310 SOUTH GRAND BOULEVARD
ST. LOUIS 4, MISSOURI
PROSPECT 1-5916 · AREA CODE 314
CABLE: MACDONALD

SUPT.	
ASST. SUPT.	
HISTORIAN	
PARK ENG. H/C	
ADMIN. OF EDUC. H/C	
INTP. SPEC.	
1 Recd.	
FILE	

National Park Service
11 North Fourth Street
St. Louis, Missouri 63102

Attention: Mr. H. Raymond Gregg,
Superintendent, Contracting Officer

Reference: Gateway Arch and Visitor Center

Gentlemen:

In accordance with our several previous discussions regarding cleaning and protection procedures for the stainless steel Arch skin, and in accordance with your recent request, Pittsburgh-Des Moines has prepared an outline of their activities in this regard. They have now submitted for approval an addendum to Section II, Paragraph #5, of our approved erection procedure entitled "Cleaning and Protection of Polished Stainless Steel Surfaces", Pages 1 through 4, dated March 25, 1964. (Two copies enclosed.)

We respectfully request your early review and approval of this addendum.

Yours very truly,

MacDONALD CONSTRUCTION COMPANY

B. A. Prichard, General Superintendent

BAP:sh
Encs.
cc: Mr. Bruce Detmar
(w. 1 enc.) Eero Saarinen & Associates
21 Davis Street
Hamden, Connecticut

Mr. C. E. Rennison
Eero Saarinen & Associates
299 Chestnut Street
St. Louis, Missouri 63102

Dr. Hanskarl Bandel
Sevrud-Elstad-Krueger and Associates
415 Lexington Avenue
New York, New York 10017

MacDonald Construction Field Office

File

CABLE: PITTDEMOIN
TELEX: 086-734

PDM STEEL COMPANY

Pittsburgh-Des Moines Steel Company

Engineers
Fabricators
Constructors

NEVILLE ISLAND · PITTSBURGH, PENNSYLVANIA 15225 · AREA CODE 412
PHONE 331-3000

April 2, 1964

MacDonald Construction Company
1310 South Grand Avenue
St. Louis, Missouri

Attention: B. A. Prichard
General Superintendent
Reference: Jefferson National Expansion Memorial
PDM Contract 12041
St. Louis, Missouri

Gentlemen:

In accordance with your request and that of the Contracting Officer by letter of February 20, 1964 we are sending you herewith one (1) reproducible and five (5) copies of addendum to the Erection Procedure entitled "Cleaning and Protection of Polished Stainless Steel Surfaces - Gateway Arch - St. Louis, Missouri".

It is our opinion that adequate "Protection" is being provided for the stainless steel surfaces, both from the standpoint of prevention and repair, in strict accordance with the specifications and we trust that the enclosed addendum to our Erection Procedure will dispel any doubts expressed by the Contracting Officer in his letter of February 20.

Will you therefore please foreward the enclosed addendum to the Contracting Officer along with our request for approval. Please advise if any further information is required by us.

Yours very truly,

PITTSBURGH-DES MOINES STEEL COMPANY

G. A. Cosby

G. A. Cosby

GAC/bg

cc: Mr. K. J. Kolkmeier - PDM
Mr. Stan Wolfe - MacDonald

A. COATINGS AND COVERINGS

Prior to and during the early stages of fabrication, Pittsburgh Des Moines investigated many types of coatings and coverings for possible use in protecting the polished stainless steel surface. The materials investigated are as listed below:

1. Permacel tapes (black #692)
2. Cloth fiber tapes (Mystic #5820 and 5800)
3. Asbestos paper cemented with a sizing compound
4. Liquid plastic films (MUNRAY PEEL-KOTE type MC and Mystic Brand A-105)
5. Paper tapes (Mylar tapes #7331 and #7332)

Samples of the above mentioned coverings were obtained and subjected to severe testing in our Plant and Research Department with the following results.

(1) Paper Tapes

The paper tapes, while offering some protection from dust accumulation proved to be least promising. As far as nicks and scratches were concerned, they were little or no protection whatever, due to the inability of the paper itself to withstand banging, scraping or knocking without tearing.

The paper tapes disintegrated over a long period of exposure to varying temperatures (120°F. to 20°F.) and eventually became impossible to remove without extensive scraping operations.

(2) Cloth and Permacel Tapes

The cloth tapes offered more protection from knocks and scratching than the paper tapes. However, further testing under varying atmospheric conditions proved that the cementing compound would break down, thereby causing the degeneration of the coverings. Again, after prolonged exposure, it was necessary to remove a large part of the tapes and adhesive by scraping.

None of the manufacturers of the paper, cloth or Permacel tapes listed above would guarantee their product to last longer than three months under the conditions of the application intended. Most in fact, stated that 6 to 9 months exposure to sun and rain would very likely destroy the protective qualities of the tape and that removal would become virtually impossible without scraping.

(3) Liquid Plastic Films

Stripable plastic films are usually applied as protective coverings to relatively small panels and it is not normally applied in thicknesses greater than 1 to 1½ mils. -- continued --

(3) Liquid Plastic Films -- continued from page #1 --

Obviously a coating this thin offers little or no protection from severe nicks and scratches. Greater thicknesses of the coating were attempted, however it was found that as many as ten to fifteen applications were required to approach 1/32" in thickness. Approximately two weeks were required to attain thicknesses of this magnitude, due to the long setting up time between coats.

Testing in extreme temperatures (120°F to 20°F) again proved the plastic films were not easily removable and again required a scraping operation. At extremely cold temperatures, the plastic film became extremely susceptible to cracking, and under extremely high temperatures the material was found to lose almost all of its tensile strength and therefore became virtually impossible to remove.

(4) Asbestos Paper with Sizing Compound

Asbestos paper applied with a sizing compound offers a small amount of protection from knocks and scratches, however, it was determined that here again this material would not stand up under the extreme conditions of atmospheric exposure.

Heavy wetting of the asbestos paper caused the sizing compound to break down and the covering would slip away.

B. METHODS OF PROTECTION BEING USED BY PITTSBURGH DES MOINES

(1) At Mills

Immediately after polishing at the mills, the polished stainless steel surface is covered with paper and stored in specially built pallets for shipment to the fabricating plant. Once stored in the pallets, the plates are wrapped in cardboard and banded with metallic strips. The plates remain untouched until they are removed for processing at the fabrication plant.

(2) In Process and Transportation to Site

For use in handling the polished plates prior to welding into panels a specially adapted vacuum cup lifting device is utilized to prevent marring the polished surface.

After the plates are welded into panels, they are again handled by lifting beams which have been specially made and covered with soft rubber padding on those members which come into direct contact with the polished stainless. All layout skids are also padded with soft rubber and are vacuum cleaned each day to prevent dust and grit build up which may scratch the polished plates. All workmen handling or working with the polished plates have been specially trained and instructed to use extreme caution to protect the polished surface.

(2) In Process and Transportation to Site --continued from page #2

Prior to shipping, the shop welds are cleaned to remove halo and excess discoloration. The cleaning process is electrolytic and was developed for the purpose of cleaning welds on stainless steel surfaces.

Rubber padded hauling racks are used on rail cars for transporting the wall sections. All padding is periodically replaced when severe wear is indicated.

(3) Protection of stainless during erection phase

During erection, only one portion of the erection equipment is actually attached to or through the polished plates. That, of course, is the connections of the track support beams to the Arch. In this instance, the stainless is protected by 4" thick Fabreka pads under the beam connections.

No other connection is made to the polished plates and a great deal of engineering and special fabrication has been done to assure that all outside scaffolds are supported by the creeper track beams or by members supported on the inner carbon shell and cantilevered out over the outer polished plates.

During unloading operations, the side sections are hoisted by specially designed equipment to attach only to the carbon shell and the interior stiffeners. Each wall section is stored in racks and bolted in place to minimize the possibility of damage to the stainless.

On the assembly pad, protection is placed under ladders and around welded joints to reduce the possibility of weld splatter and dropped objects from marring the stainless. Sections which do become soiled are washed before final hoisting and weld halos are removed prior to hoisting.

During hoisting of the section, tag lines are anchored to deadmen to prevent the section from hitting previously erected sections. No fitting equipment is attached to the stainless during fitting operations, as is normal, and cardboard protection is used during tacking operations to prevent weld splatter. An asbestos blanket is taped below the weld seam during welding to catch welding sparks and dirt during grinding. Weld halos are removed after welding. During concreting operations, the outside plates are covered with tarps or plastic to minimize concrete splashing.

All outside scaffolds have Fabreka pads to prevent mild steel from coming into contact with the stainless and each scaffold is fitted with a rubber strip which catches miscellandous objects from sliding off the scaffolds and down the sides of the arch.

C. TEST PANEL RESULTS

In order to demonstrate Pittsburgh Des Moines' ability to remove various scars and blemishes, a 4'x4' test panel was defaced in the following manner:

1. Wet concrete splashed on it.
2. Welding cable pulled across it.
3. Suction cup attached and removed.
4. Grease spilled on it.
5. Bruised by Fabreka pad.
6. Deeply scratched by sharp instrument.

All the above mentioned scars were present on the plate approximately one month before repair procedures were started. At the start of the repair several weld passes were made on the plate and one circular pass made to depict a repair of the track connections.

All the above mentioned scars were removed to the satisfaction of the Resident Architect and the plate was refinished to his complete satisfaction.

D. CONCLUSIONS

In addition to the above simulated accidents, Pittsburgh-Des Moines has been subjected to several actual repairs which have been of a far more serious nature. This type of repair would be one which required the complete removal and replacement of plates which can not be refinished. Specifically, this has been done by Pittsburgh-Des Moines on three occasions to the complete satisfaction of the Resident Architect.

In view of the foregoing, it can only be concluded that Pittsburgh-Des Moines is furnishing adequate protection againat minor scratching and denting and is completely capable of making any repair of major damage that can conceivably be required, as is historically indicated, on the Arch sections.

As outlined above, Pittsburgh-Des Moines has investigated and tested many protective coverings. Although coverings would be much more economical when compared with the finally selected alternatives, none have proved to be satisfactory from the standpoint of protection against nicks and scratches or from the standpoint of keeping the Arch clean. Therefore, the protection is being accomplished as herein described and the final cleaning will be performed as the creeper derricks are removed as described in our letter of December 5, 1963.

July 22, 1966

Mr. LeRoy Brown, Superintendent
National Park Service
11 North Fourth Street
St. Louis, Missouri

Re: Jefferson National Expansion Memorial

Dear Mr. Brown:

On June 28, 1966 a final inspection of the Gateway Arch inner and outer skin surfaces was made with the Contractor.

The Contractor in erecting the Arch has caused and left abrasions and suction cup marks on the outer stainless steel skin. The specifications called for a covering to be maintained during all phases of the work over the outer surfaces during erection of the Arch. The covering, which would have prevented these marks, was not applied to the Arch surface during the erection period. The Contractor assured the Government that the Arch could be adequately protected during fabrication and erection and minor marks corrected without application of the protective covering. There are, however, marks which the Contractor could not repair on sample test panels before erection and has not been able to repair on the Arch proper. The location of these marks on the Arch has been previously provided you.

We estimate the cost of applying and maintaining an adequate covering over the entire exterior surface is $86,589.00. (See estimate enclosed) The Contractor has indicated repeatedly that a surface covering would not have been of any help. Never the less, the Contractor has not provided the Government with the protection on the Arch specified. Therefore, a Change Order should be written for the labor and materials omitted from the work.

In addition to the impairment to the surface finish of the steel plate, there are wrinkles on the Arch stainless steel surfaces beyond the flatness tolerances specified. These wrinkles exist even though every effort has been made to have the Contractor eliminate them. None of the wrinkles in the plate are of structural significance. As in the case of the marks on the stainless steel surfaces, we know of no way to repair or replace the wrinkled panels, the damage is ir-reparable.

We recommend that another Change Order be written relieving the Contractor of providing an Arch with surface flatness-tolerance of ± 1/4 inch as specified and allowing abrasions and tool marks on the stainless plate surfaces. Since the panels with wrinkles and abrasions cannot be replaced with out rebuilding the entire Arch, we recommend the value of the credit should be established on the basis of the cost of material in place. This in effect then means the Government would not pay for the damaged panels.

Attached is a copy of an Index of Letters regarding the protection of stainless steel.

If you have any questions please do not hestitate to contact us.

Very truly yours,

EERO SAARINEN AND ASSOCIATES

Bruce R. Detmers

Bruce R. Detmers

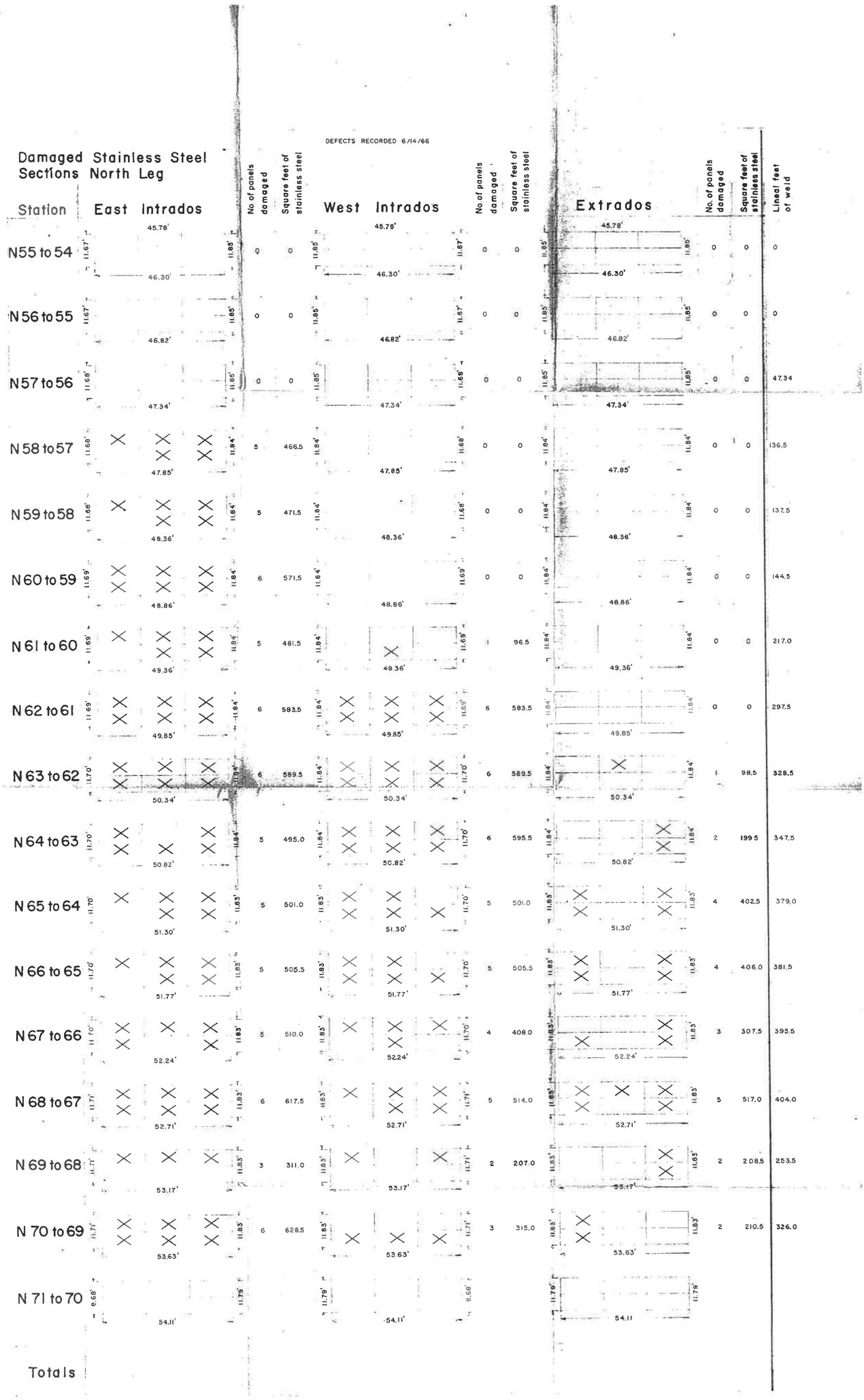
BRD/eb

w/o Encl.

cc: Mr. John B. Cabot w/encl.
Mr. Kramer Chapman w/encl.
Mr. C. E. Rennison w/encl.

Damaged Stainless Steel Sections North Leg

DEFECTS RECORDED 6/14/66



Station	East Intrados No. of panels damaged	East Intrados Square feet of stainless steel	West Intrados No. of panels damaged	West Intrados Square feet of stainless steel	Extrados No. of panels damaged	Extrados Square feet of stainless steel	Lineal feet of weld
N55 to 54	0	0	0	0	0	0	0
N56 to 55	0	0	0	0	0	0	0
N57 to 56	0	0	0	0	0	0	47.34
N58 to 57	5	466.5	0	0	0	0	136.5
N59 to 58	5	471.5	0	0	0	0	137.5
N60 to 59	6	571.5	0	0	0	0	144.5
N61 to 60	5	481.5	1	96.5	0	0	217.0
N62 to 61	6	583.5	6	583.5	0	0	297.5
N63 to 62	6	589.5	6	589.5	1	98.5	328.5
N64 to 63	5	495.0	6	595.5	2	199.5	347.5
N65 to 64	5	501.0	5	501.0	4	402.5	379.0
N66 to 65	5	505.5	5	505.5	4	406.0	381.5
N67 to 66	5	510.0	4	408.0	3	307.5	395.5
N68 to 67	6	617.5	5	514.0	5	517.0	404.0
N69 to 68	3	311.0	2	207.0	2	208.5	253.5
N70 to 69	6	628.5	3	315.0	2	210.5	326.0
N71 to 70							
Totals							

Damaged Stainless Steel Sections South Leg

DEFECTS RECORDED 6/14/66

Station	East Intrados	No. of panels damaged	Square feet of stainless steel	West Intrados	No. of panels damaged	Square feet of stainless steel	Extrados	No. of panels damaged	Square feet of stainless steel	Lineal feet of weld
S55 to 54	45.78', 46.30'	6	541.0	45.78', 46.30'	0	0	45.78', 46.30'	0	0	231.0
S56 to 55	46.82'	4	365.0	46.82'	0	0	46.82'	6	551.5	257.5
S57 to 56	47.34'	4	368.0	47.34'	1	93.0	47.34'	3	278.0	285.0
S58 to 57	47.85'	6	559.5	47.85'	4	373.5	47.85'	3	281.0	374.5
S59 to 58	48.36'	6	565.5	48.36'	3	283.5	48.36'	5	474.0	383.5
S60 to 59	48.86'	4	381.0	48.86'	3	286.5	48.86'	3	287.0	369.0
S61 to 60	49.36'	5	481.0	49.36'	3	289.5	49.36'	3	290.0	377.5
S62 to 61	49.85'	6	583.5	49.85'	6	583.5	49.85'	6	587.0	404.0
S63 to 62	50.34'	6	589.5	50.34'	6	589.5	50.34'	6	593.0	407.0
S64 to 63	50.82'	6	595.0	50.82'	6	595.0	50.82'	6	598.5	410.0
S65 to 64	51.30'	6	600.5	51.30'	6	600.5	51.30'	6	604.0	413.0
S66 to 65	51.77'	6	606.0	51.77'	4	403.5	51.77'	6	609.5	381.5
S67 to 66	52.24'	6	611.5	52.24'	0	0	52.24'	5	512.5	291.0
S68 to 67	52.71'	6	617.5	52.71'	0	0	52.71'	5	517.5	310.5
S69 to 68	53.17'	3	311.0	53.17'	4	415.0	53.17'	4	417.5	371.0
S70 to 69		5	524.0		4	419.5		4	421.5	403.0
S71 to 70										
Totals										

OPTIONAL FORM NO. 10
5010-104
UNITED STATES GOVERNMENT

Memorandum

TO : Superintendent, JNEM DATE: September 14, 1966

FROM : Project Supervisor, JNEM

SUBJECT: The Extent and Cost Value of Damages, Marks, etc., on the Stainless Steel Skin of Arch to Date for Informational Purposes

As you know, there have been considerable discussions, meetings, correspondence, etc., concerning the marks placed on the surface of the stainless steel skin of the Gateway Arch by MacDonald and their subcontractor, PDM, in the assembly of units, transportation, and erection of the units to form a completed structure.

After the contractor told us he could not repair these defects, Resident Architect Rennison, ES&A, and I together, and separately, walked around the bases of the Arch and recorded marks that were visible and objectionable to the eye from positions on the ground where the public will walk. It was found that these marks from this point of observation do not show up above Sta 54. These defects are recorded on the attached sheets as they appeared to us on June 14, 1966. The bottom section #71 was not recorded as it was covered with plywood for protection from workmen passing close to it.

The rejects include suction cup marks, marks caused by scaffolding rubbing the surface, marks caused by standards used to hold units in position on railroad cars in transportation, and various other marks from unknown causes. These marks left by the contractor, which he declares he is unable to correct, are recorded on individual sheets for each side of the Arch from station to station.

A chart for each leg has been made and accompanies this memo which shows each stainless steel sheet in each section which has one or more damages on its face. The sheet location is marked with an X on the chart. We then listed in a column for each side of each section the number of sheets damaged to a side, the square feet of stainless steel contained in the damaged sheets, and the total lineal feet of weld surrounding the damaged sheets for each section. Using the lesser value placed on the square feet of stainless steel and lineal feet of weld as given us by ES&A in their letter of August 23, 1966, we have the following evaluation of costs:

13,398.0 sq. ft. SS @ $6.00 =	$80,388.00	20,254.5 sq. ft. SS @ $6 =	$121,527.00
4,221.9 lin. ft. weld @ $8.00 =	33,775.20	5,669.0 lin. ft. weld @ $8 =	45,352.00
Total for North Leg	$114,163.20	Total for South Leg	$166,879.00

TOTAL FOR BOTH LEGS = $281,042.20

Please Note:

1. This does not include Section 71 of either leg because they are not as yet uncovered and cleaned sufficiently to evaluate the extent of damage, if any.

2. Bulges, dents, etc. are to be recorded on another sheet, with evaluation, which are in the process of being computed.

3. These figures do not include the amount ES&A (RD&A) gave us for expenditures which MacDonald's subcontractor, PDM, should have made to place protective coating on the Arch sections which could have prevented these scratches and marks. ($86,589.00)

Kramer L. Chapman

Kramer L. Chapman

Enclosures

cc:
Chief Architect, D & C, WSC, w/enc & inc
Mr. Detmers, RD&A, w/enc & inc

KLChapman:jch

STAINLESS STEEL CLEANING PROCEDURE April 10, 1963

1. Provide area for washing which is well equipped with water supply and so designed to carry off excess drainage during washing operations.

2. Apply Oakite 33 to S.S. surface using foamizer unit by Oakite Products, Inc. over entire surface of one wall section.

3. Agitate with soft brush over entire surface. Only one man should be used for this operation so that some small amount of time will be allowed for the Oakite to set and work on hard to remove rust and discoloration spots.

   Severe rust spots and discoloration, localized, will require a double application of Oakite 33. Second application can be made at time of the brushing or agitation operation.

4. Hose rinse.

5. A small quantity of Oakite 74L should be kept at the job site. Oakite 33 will dry leaving a minor streaking effect if not well rinsed or under severe dust conditions,

   If it become necessary to do a quick wash with Oakite 74L, the application can be made with the same foamizer unit used to apply the 33.

   The 74L would be applied after rinsing the 33 and hose rinsed without agitation.

APPENDIX B -
SUMMARY OF VIDEO CAMERA FOOTAGE FROM IRA INSPECTION

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

Summary of video camera footage from industrial rope access (IRA) inspections provided to the Jefferson National Expansion Memorial (JEFF).

Table 1. Summary of Video Camera Footage from IRA

Date	File Name	Length	Description
10/14/2014	GoPro_2014-10-14_01	00:00:40	Rigging at top of Arch; Weather station
10/14/2014	GoPro_2014-10-14_02	00:03:50	Rigging at top of Arch
10/14/2014	GoPro_2014-10-14_03	00:01:29	Rigging at top of Arch
10/14/2014	GoPro_2014-10-14_04	00:09:13	Rigging at top of Arch
10/14/2014	GoPro_2014-10-14_05	00:17:24	Rigging at top of Arch
10/14/2014	GoPro_2014-10-14_06	00:04:00	Rigging at top of Arch
10/15/2014	GoPro_2014-10-15_01	00:04:26	Inside tram from base to observation deck
10/15/2014	GoPro_2014-10-15_02	00:03:53	Rigging at top of Arch
10/15/2014	GoPro_2014-10-15_03	00:03:23	Rigging at top of Arch; Attempt at caution fence
10/15/2014	GoPro_2014-10-15_04	00:05:24	Outside tram from observation deck to base
10/16/2014	GoPro_2014-10-16_F1	00:17:26	Rigging at top of Arch
10/16/2014	GoPro_2014-10-16_F2	00:17:26	Rigging at top of Arch
10/16/2014	GoPro_2014-10-16_F3	00:05:57	Rigging at top of Arch
10/16/2014	GoPro_2014-10-16_AS_01	00:00:49	Rigging at top of Arch
10/16/2014	GoPro_2014-10-16_AS_02	00:00:30	Rigging at top of Arch
10/16/2014	GoPro_2014-10-16_AS_03	00:01:24	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_04	00:04:46	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_05	00:02:16	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_06	00:02:32	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_07	00:04:33	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_08	00:02:09	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_09	00:01:48	Rigging - lowering midstation; setting intermediate straps
10/16/2014	GoPro_2014-10-16_AS_10	00:01:59	Rigging - lowering midstation; setting intermediate straps
10/18/2014	GoPro_2014-10-18_F1	00:01:20	Setting up fixed camera on beacon; Looking north; Looking south
10/18/2014	GoPro_2014-10-18_F2	00:03:33	Rigging at top of Arch; DM ascending
10/18/2014	GoPro_2014-10-18_F3	00:07:42	Rigging at top of Arch; AS ascending
10/18/2014	GoPro_2014-10-18_AS_01	00:00:53	Start of decent
10/18/2014	GoPro_2014-10-18_AS_02	00:05:52	Rigging - lowering midstation; setting intermediate straps
10/18/2014	GoPro_2014-10-18_AS_03	00:04:14	Rigging - lowering midstation; setting intermediate straps

10/18/2014	GoPro_2014-10-18_AS_04	00:03:41	Rigging - lowering midstation; setting intermediate straps
10/18/2014	GoPro_2014-10-18_AS_05	00:02:48	Rigging - lowering midstation; setting intermediate straps
10/18/2014	GoPro_2014-10-18_AS_06	00:00:29	Ascending to Arch; Checking carabineer to see if scratched surface
10/18/2014	GoPro_2014-10-18_AS_07	00:05:36	Ascending to top of Arch; passing vent
10/18/2014	GoPro_2014-10-18_AS_08	00:00:51	Rigging at top of Arch
10/18/2014	GoPro_2014-10-18_AS_09	00:00:18	Rigging at top of Arch
10/18/2014	GoPro_2014-10-18_DM_01	00:17:26	Rigging - lowering midstation; setting intermediate straps
10/18/2014	GoPro_2014-10-18_DM_02	00:17:26	Rigging - lowering midstation; setting intermediate straps
10/18/2014	GoPro_2014-10-18_DM_03	00:09:09	Rigging - lowering midstation; setting intermediate straps
10/19/2014	GoPro_2014-10-19_F1	00:17:26	Rigging at top of Arch; Prep for Extrados Inspection
10/19/2014	GoPro_2014-10-19_F2	00:17:26	Rigging at top of Arch; Start of Extrados Inspection
10/19/2014	GoPro_2014-10-19_F3	00:13:11	Rigging at top of Arch; Start of Extrados Inspection
10/19/2014	GoPro_2014-10-19_DM_01	00:12:54	Rigging at top of Arch; Prep for Extrados Inspection
10/20/2014	GoPro_2014-10-20_AS_01	00:01:00	Panoramic at top of Arch; Getting ready for decent
10/20/2014	GoPro_2014-10-20_AS_02	00:01:31	Decent at mid-station; DM preparing to descend onto Intrados
10/20/2014	GoPro_2014-10-20_DM_01	00:17:25	At top of Arch; Descending to midstation
10/20/2014	GoPro_2014-10-20_DM_02	00:17:26	Descending to midstation; Rigging at midstation
10/20/2014	GoPro_2014-10-20_DM_03	00:17:26	Rigging at midstation; Tensioning line
10/20/2014	GoPro_2014-10-20_DM_04	00:17:26	Rigging at midstation
10/20/2014	GoPro_2014-10-20_DM_05	00:02:30	Rigging at midstation
10/21/2014	GoPro_2014-10-21_F1	00:00:19	Overall view down the north leg; DM on Intrados
10/21/2014	GoPro_2014-10-21_F2	00:09:06	Pulling ropes up at top of Arch
10/21/2014	GoPro_2014-10-21_F3	00:02:04	Overall view down the north leg; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_01	00:03:12	At midstation; DM preparing for Intrados
10/21/2014	GoPro_2014-10-21_AS_02	00:03:15	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_03	00:08:58	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_04	00:08:51	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_05	00:01:18	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_06	00:02:34	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_07	00:01:37	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_08	00:02:13	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_09	00:05:38	At midstation; DM on Intrados
10/21/2014	GoPro_2014-10-21_AS_10	00:00:33	At midstation; DM ascending Intrados
10/21/2014	GoPro_2014-10-21_AS_11	00:02:19	At midstation; DM coming back on Extrados

10/21/2014	GoPro_2014-10-21_AS_12	00:04:04	At midstation; DM and AS on extrados
10/21/2014	GoPro_2014-10-21_AS_13	00:02:30	At midstation; Start to demobilize equipment
10/21/2014	GoPro_2014-10-21_DM_01	00:17:26	At midstation; Transition to Intrados
10/21/2014	GoPro_2014-10-21_DM_02	00:08:56	Intrados inspection; Working with the suction cups
10/21/2014	GoPro_2014-10-21_DM_03	00:09:20	Intrados inspection; Working with the suction cups
10/21/2014	GoPro_2014-10-21_DM_04	00:17:26	Intrados inspection; GSR
10/21/2014	GoPro_2014-10-21_DM_05	00:17:26	Intrados inspection; silicon mold; level;
10/21/2014	GoPro_2014-10-21_DM_06	00:17:09	Intrados inspection; GSR; cleaning trials
10/21/2014	GoPro_2014-10-21_DM_07	00:01:26	Intrados inspection; cleaning trials
10/21/2014	GoPro_2014-10-21_DM_08	00:05:02	Intrados inspection; cleaning trials

Notes: DM = Dave Megerle, WJE DAT member who completed the intrados inspection
AS = Aaron Sterns, WJE DAT member who is a certified weld inspector

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APPENDIX C -
SUMMARY OF GLOSS METER READINGS

Table 1. Panel Locations for Gloss and Surface Profile Readings

Panel Reference	Location	Visual Appearance
A	East intrados of North Leg, north panel, 7th from base	Lighter visual appearance
B	West intrados of North Leg, north panel, 11th from base	Lighter visual appearance
C	West intrados of North Leg, south panel, 6th from base	Lighter visual appearance
D	East intrados of North Leg, north panel, 6th from base	Darker visual appearance
E	West intrados of North Leg, north panel, 12th from base	Darker visual appearance
F	West intrados of North Leg, south panel, 7th from base	Darker visual appearance

Table 2. Gloss and Surface Profile Readings for Panels with Lighter Visual Appearance Horizontal Scan

Measurement	Panel A	Panel B	Panel C	Average
GLOSS20	83.4	132.8	101.1	106
GLOSS60	118.6	178.7	118.6	139
GLOSS85	80.6	93.9	70.9	82
HAZE	9.9	0.0	10.4	7
LogHAZE	225.0	0.0	234.0	153
DOI	70.9	31.4	41.1	48
Rspec	34.3	26.6	23.8	28
Surface Profile, Ra	16.0	11.0	17.0	15

Table 3. Gloss and Surface Profile Readings for Panels with Lighter Visual Appearance Vertical Scan

Measurement	Panel A	Panel B	Panel C	Average
GLOSS20	13.7	21.8	14.3	17
GLOSS60	23.6	41.2	27.7	31
GLOSS85	14.2	44.6	20.9	27
HAZE	45.3	66.6	47.9	53
LogHAZE	660.0	818.0	682.0	720
DOI	23.7	25.0	22.7	24
Rspec	3.1	4.7	3.2	4
Surface Profile, Ra	35.0	16.0	42.0	31

Table 4. Gloss and Surface Profile Readings for Panels with Darker Visual Appearance Horizontal Scan

Measurement	Panel D	Panel E	Panel F	Average
GLOSS20	81.4	154.4	110.5	115
GLOSS60	118.6	214.5	150.6	161
GLOSS85	64.3	107.8	86.4	86
HAZE	10.3	0.0	7.6	6
LogHAZE	232.0	0.0	168.0	133
DOI	36.4	40.5	50.9	43
Rspec	20.3	38.7	34.2	31
Surface Profile, Ra	6.0	16.0	7.0	10

Table 5. Gloss and Surface Profile Readings for Panels with Darker Visual Appearance
Vertical Scan

Measurement	Panel D	Panel E	Panel F	Average
GLOSS20	14.2	12.1	23.3	17
GLOSS60	27.2	19.8	51.1	33
GLOSS85	31.6	9.3	69.0	37
HAZE	45.4	40.5	70.7	52
LogHAZE	657.0	618.0	843.0	706
DOI	21.1	22.7	26.1	23
Rspec	3.1	2.7	5.1	4
Surface Profile, Ra	21.0	51.0	12.0	28

Based on the Rhopoint manual, the glossmeter records the following measurements:

- GLOSS20/60/85 - A measurement proportional to the amount of light reflected from a surface. The 20/60/85 refers to the measuring angle. Different measuring angles are more appropriate for different types of surfaces.
- HAZE - A measurement of the optical effect caused by microscopic textures or residue on a surface.
- LogHAZE - Similar to the HAZE recording, but this unit has an increased resolution at haze levels used for paints and coatings.
- DOI - A measurement of how clearly a reflected image will appear in a reflection surface.
- Rspec - A measurement of peak gloss over a very narrow angle, and is very sensitive to small changes in texture used to identify subtle differences in surface smoothness.

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APPENDIX D -

SUMMARY OF OBSERVATIONS AND DOCUMENTATION PHOTOGRAPHS FROM EXTRADOS IRA INSPECTION

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

Table 1. Summary of Extrados Inspection Field Notes taken on October 19, 2014

St.	Weld	Location Comments	Pictures		Notes During Inspection per A. Sterns
		CMF Notes	A. Sterns	iLoupe	
0	0				
	1				
1	2		0149 - 0154	0067 - 0069	
	3				
2	4				
	5				
3	6				
	7				
4	8	Lowest panel of observation deck	0155 - 0163		Welds not magnetic at this location
	9				
5	10				
	11				
6	12	Vent location	0042-0047		Vent slats with cracked welds on one side; black residue at top of vent with GSR (#14); reddish tint between slats with GSR (#13)
	13				
7	14				
	15				
8	16				
	17				
9	18				
	19				
10	20				
	21				
11	22				
	23				
12	24	Dented panel based on archival research			No sign of dented panel at extrados
	25				
13	26		0166 - 0168		Grinding at weld; black residue on weld observed
	27				
14	28	Lowest conditioned space			Not magnetic; 1/8 inch typical for 'oil canning' on panels
	29		0169 - 0170	0070 - 0072	Derrick crane attachment observed without distress
15	30		0171 - 0175		
	31				
16	32		0176 - 0177		Heavy weld reinforcing
	33				
17	34				
	35				

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

St.	Weld	Location Comments	Pictures		Notes During Inspection per A. Sterns
		CMF Notes	A. Sterns	iLoupe	
18	36				
	37				Derrick crane attachment observed without distress
19	38				
	39				
20	40		0178 - 0183		Typical weld profile
	41		0184 - 0187		1/32 inch removed at grinding location; no corrosion observed
21	42				
	43				
22	44	Stabilizing bridge; proper texture not restored (ST 22 and 23) based on archival research			
	45	Water froze on surface during construction causing staining (ST 22 to 30) based on archival research			
23	46				
	47				
24	48				
	49		0188 - 0191		Slightly magnetic; light repairs at welds
25	50				
	51				
26	52				
	53				
27	54	1-1/8 inch out of camber (ST 27) based on archival research			
	55				
28	56				
	57				
29	58				
	59				
30	60				
	61		0192 - 0198		Typical photos
31	62				
	63		0199 - 0205	0073 - 0081	Different finish at panels; black residue with GSR (#4) at center panel
32	64				
	65				
33	66				
	67				
34	68				
	69				
35	70		0206 - 0215		Dent (1/2x2 panels vertical x 24 inches wide) centered on one stiffener; no scratches observed
	71				

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

St.	Weld	Location Comments	Pictures		Notes During Inspection per A. Sterns
		CMF Notes	A. Sterns	iLoupe	
36	72		0216 - 0217	0082 - 0084	Different finish at stainless steel
	73	Significant deflections during construction (ST 36 and 37) based on archival research			
37	74				
	75				
38	76				
	77				
39	78				
	79				
40	80	Surface damage and carbon staining noted during construction based on archival research			
	81				Confirmed 'oil canning' typically at 1/8 inch depth
41	82				
	83				
42	84				Confirmed black residue is typical
	85				
43	86	End of concrete fill	0218 - 0223		Some magnetism; heat time observed at weld
	87		0224 - 0225		
44	88	Jacking during construction (ST 44 and 45) based on archival research			
	89				
45	90				
	91				
46	92				
	93				
47	94				
	95				
48	96				
	97				
49	98				
	99				Black residue with GSR (#15)
50	100		0226 - 0227		Overheated area with more heat tint
	101				
51	102				
	103				
52	104				
	105				
53	106				
	107				

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St.	Weld	Location Comments	Pictures		Notes During Inspection per A. Sterns
		CMF Notes	A. Sterns	iLoupe	
54	108				
	109				
55	110				
	111				
56	112				
	113				
57	114				
	115				
58	116				
	117				
59	118				
	119				
60	120				
	121		0228 - 0238		At welds, black residue appears with welds narrower in width, and with weld overlap
61	122				
	123				
62	124	Double and triple rewelds (ST 62 and 71) based on archival research			
	125	Refinishing issues (ST 62 to 71) based on archival research			
63	126				
	127				
64	128				
	129				
65	130				
	131				
66	132				
	133				Heavy black residue here to base; welds look good, no spatter
67	134	Range of lift access			
	135				
68	136				
	137				
69	138				
	139				
70	140				
	141				
71	142				
	143				

Overall notes:

- Weld spatter increased up the Arch
- Black residue increased down the Arch

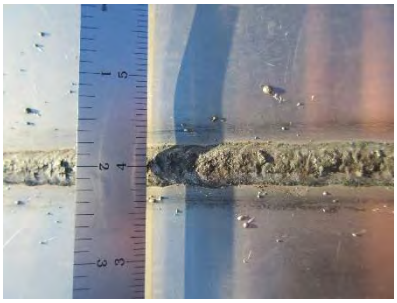
A. Sterns

IMG_0149

IMG_0150

IMG_0151

IMG_0152



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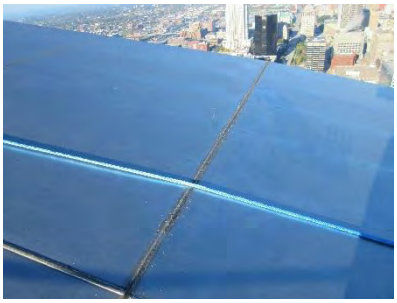

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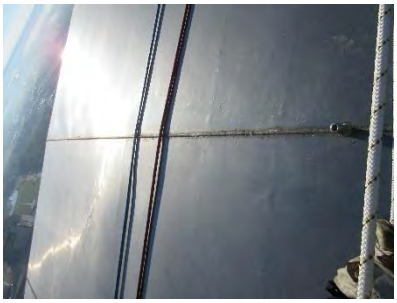

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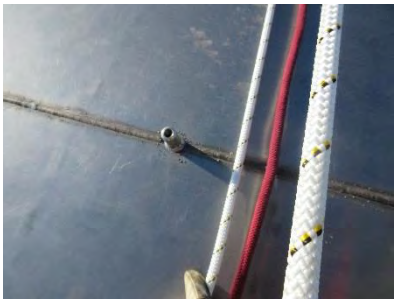

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IMG_0159

IMG_0160

IMG_0161

IMG_0162

IMG_0163

IMG_0042

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IMG_0045

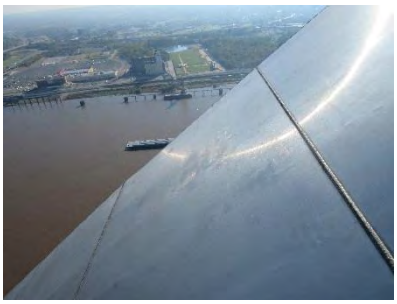
IMG_0046

IMG_0047

IMG_0166

IMG_0167

IMG_0168



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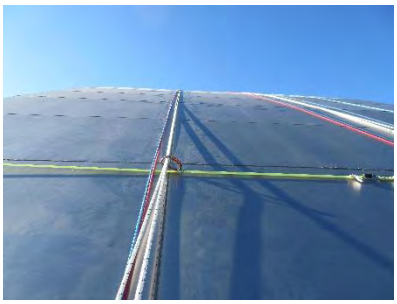

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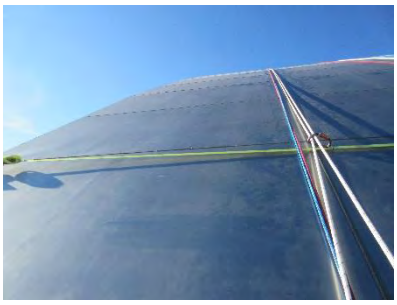

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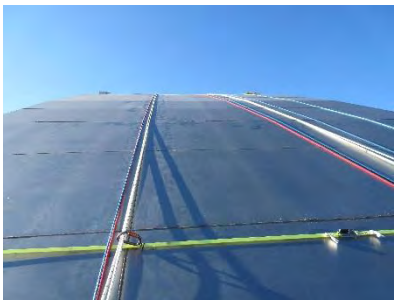

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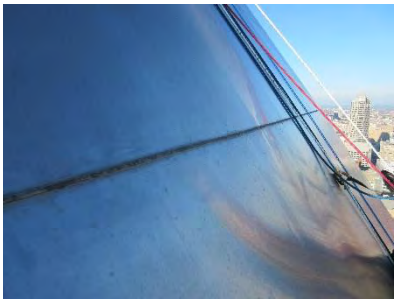

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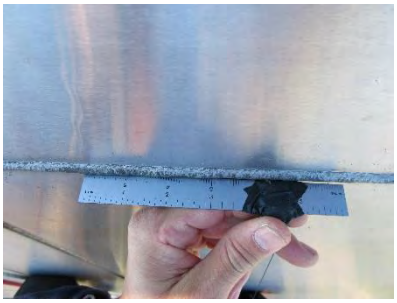

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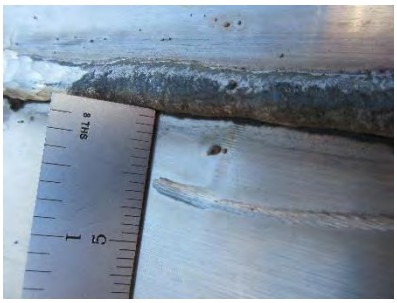
IMG_0186



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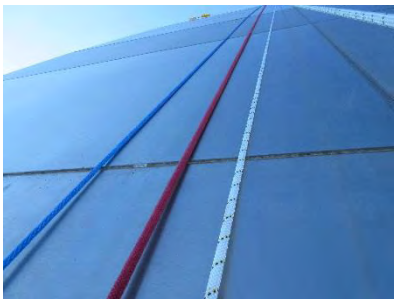

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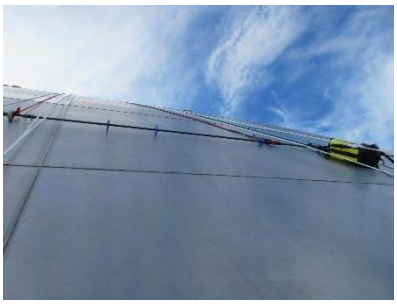

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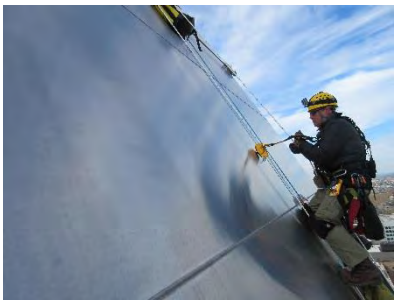

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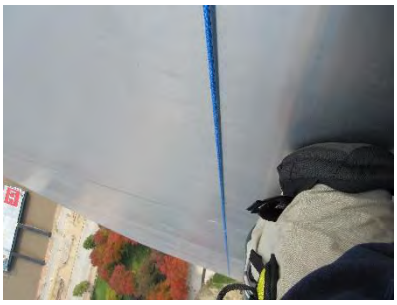

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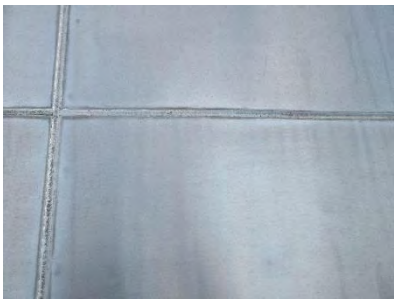
IMG_0197

IMG_0198

IMG_0199



IMG_0200

IMG_0201

IMG_0202

IMG_0203

IMG_0204

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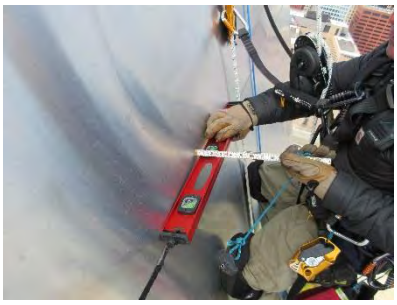
IMG_0205

IMG_0206

IMG_0207

IMG_0208

IMG_0209



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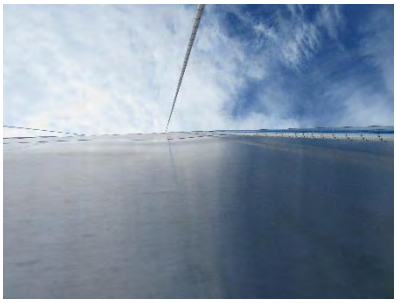

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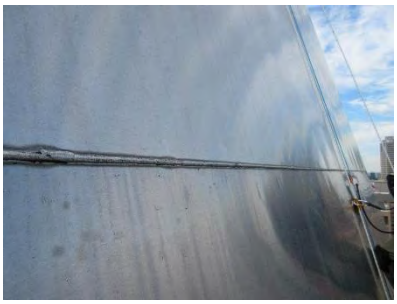

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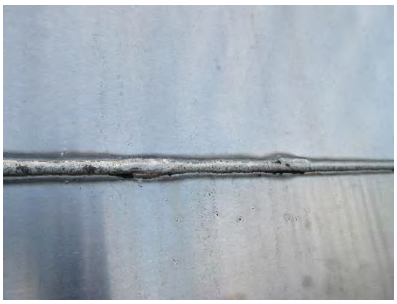

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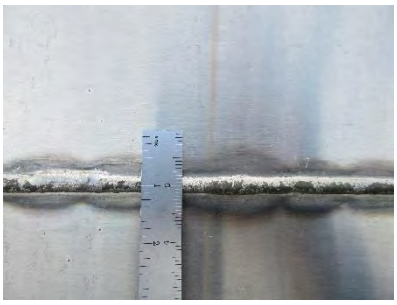

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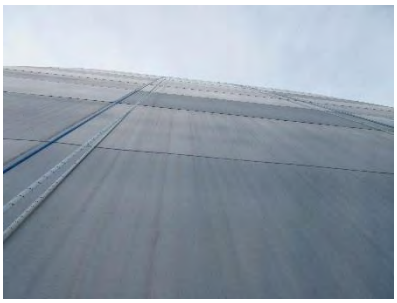

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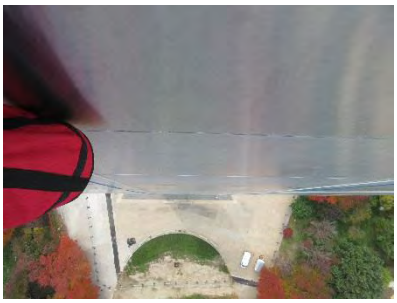

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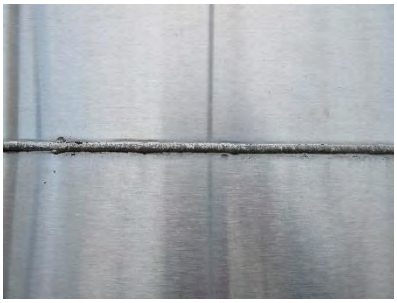

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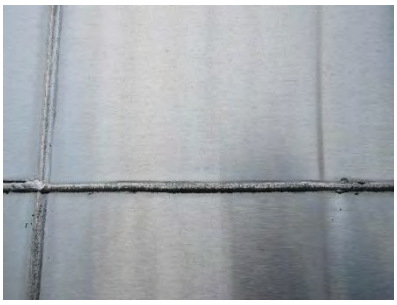

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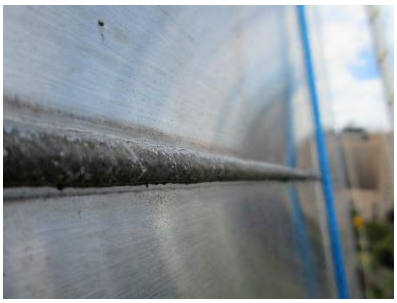
IMG_0235



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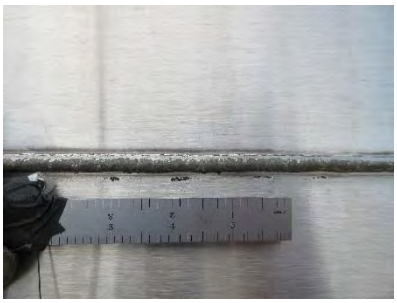

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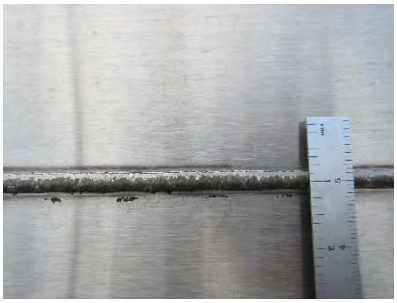

IMG_0238

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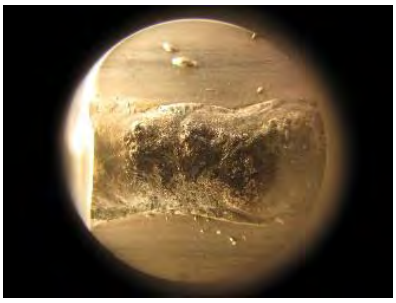
iLoupe



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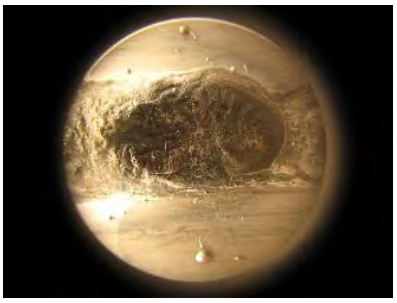

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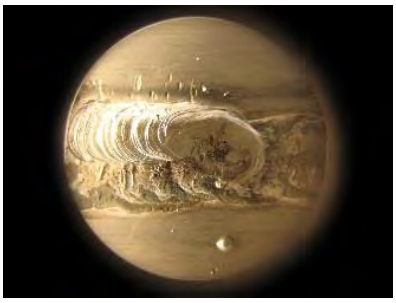

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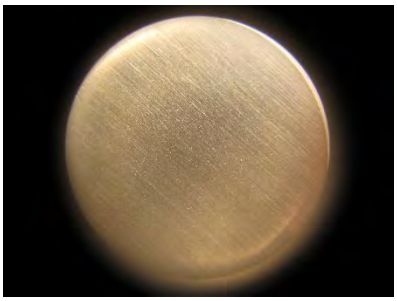

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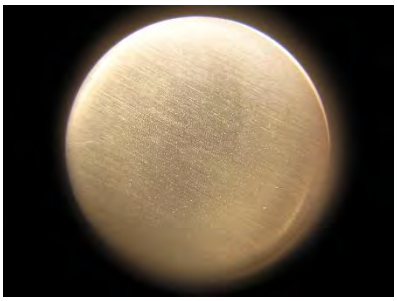

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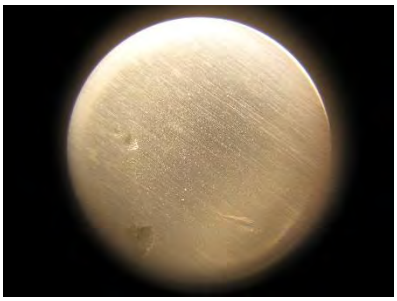

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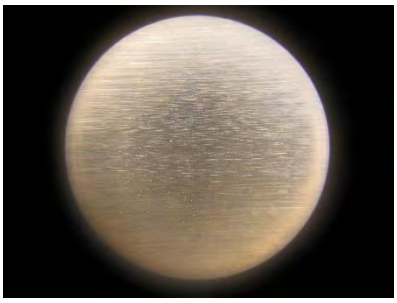

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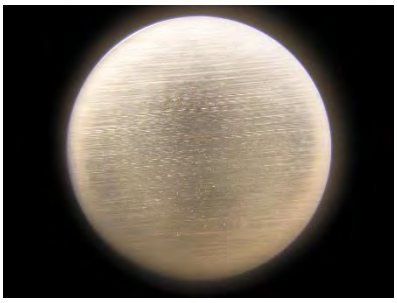

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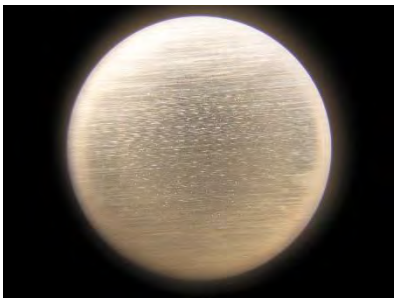

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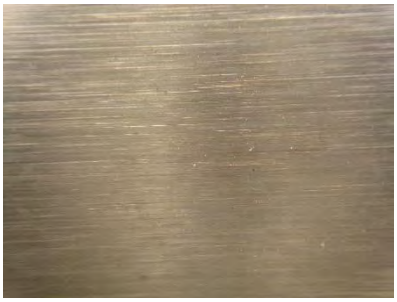

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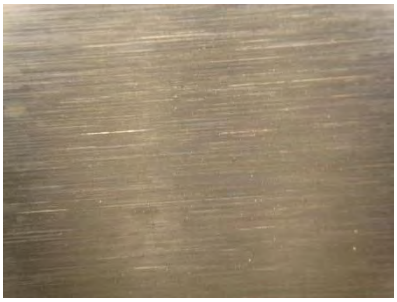

IMG_0081

IMG_0082

IMG_0083

IMG_0084

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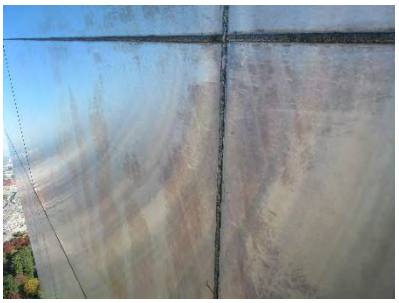
APPENDIX E -

DOCUMENTATION PHOTOGRAPHS FROM INTRADOS IRA INSPECTION AT STATION 35

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

D. Megerle



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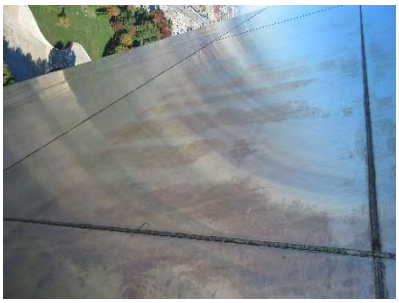

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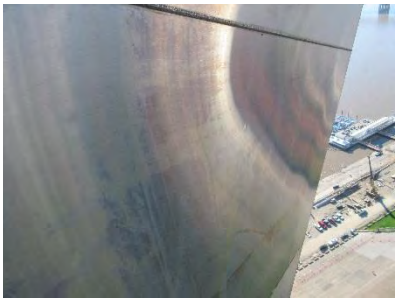

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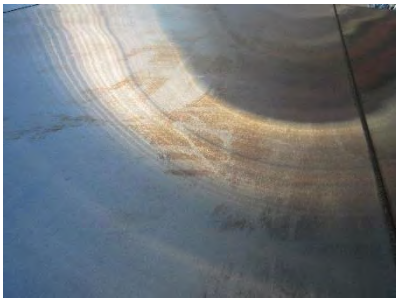

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IMG_0008

IMG_0009

IMG_0010

IMG_0011

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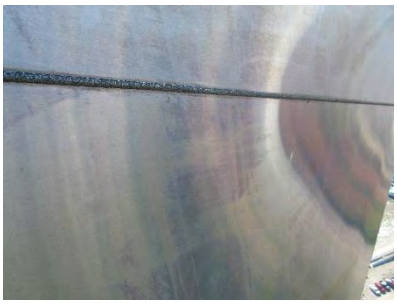
IMG_0013

IMG_0014



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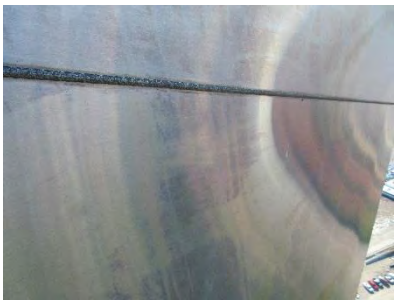

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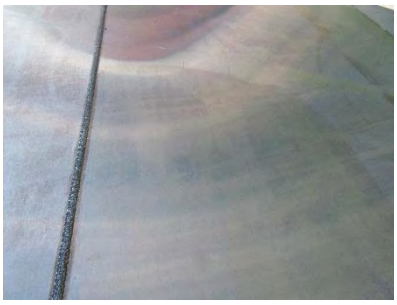
IMG_0017

IMG_0018



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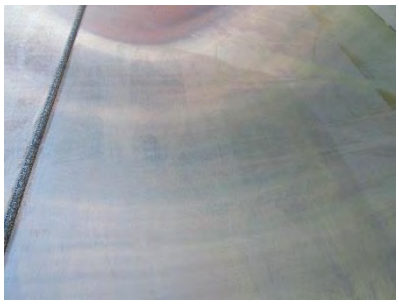

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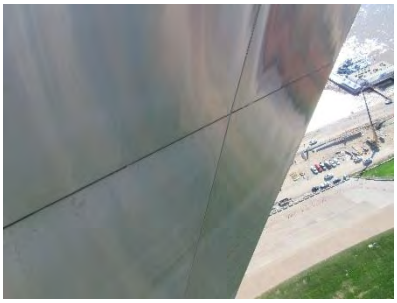
IMG_0021

IMG_0022

IMG_0023

IMG_0024



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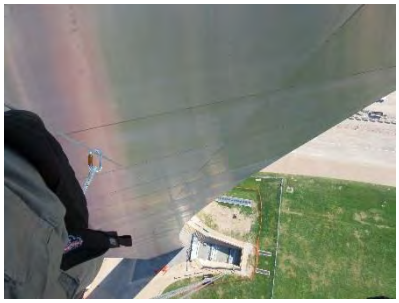
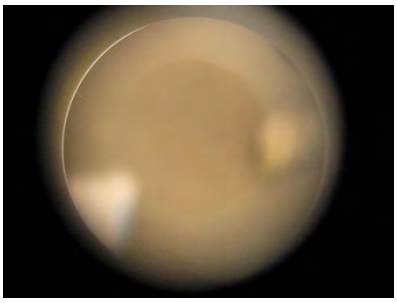


IMG_0026

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

iLoupe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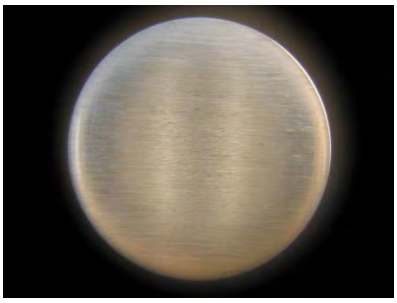

IMG_0086


IMG_0087


IMG_0088


IMG_0089


IMG_0090

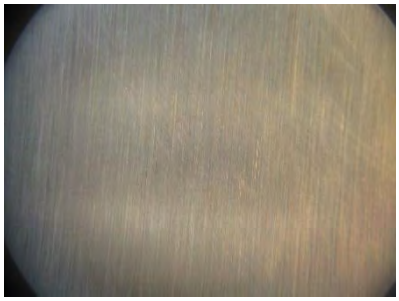

IMG_0091


IMG_0092


IMG_0093


IMG_0094


IMG_0095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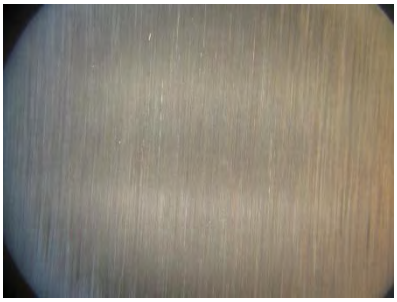

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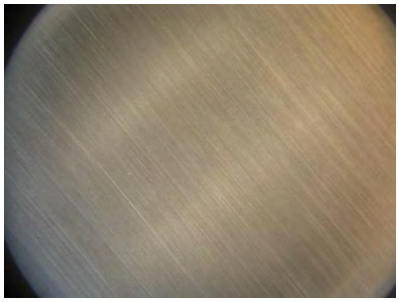

IMG_0099

APPENDIX F -
MILL CERTIFICATION FOR STAINLESS STEEL PLUGS

Certificate of Mill Test Results

BL-LIB-000000-000

Pg 1/1

Attn: WENDELL

METALS USA - FLAT ROLLED NBK

PO/Rel

PART NO.

Manufacturer / Fabricante / Herstellerwerk

outokumpu

Type of document / Tipo de documento / Art der Prüfbescheinigung

INSPECTION CERTIFICATE

CERTIFICADO DE INSPECCION

ABNAHMEPRÜFZEUGNIS

according to / de acuerdo con / nach

EN 10204-3.1

Document number / N° de certificado / Bescheinigungsnr. 07/16/2014

0000096467 / 2

Page / Pagina / Seite: **1 / 1**

1 ThyssenKrupp Drive; P.O. Box 13000; Calvert, AL 36513-1300

METALS USA, INC.
2840 HEARTLAND DRIVE
LIBERTY MO 64068
USA

Customer/Ship to / Cliente / Besteller/Empfänger: METALS USA, INC.,LIBERTY

Customer's order number / N° de Pedido Cliente / Kundenbestellnr.: LIB-28338

Manufacturer's works order no. / N° de Pedido Manufactura / Werksauftragsnr.: 901172316 / 001

Delivery note no. / N° de Entrega / Lieferanzeige Nr.: 85298568 / 010

Product / Producto / Erzeugnis: COIL/BOBINA/BAND

Terms of delivery / Condiciones de entrega / Lieferbedingungen:
ASTM A240/240M, ASME SA-240 Sec.II Part A Ed. 2013
ASTM A480/480M, ASME SA-480 Sec.II Part A Ed. 2013
ASTM A 666-10

Steel grade and quality / Acero / Stahlsorte und Gütegruppe: TYPE 304L/304

Customer's material no./ N° de material del cliente/ Kundenmaterial-Nr.	Product dimensions (Thickness / Width / Length) / Dimensiones (Espesor / Ancho / Largo) / Maße des Erzeugnisses (Dicke / Breite / Länge)	Steelmaking procedure/ Proceso de manufact./ Herstellart	Finish/ Acabado/ Ausführung
	6.35 mm x 1,219.20 mm 0.2500 inch x 48.0000 inch	AOD	IIa / 1D / No.1

Packing-No./ N° de Empaque/ Paket-Nr.	No.of pieces/ Piezas/ Stückzahl	Actual weight/ Peso actual/ Ist-Gewicht	Coil No./ Bobina No./ Band-Nr.	Heat No./ Colada/ Schmelzennr.	Sample Id./ N° de muestra/ Proben-Id.	Sample Id./ N° de muestra/ Proben-Id.
6146329	1	20,768 lb / 9,420 kg	739554	503577	1000207074	1000207075
Sum / Suma / Summe	1	20,768 lb / 9,420 kg				

Heat / Colada / Schmelze	Country of heat / Pais de colada / Erschmelzungsland	Chemical composition / Composicion Quimica/ Chemische Zusammensetzung										
		% C	% Si	% Mn	% P	% S	% Cr	% Ni	% N			
503577	USA	0.024	0.35	1.61	0.028	0.0010	18.09	8.06	0.072			

Sample Position/ Localiz.de la muestra/ Probenlage: TRANSVERSE

Inspection lot/ Lote de inspección/ Prüflos	YS0.2% PSI / MPa	TS PSI / MPa	El. A2" %	HRB		
1000207074	51,051 / 352	93,981 / 648	54	82		
1000207075	47,425 / 327	93,401 / 644	55.5	82		

Dimensions-surface / Dimensiones-Superficie / Maße-Oberfläche: OK

Test of identity (spectrum analysis) / Control de identidad (análisis espectográfico) / Verwechslungsprüfung (Spektralanalyse): OK

No welding or weld repairs were performed on this material

Bending test O.K.

No intentional additions of Mercury compounds were made or used

Free of radioactive contamination

EU RoHS Directive 2011/65/EU Compliant

Product manufactured in the USA

Country of Heat as per ISO 3166-1

Originator of the document / Originador del documento / Aussteller der Bescheinigung

Outokumpu Stainless USA, LLC

An ISO 9001: 2008 certified company
Quality Management System EU PED 97/23/EC certified

Certificate is generated automatically / Certificado es generado automaticamente / Das Zeugnis wurde elektronisch erstellt

The information provided is a true copy of data on file / Los valores mostrados corresponden a los datos archivados / Die generierten Werte entsprechen den gespeicherten Daten

Andrew Faucett
Phone: +1 251 829 3492

Name of expert / hombre del experto / Name des Sachverständigen

Date of issue and validation / Fecha de emisión y validación / Datum Ausstellung / Bestätigung: 07/16/2014

Doc No. 179700 Indexed 21Jul14 by 166ajs

WJE | ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

APPENDIX G -
LABORATORY ANALYSIS OF WELD SAMPLES

SAMPLE 1

Figure 1. Sample 1 before

Figure 2. Sample 1 before

Figure 3. Sample 1 before

Figure 4. Sample 1 (Scale=1/32")

Figure 5. Sample 1

Figure 6. Sample 1

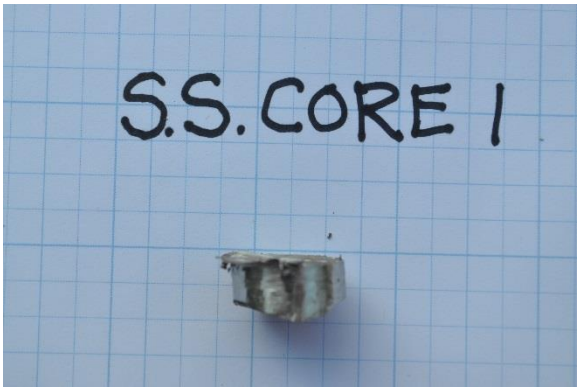

Figure 7. Sample 1

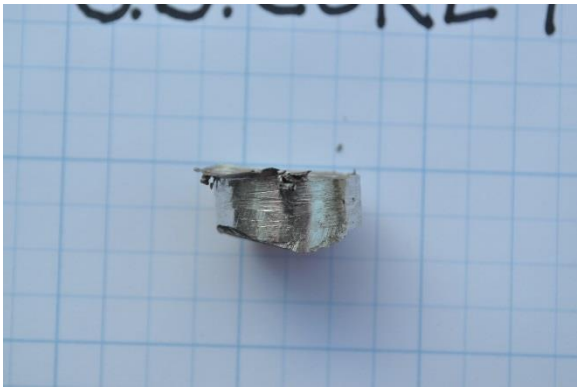

Figure 8. Sample 1

Figure 9. Etched cross section

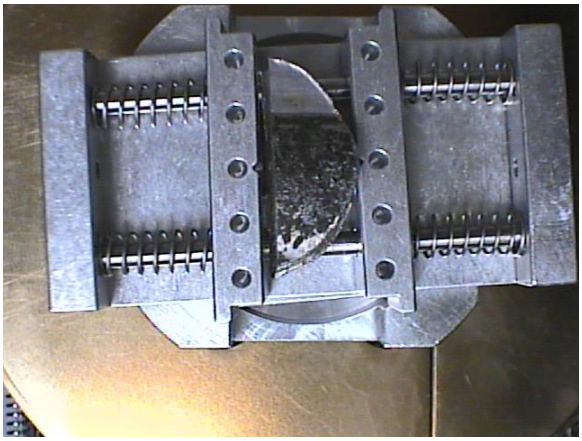

Figure 10. Surface analysis sample

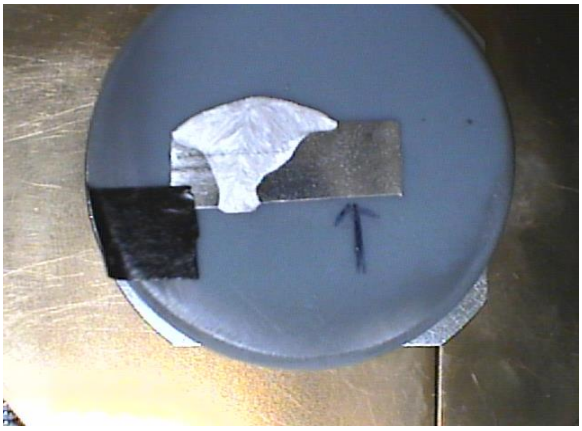

Figure 11. Overall etched cross section

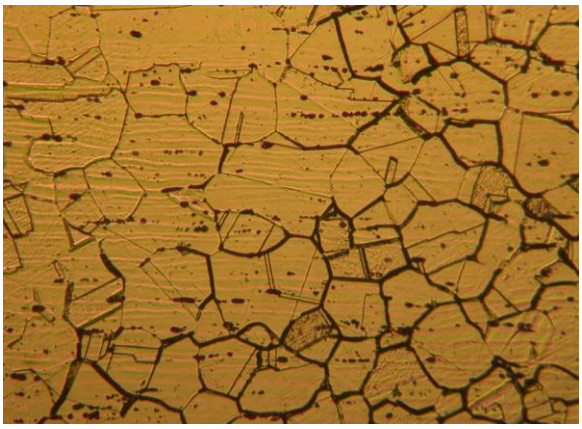

Figure 12. Optical micrograph in the etched condition (256x)

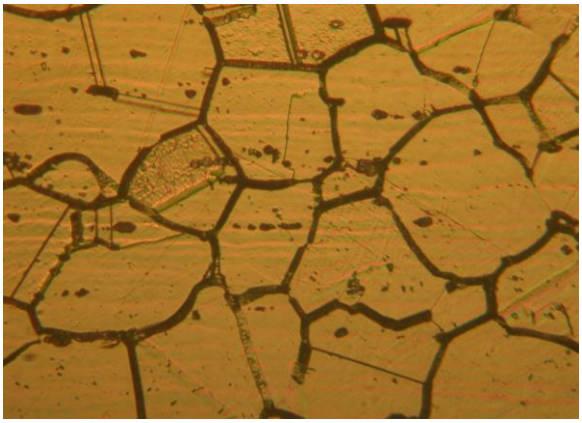

Figure 13. Optical micrograph in the etched condition (517x)

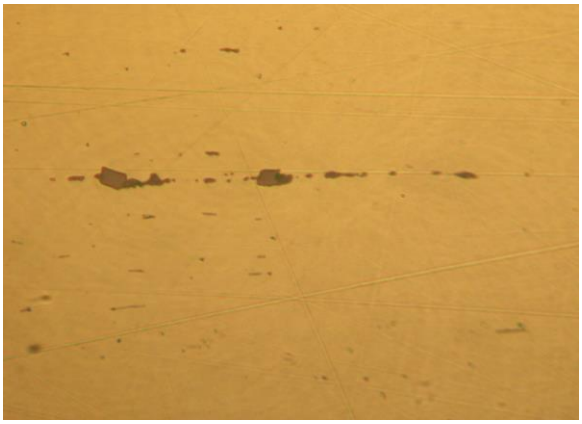

Figure 14. Optical micrograph of polished plate inclusion (517x)

Figure 15. Optical micrograph of manganese sulfide stringers in the plate, as-polished condition (256x)

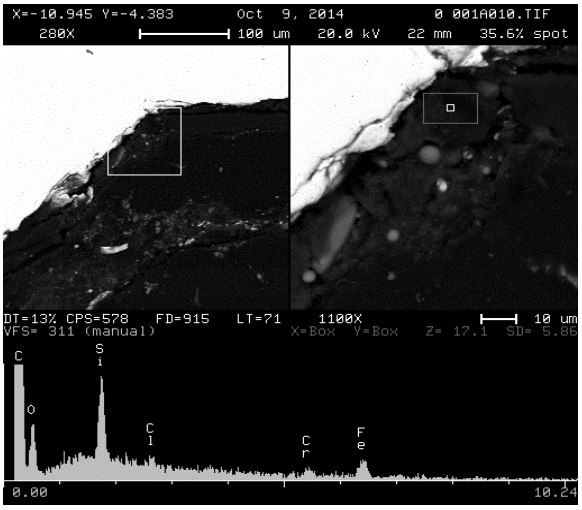

Figure 16. SEM photomicrograph

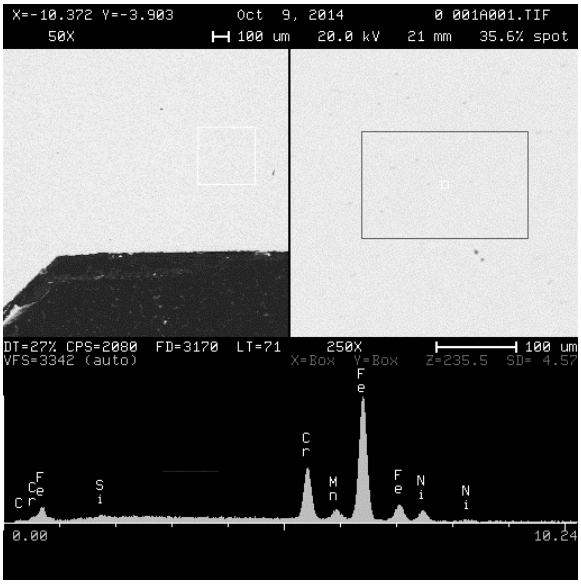

Figure 17. SEM photomicrograph

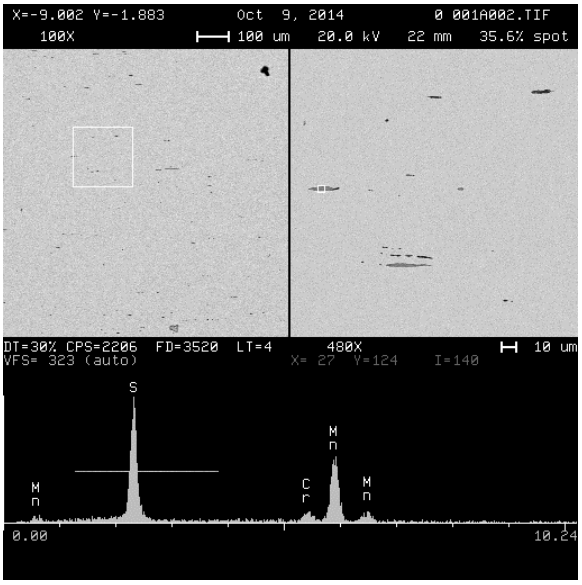

Figure 18. SEM photomicrograph

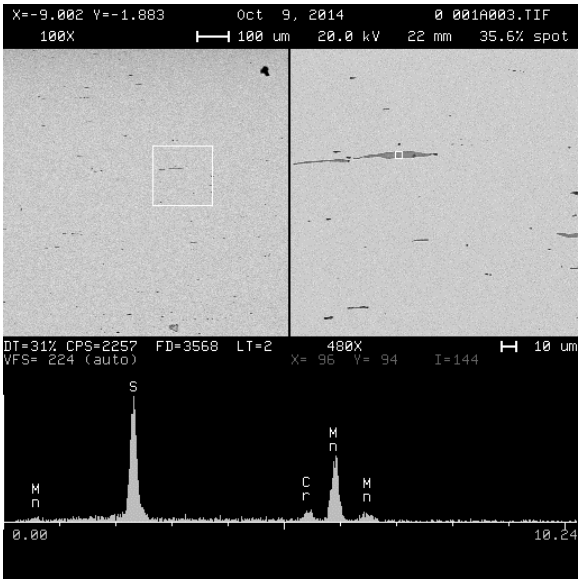

Figure 19. SEM photomicrograph

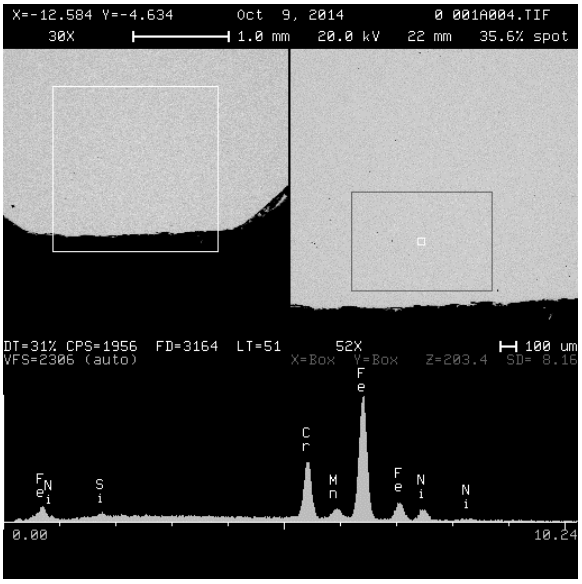

Figure 20. SEM photomicrograph

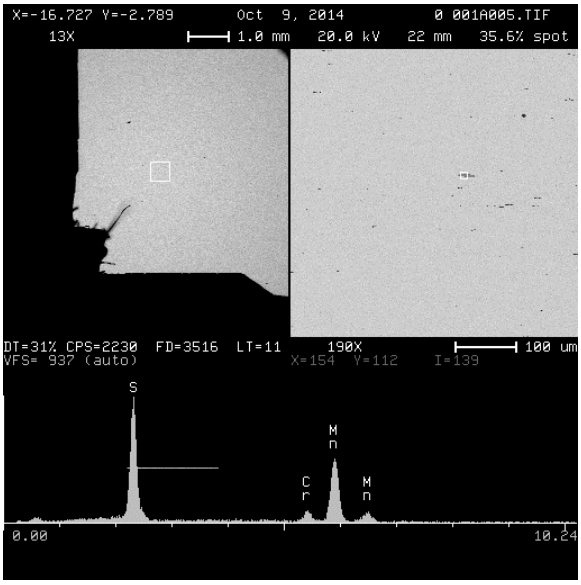

Figure 21. SEM photomicrograph

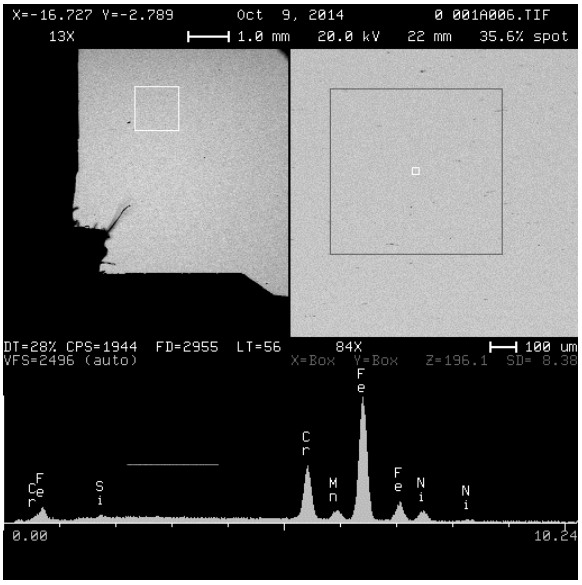

Figure 22. SEM photomicrograph

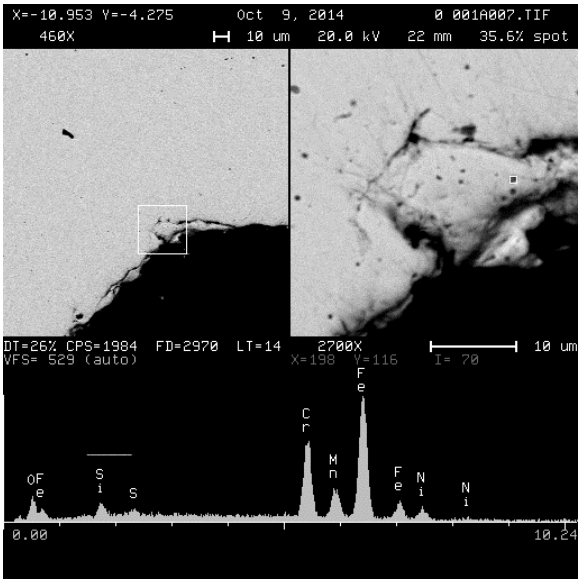

Figure 23. SEM photomicrograph

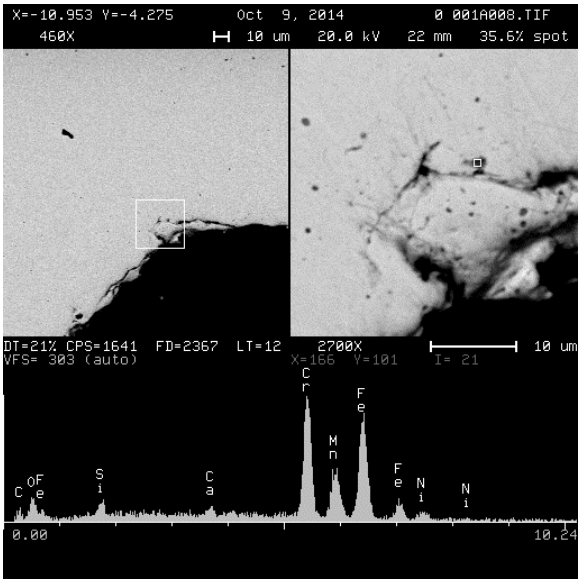

Figure 24. SEM photomicrograph

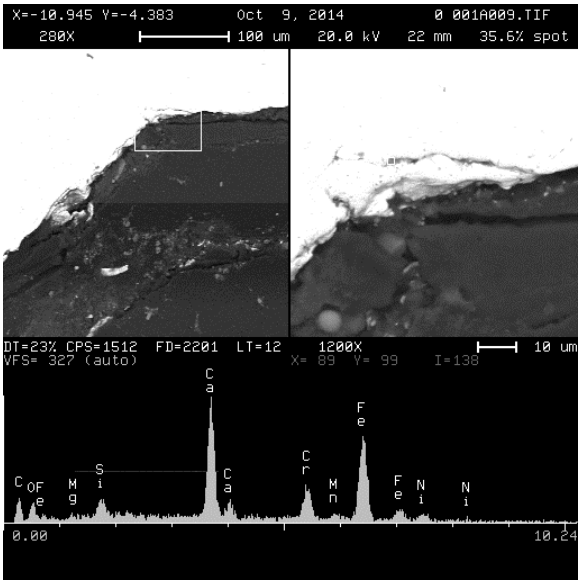

Figure 25. SEM photomicrograph

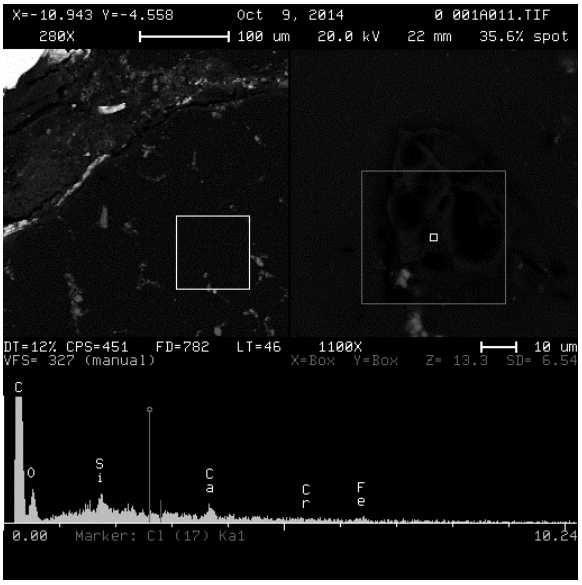

Figure 26. SEM photomicrograph

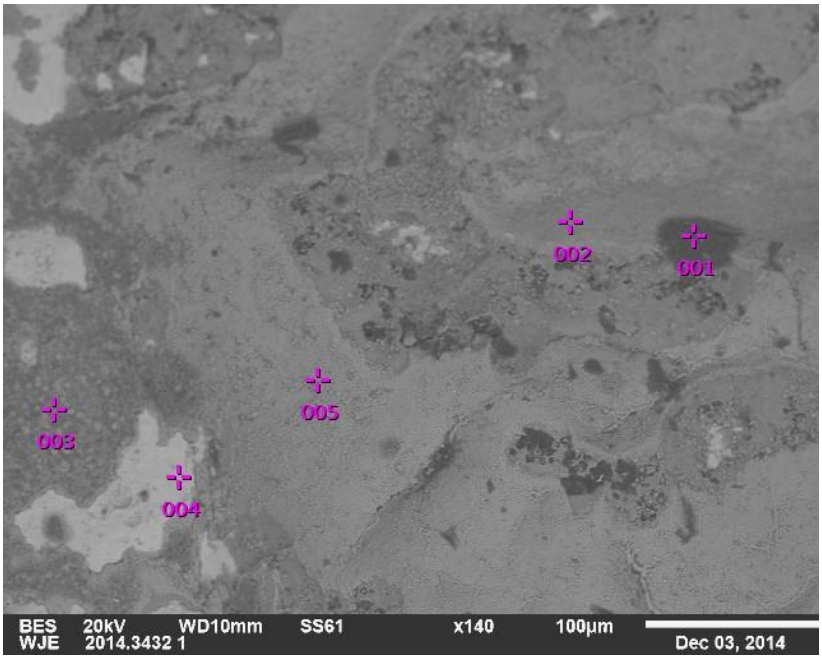

Figure 27. SEM image of surface of stainless steel weld

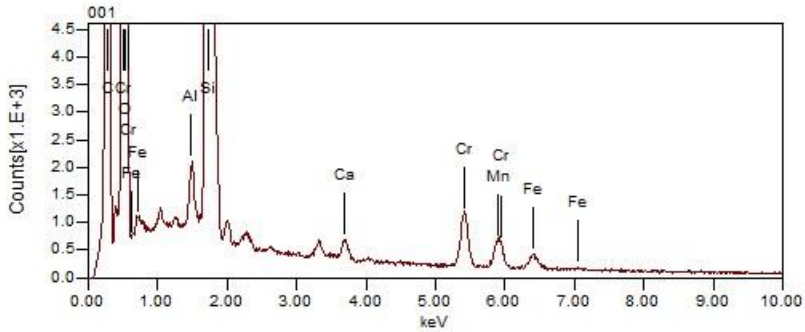

Figure 28. EDS Spectra location 1 of surface of stainless steel weld

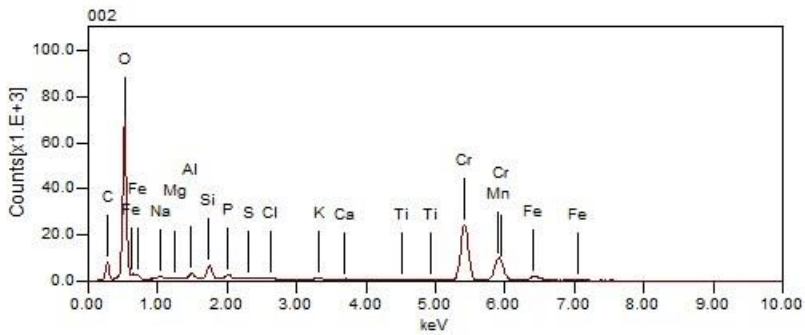

Figure 29. EDS Spectra Location 2 of surface of stainless steel weld

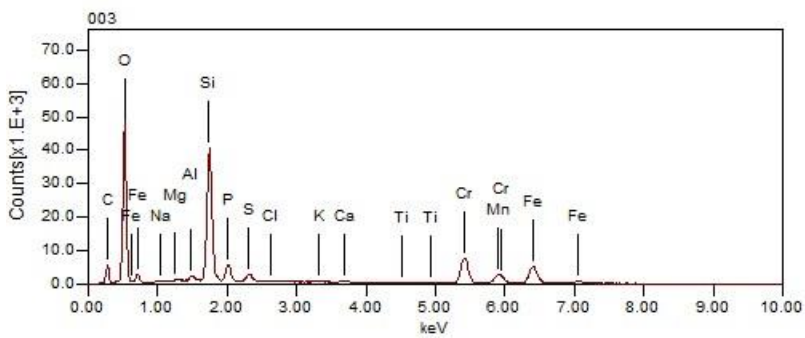

Figure 30. EDS Spectra Location 3 of surface of stainless steel weld

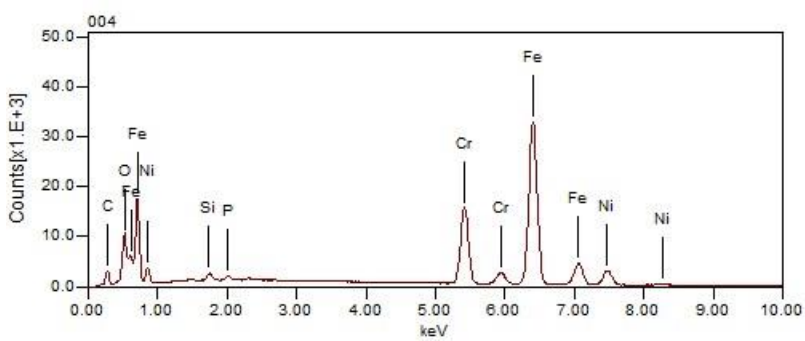

Figure 31. EDX Spectra Location 4 of surface of stainless steel weld

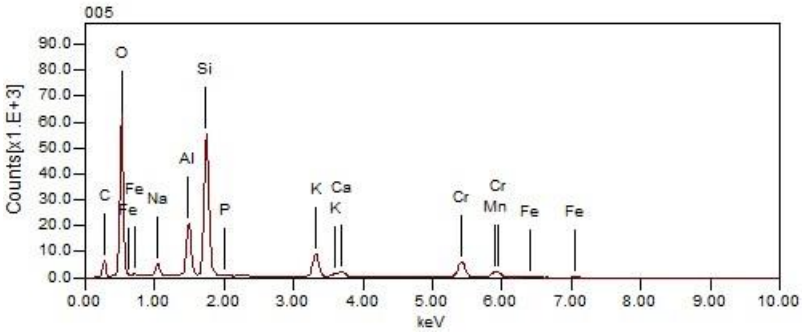

Figure 32. EDX Spectra Location 5 of surface of stainless steel weld

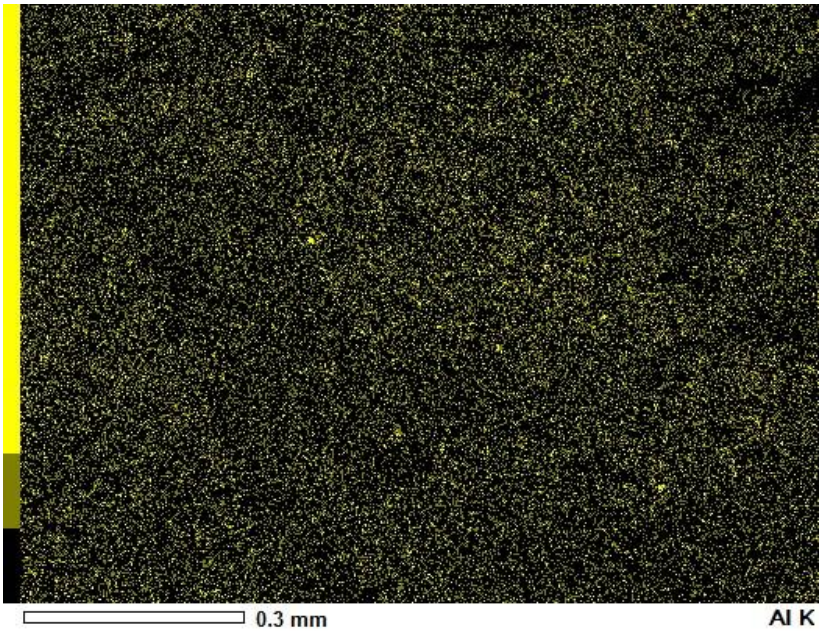

Figure 33. EDS Dot map showing aluminum on surface of stainless steel weld

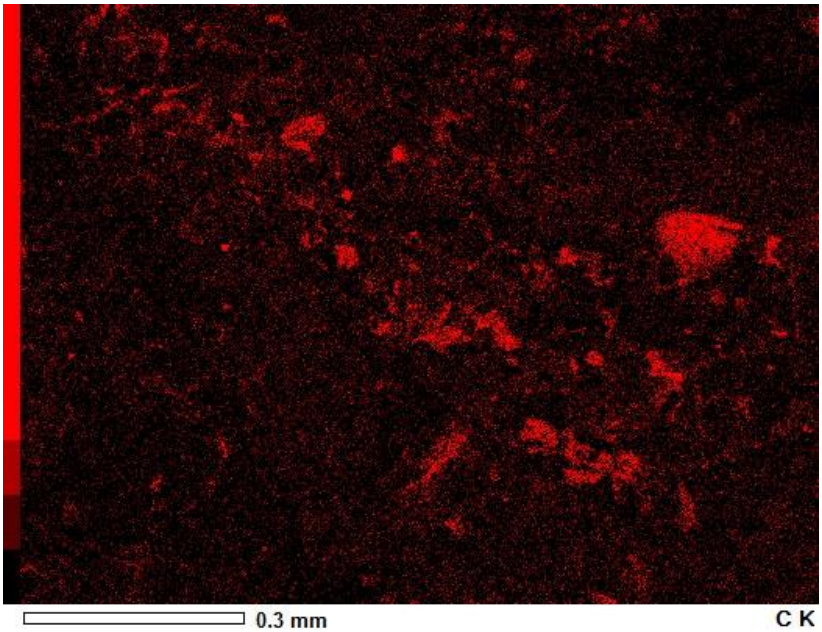

Figure 34. EDS Dot map showing carbon on surface of stainless steel weld

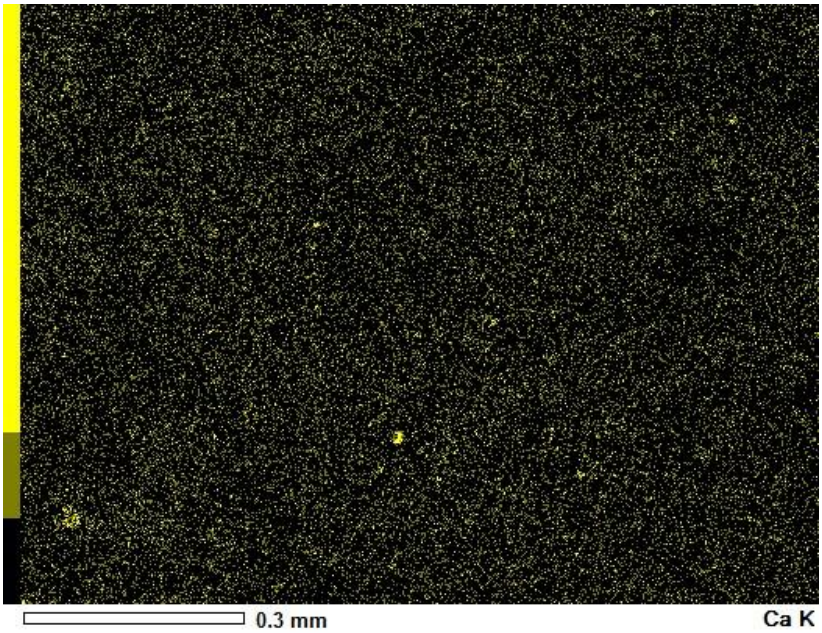

Figure 35. EDS Dot map showing calcium on surface of stainless steel weld

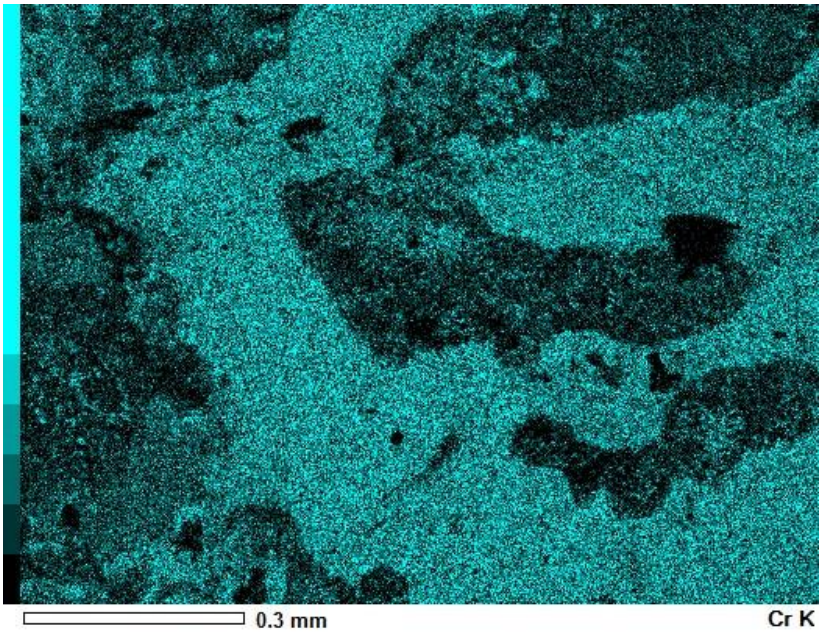

Figure 36. EDS Dot map showing chromium on surface of stainless steel weld

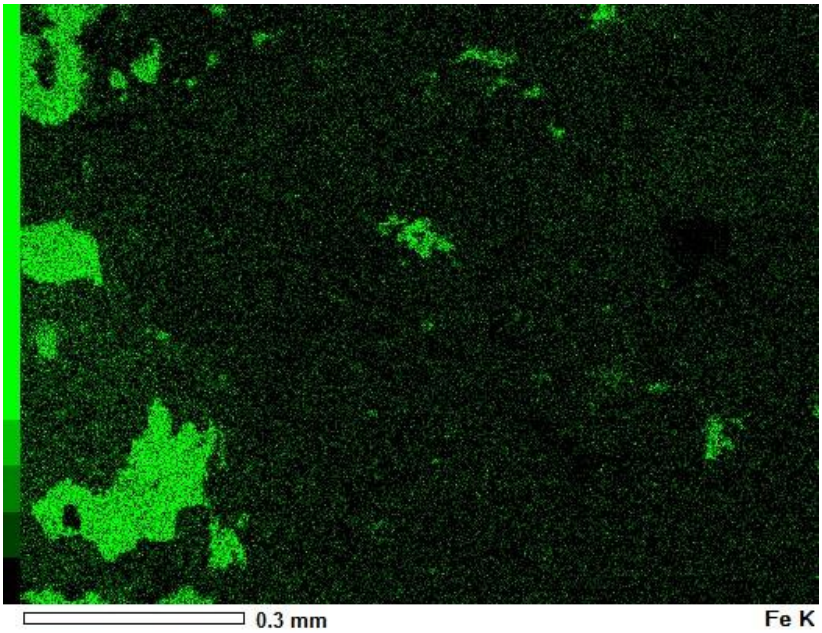

Figure 37. EDS Dot map showing iron on surface of stainless steel weld

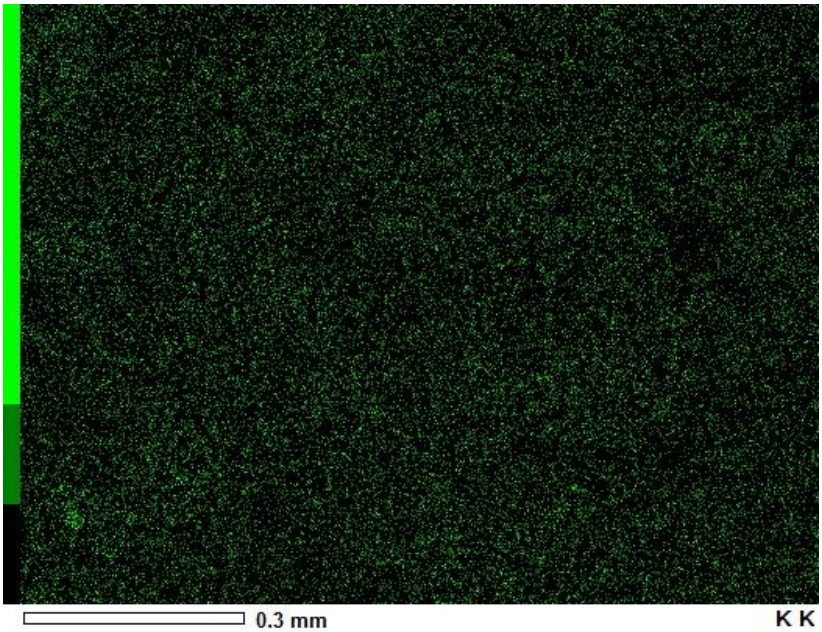

Figure 38. EDS Dot map showing potassium on surface of stainless steel weld

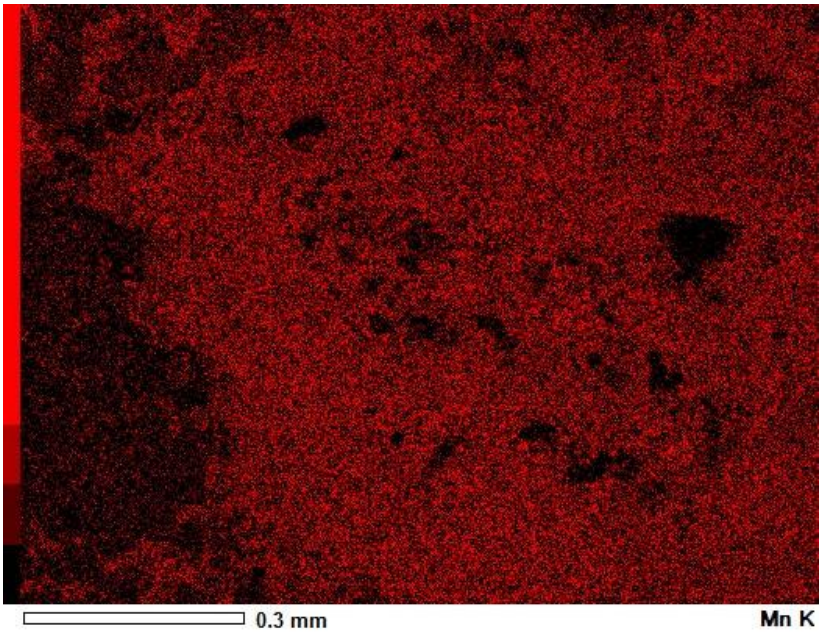

Figure 39. EDS Dot map showing manganese on surface of stainless steel weld

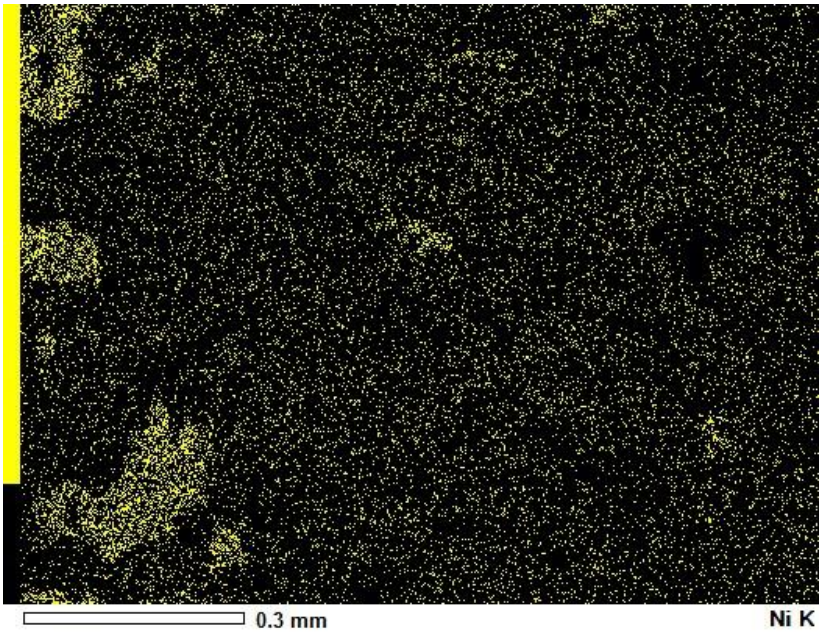

Figure 40. EDS Dot map showing nickel on surface of stainless steel weld

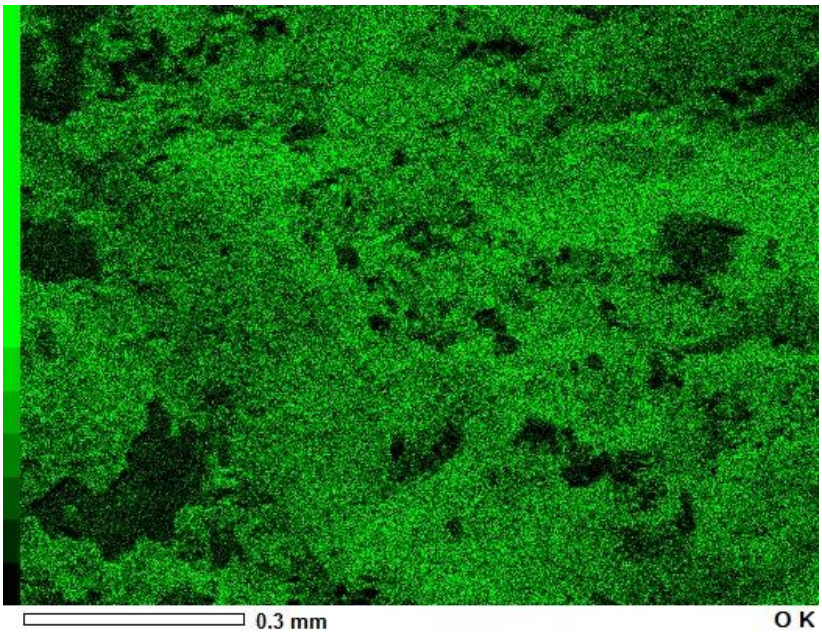

Figure 41. EDS Dot map showing oxygen on surface of stainless steel weld

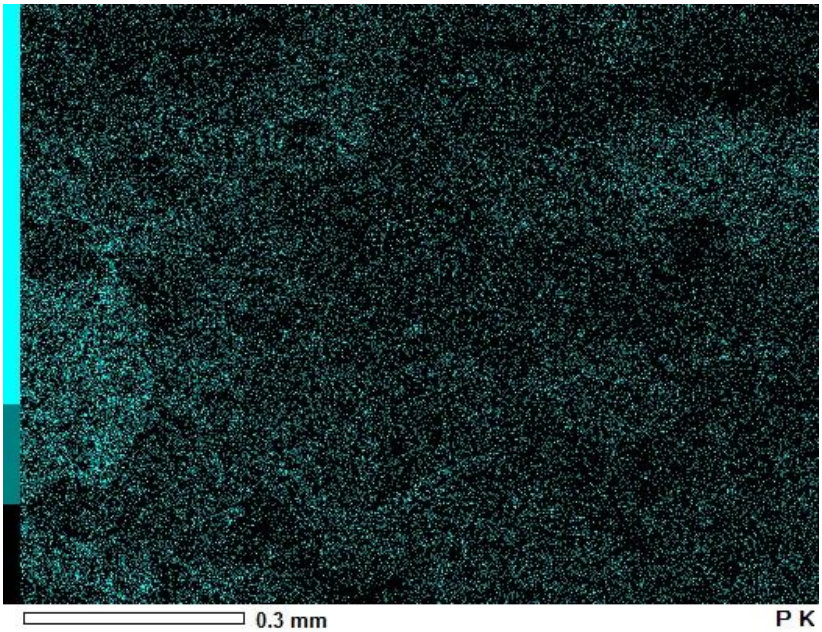

Figure 42. EDS Dot map showing phosphorous on surface of stainless steel weld 1

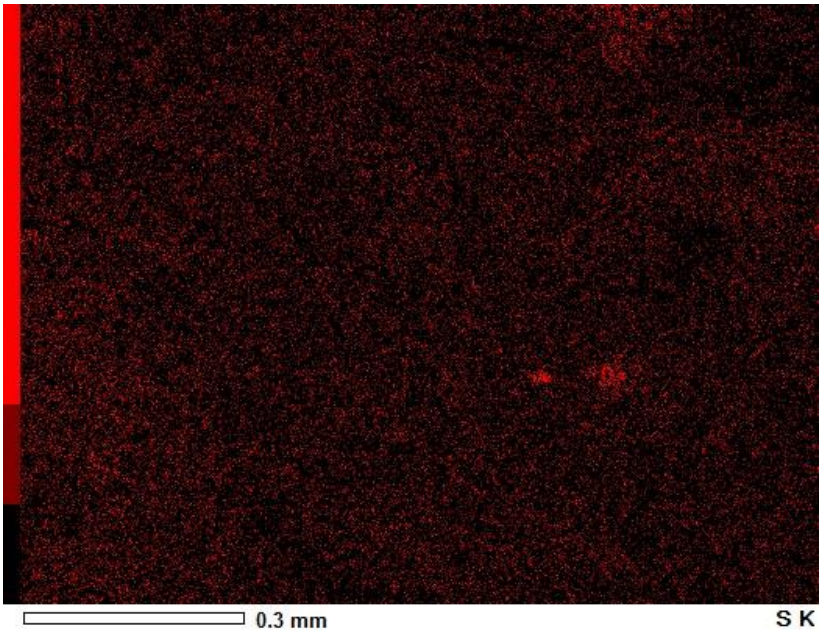

Figure 43. EDS Dot map showing sulfur on surface of stainless steel weld

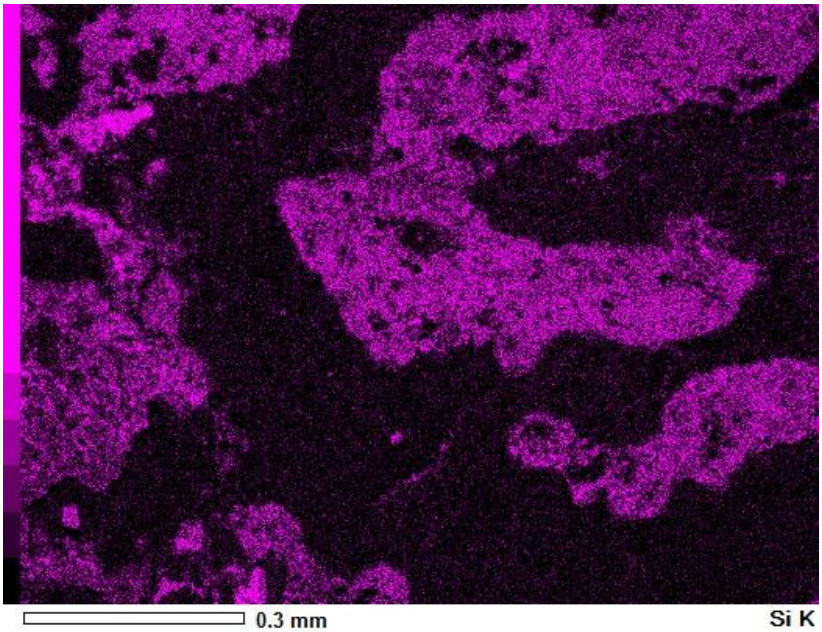

Figure 44. EDS Dot map showing silicon on surface of stainless steel weld

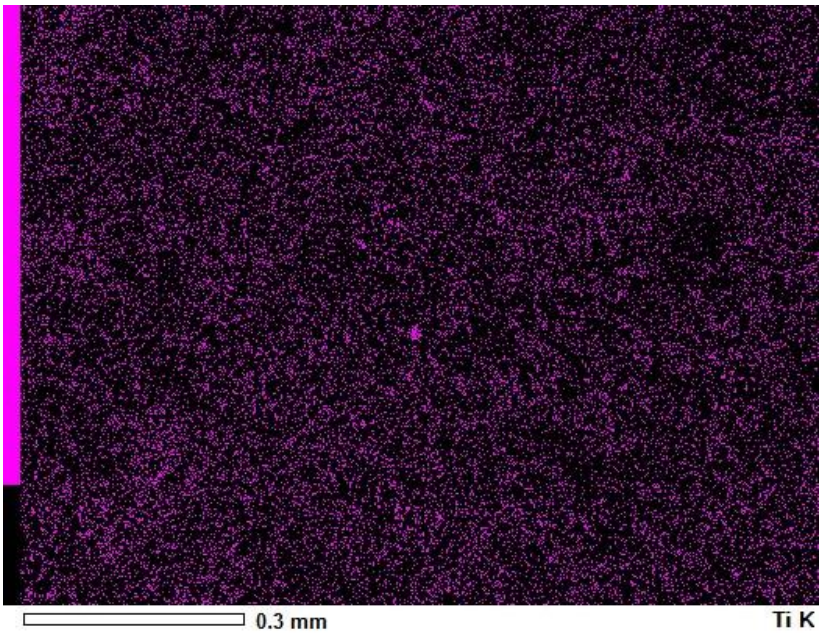

Figure 45. EDS Dot map showing titanium on surface of stainless steel weld

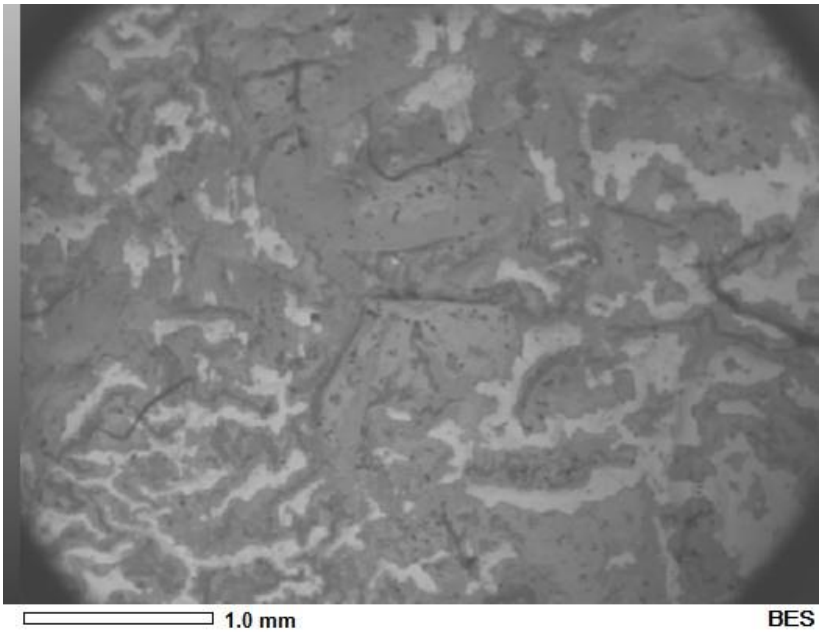

Figure 46. SEM image of surface on surface of stainless steel weld

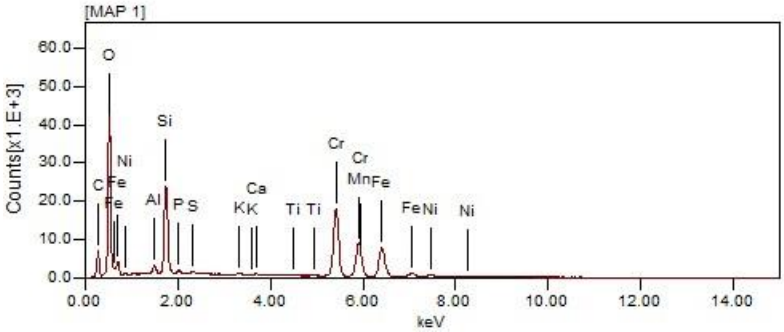

Figure 47. EDX spectra of surface on surface of stainless steel weld

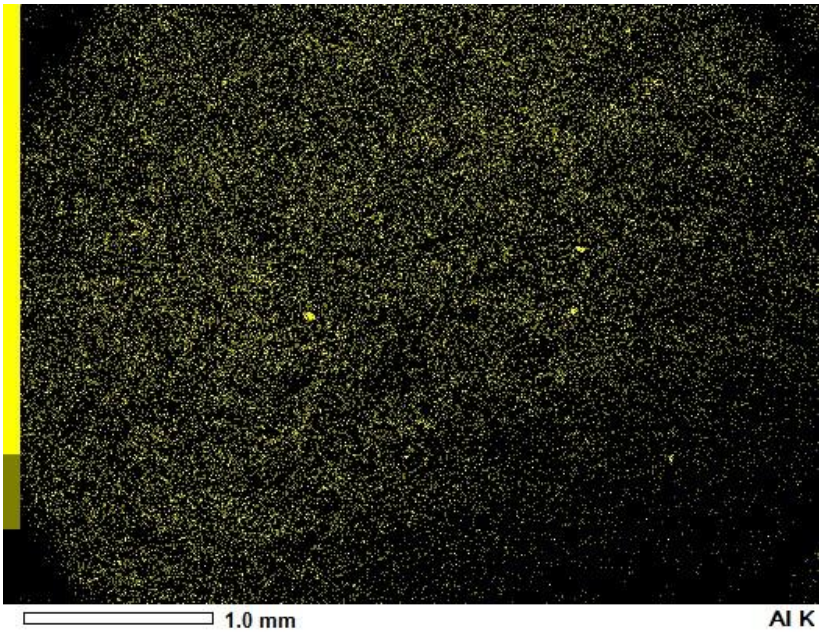

Figure 48. EDS Dot map showing aluminum on surface of stainless steel weld

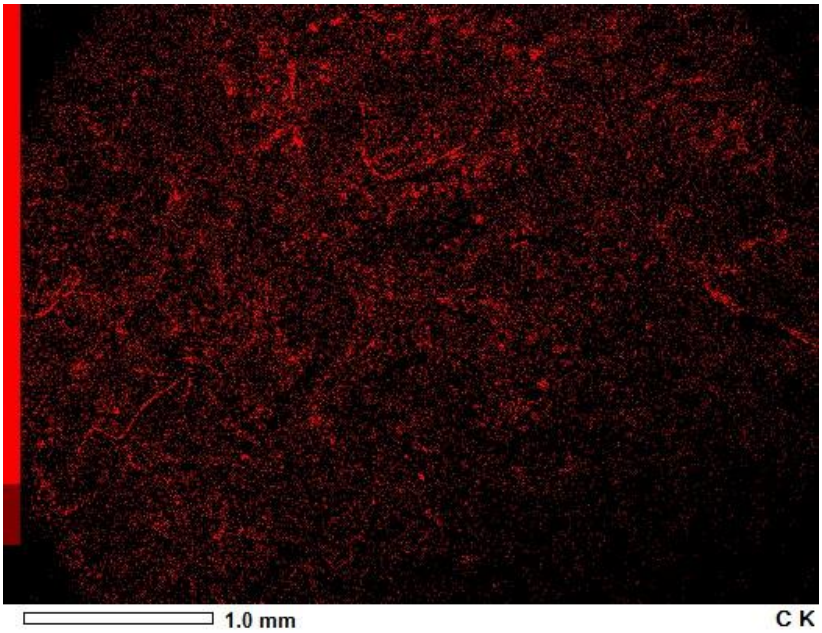

Figure 49. EDS Dot map showing carbon on surface of stainless steel weld

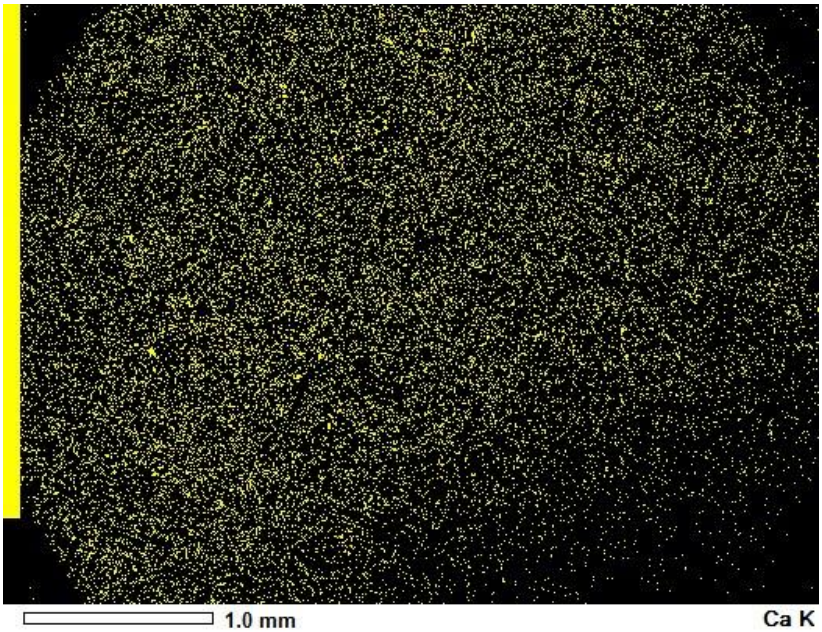

Figure 50. EDS Dot map showing calcium on surface of stainless steel weld

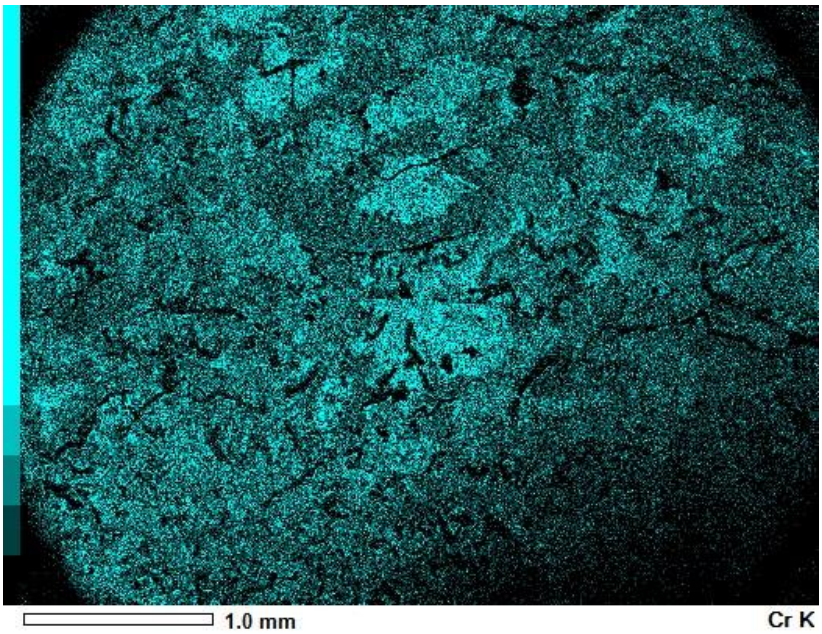

Figure 51. EDS Dot map showing chromium on surface of stainless steel weld

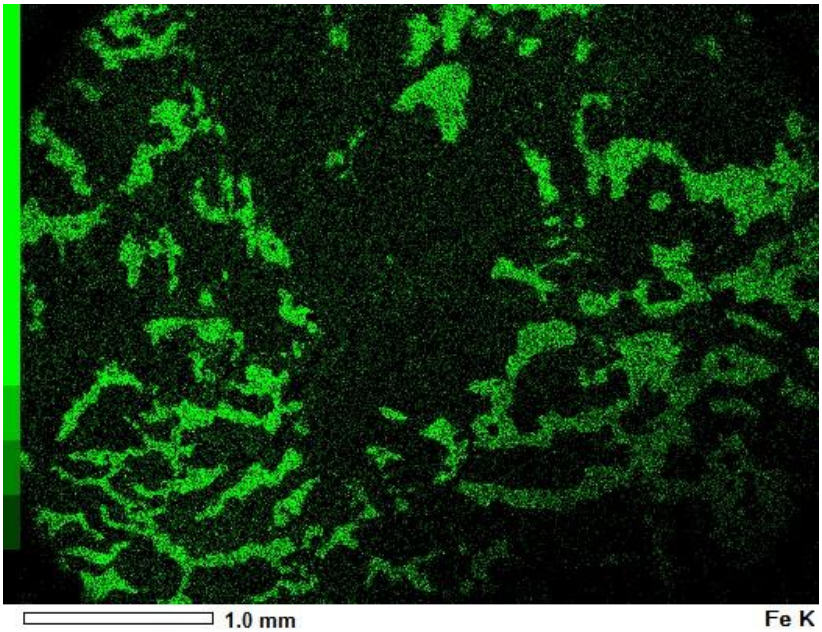

Figure 52. EDS Dot map showing iron on surface of stainless steel weld

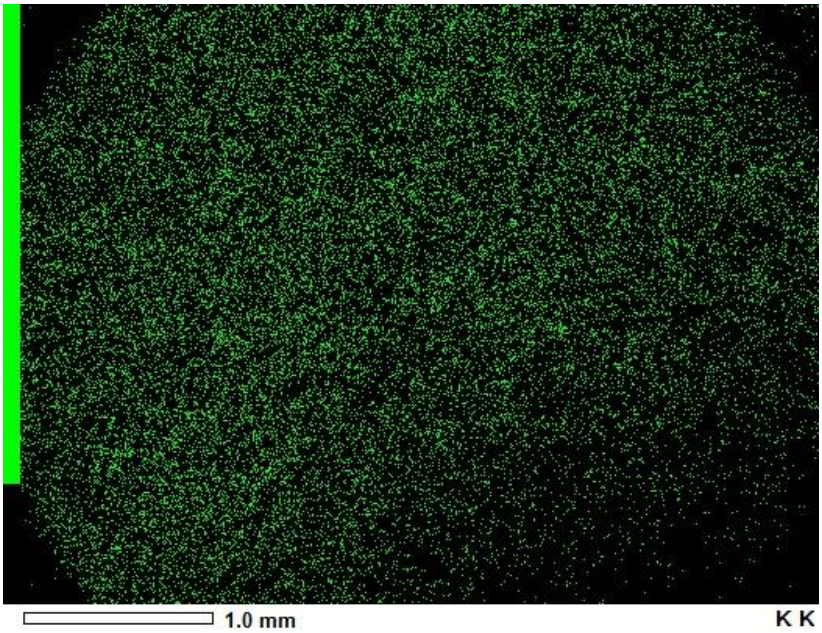

Figure 53. EDS Dot map showing potassium o on surface of stainless steel weld

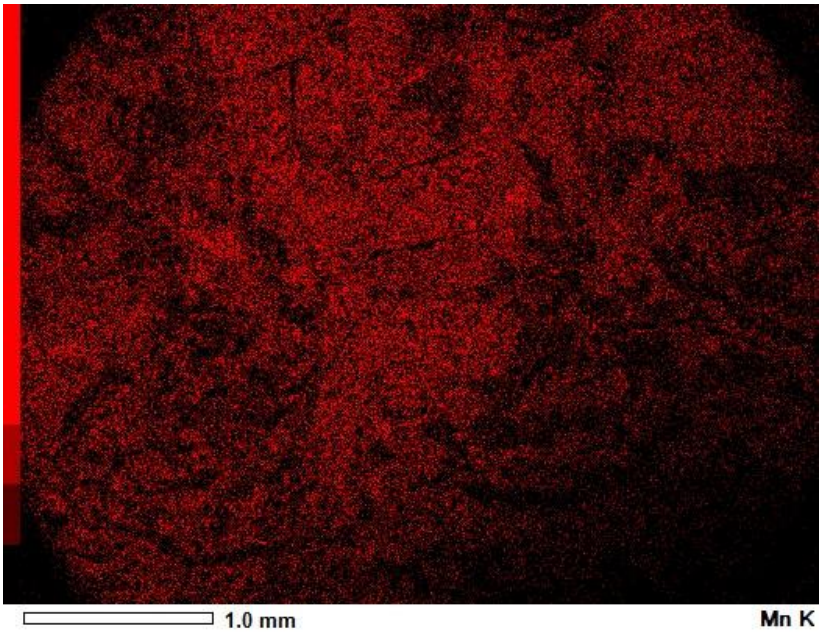

Figure 54. EDS Dot map showing manganese on surface of stainless steel weld

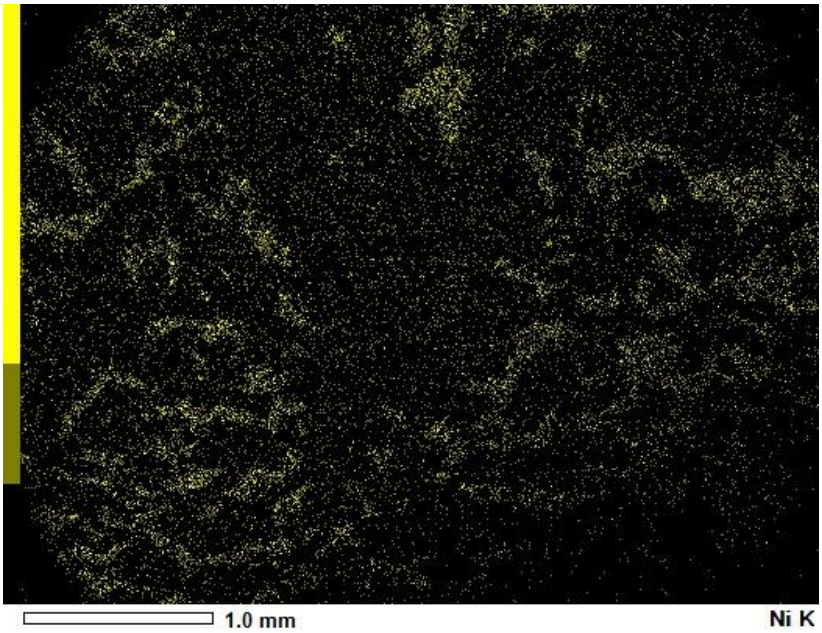

Figure 55. EDS Dot map showing nickel on surface of stainless steel weld

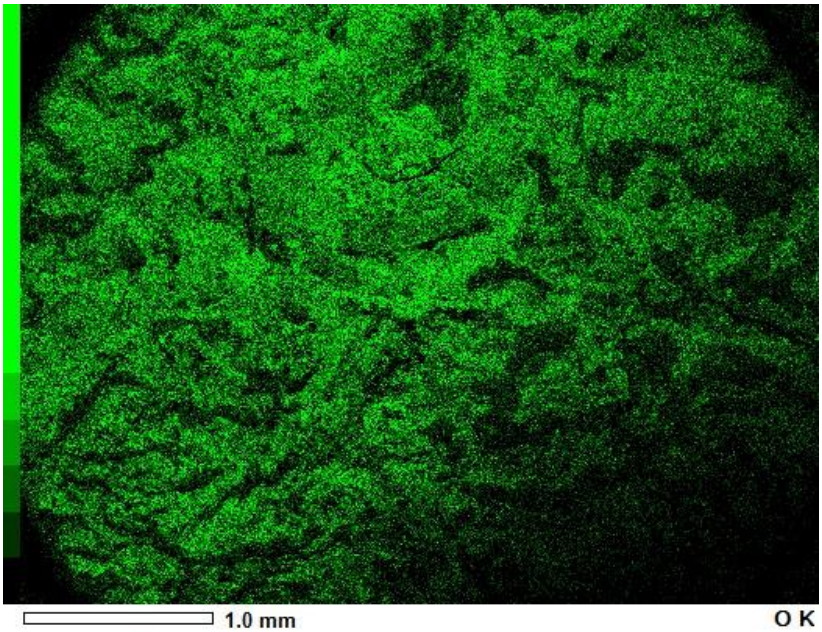

Figure 56. EDS Dot map showing oxygen on surface of stainless steel weld

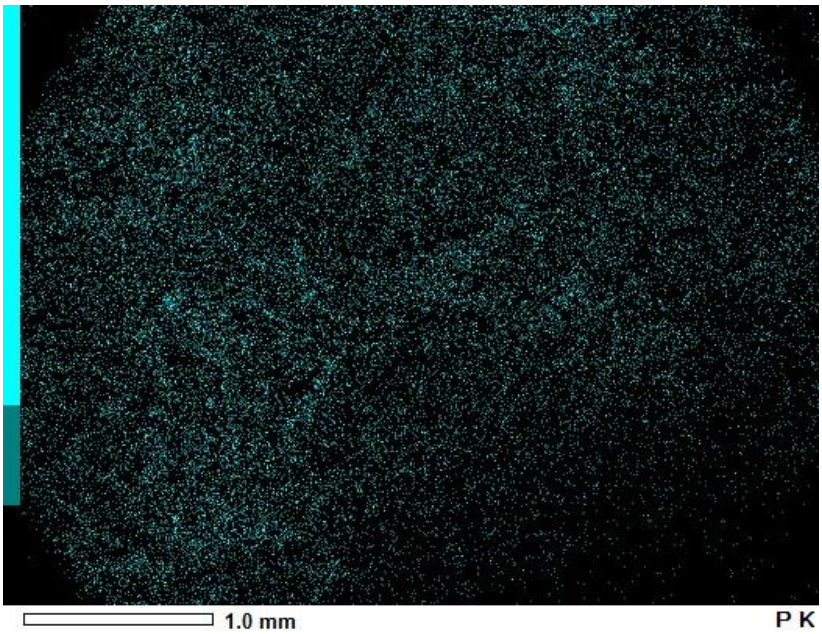

Figure 57. EDS Dot map showing phosphorous on surface of stainless steel weld

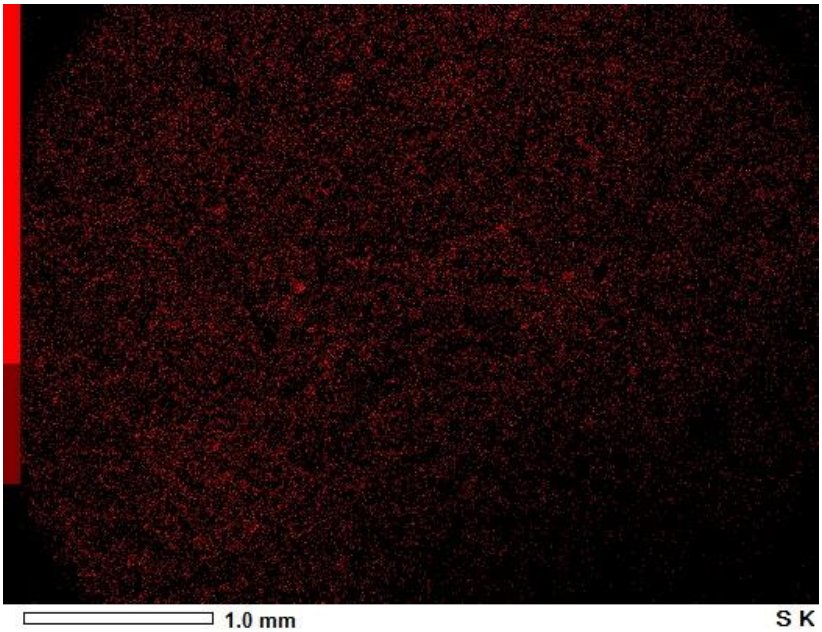

Figure 58. EDS Dot map showing sulfur on surface of stainless steel weld

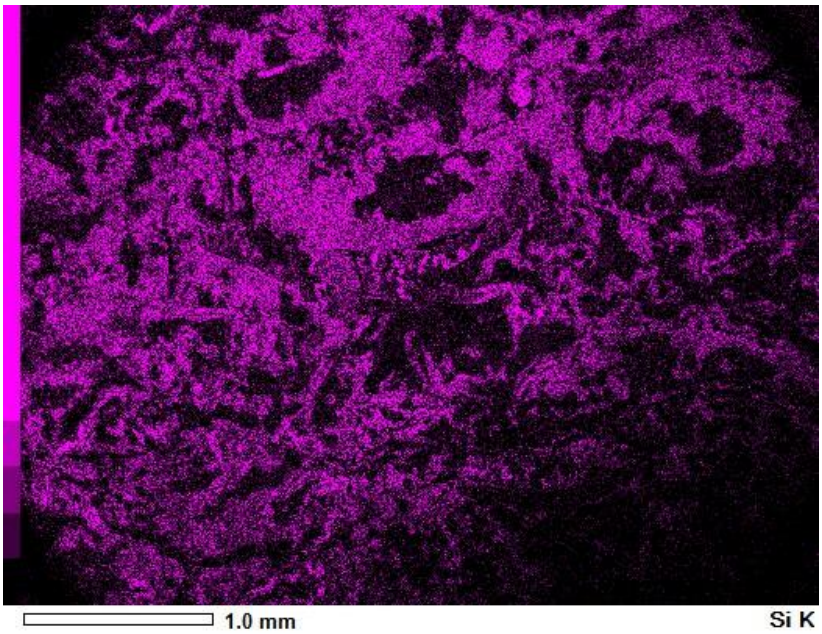

Figure 59. EDS Dot map showing silicon on surface of stainless steel weld

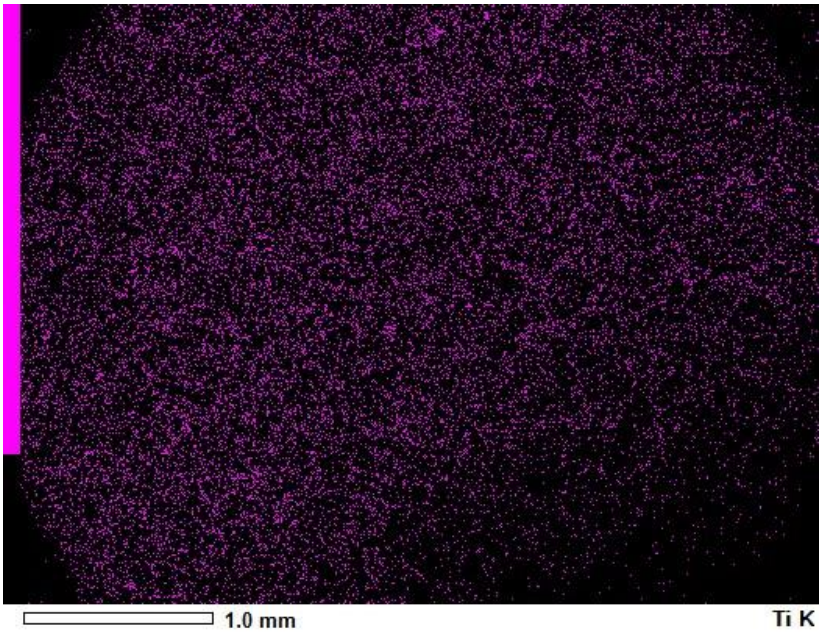

Figure 60. EDS Dot map showing titanium on surface of stainless steel weld

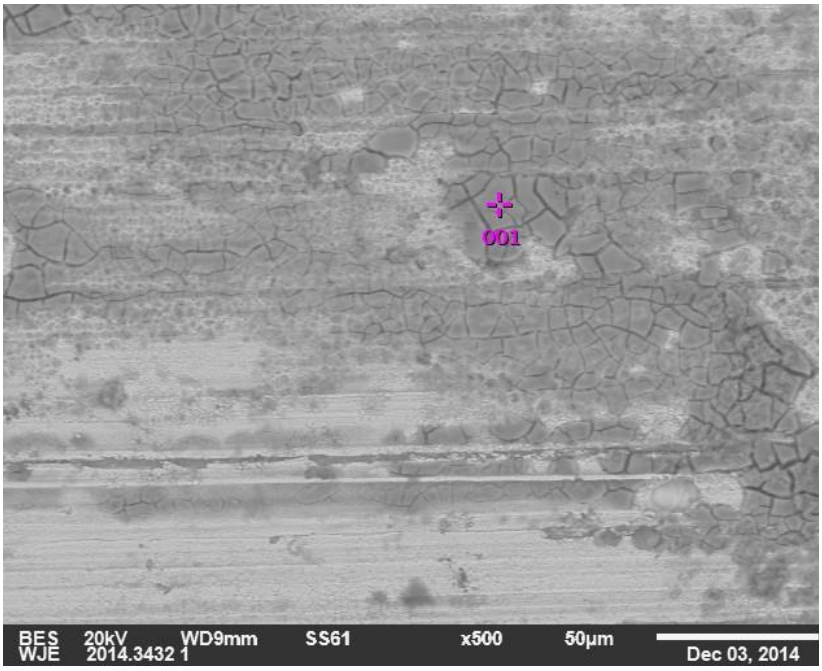

Figure 61. SEM image of surface of stainless steel plate

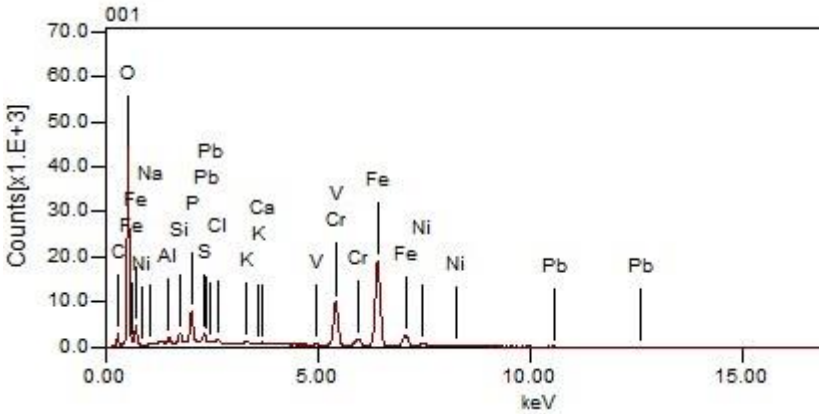

Figure 62. EDX spectra of cross section of stainless steel plate

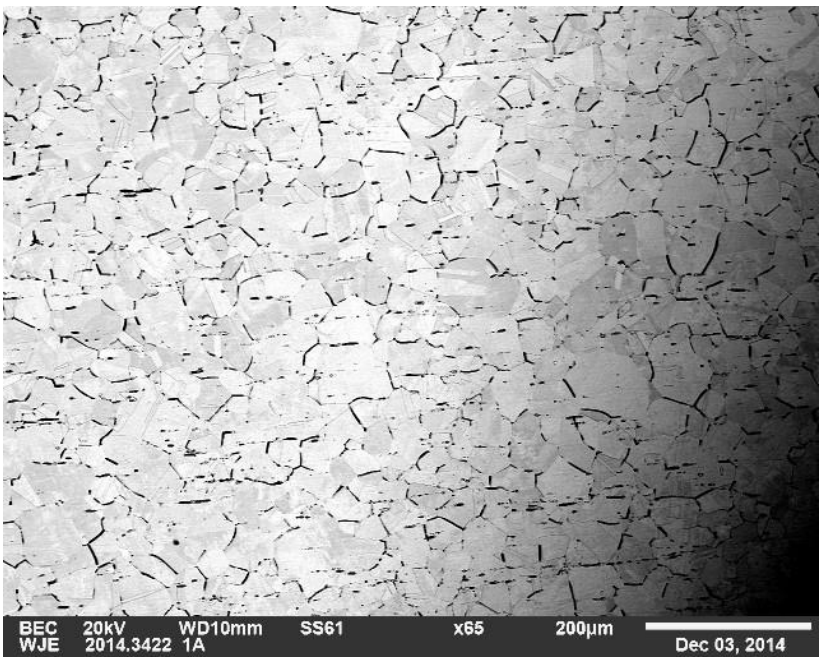

Figure 63. EM image of cross section of stainless steel plate

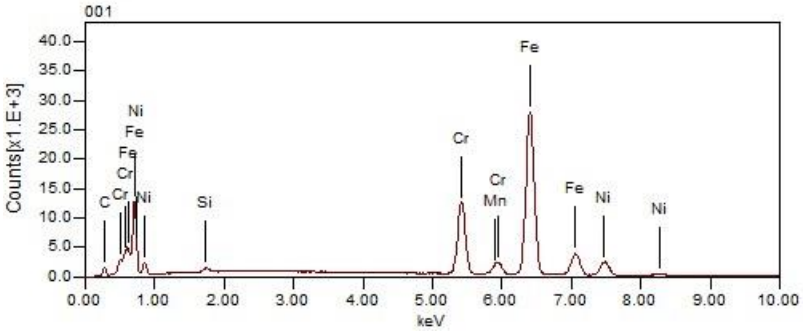

Figure 64. EDX spectra of polished cross section of stainless steel plate

Figure 65. SEM image of cross section of stainless steel weld

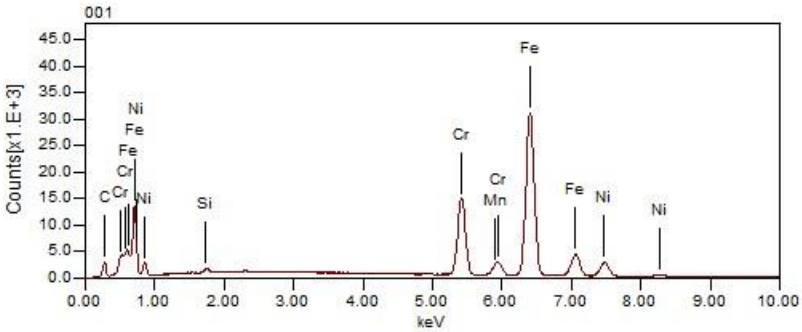

Figure 66. EDX spectra of cross section of stainless steel weld

SAMPLE 2

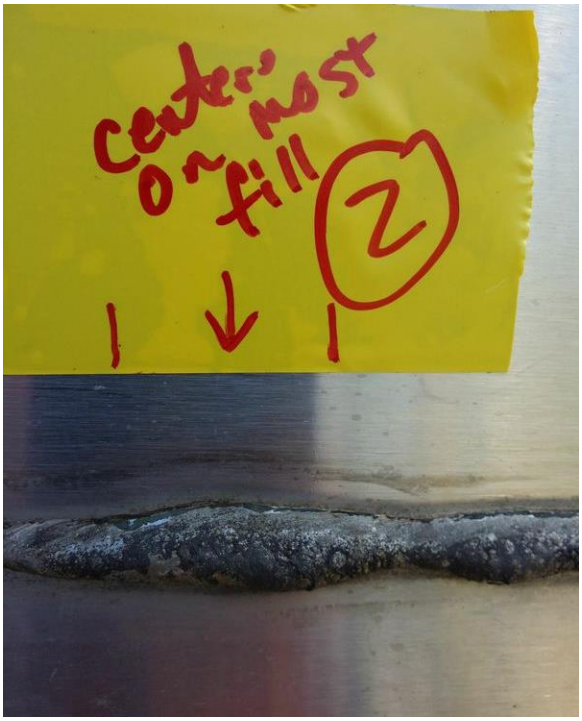

Figure 67. Sample 2 before

Figure 68. Sample 2 before

Figure 69. Sample 2 before

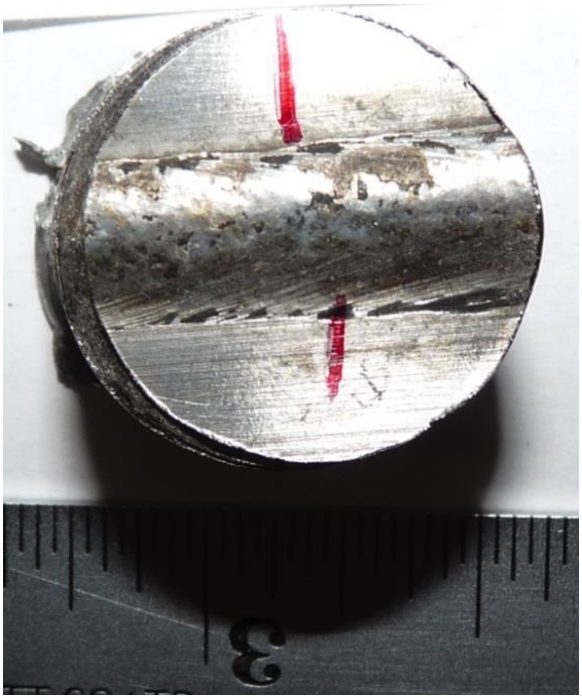

Figure 70. Sample 2 (Scale=1/32")

Figure 71. Sample 2

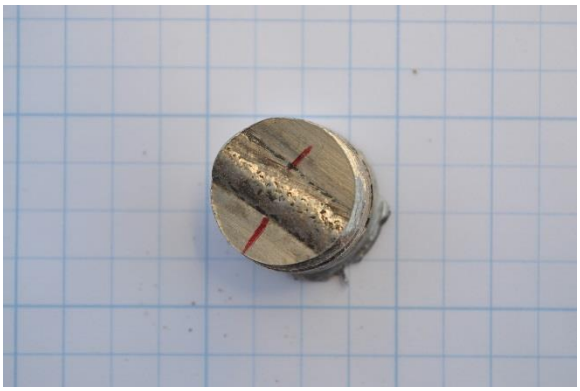

Figure 72. Sample 2

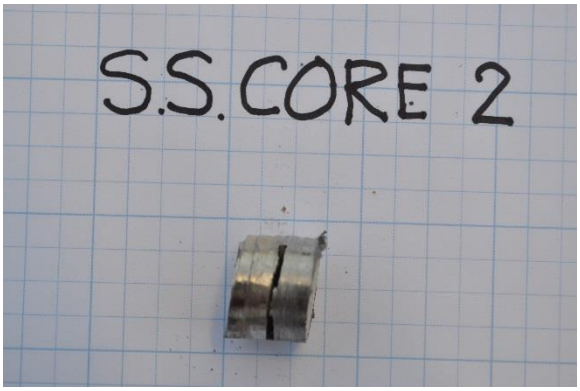

Figure 73. Sample 2

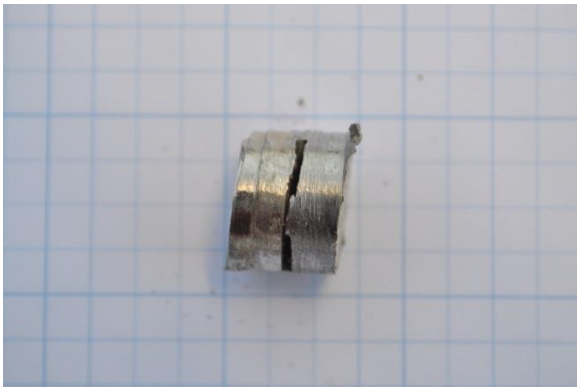

Figure 74. Sample 2

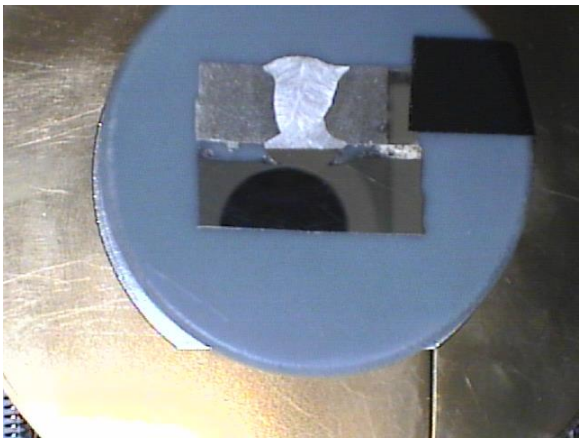

Figure 75. Overall etched cross section

Figure 76. Etched cross section

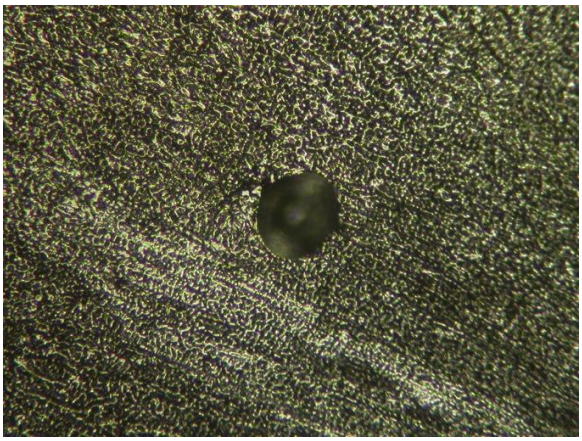

Figure 77.Optical micrograph, etched condition, weld porosity, approximate diameter 0.004"

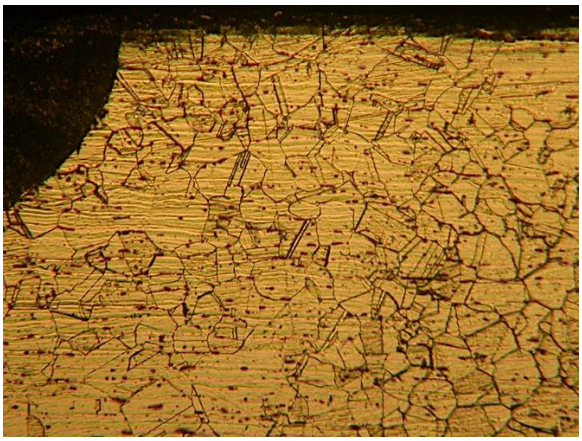

Figure 78.Optical micrograph, etched condition (122x)

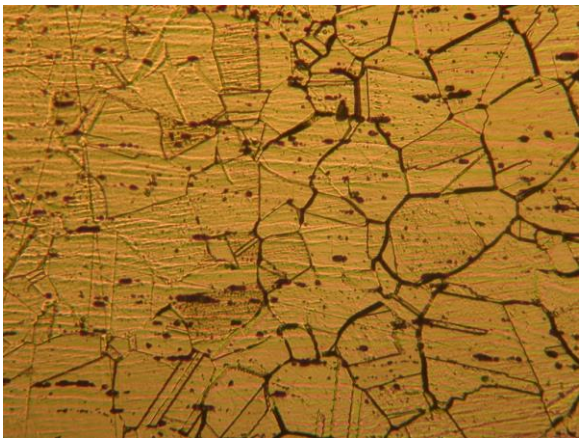

Figure 79. Optical micrograph, etched condition (256x)

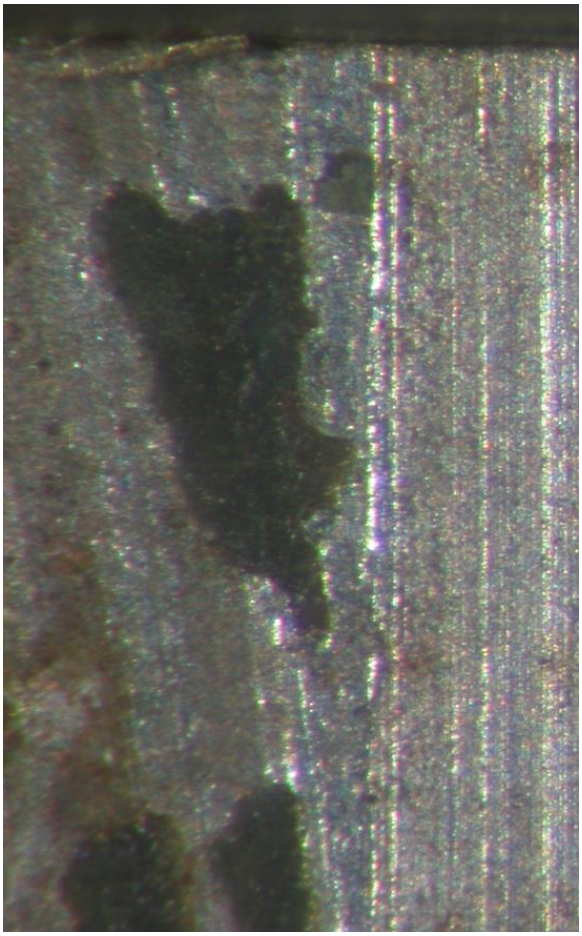

Figure 80. Photographs of the surface of the cut, un-mounted portion

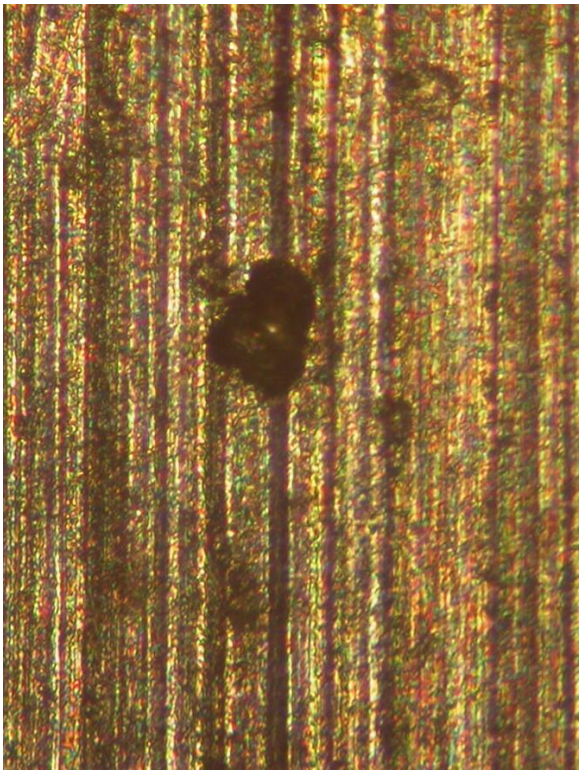

Figure 81. Photographs of the surface of the cut, un-mounted

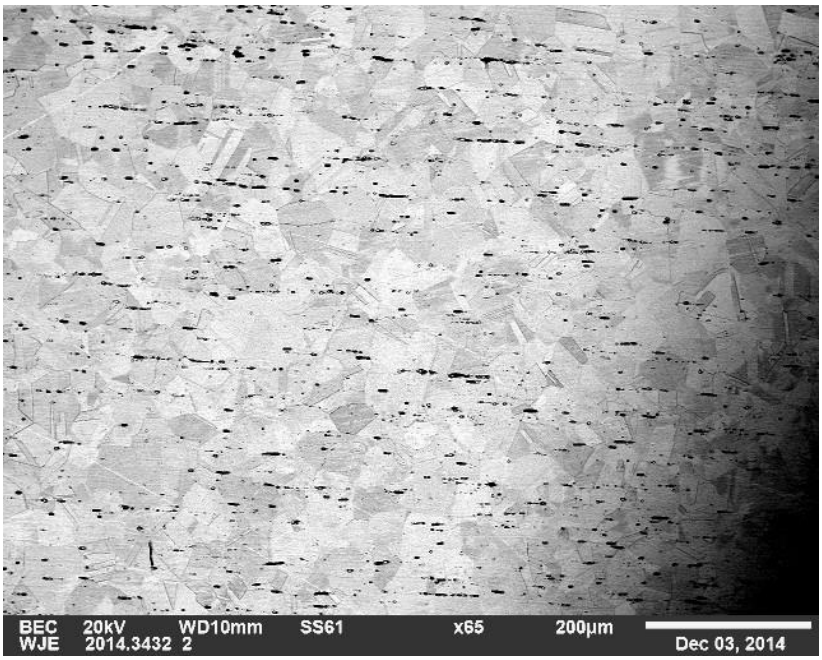

Figure 82. SEM image of cross section of stainless steel plate

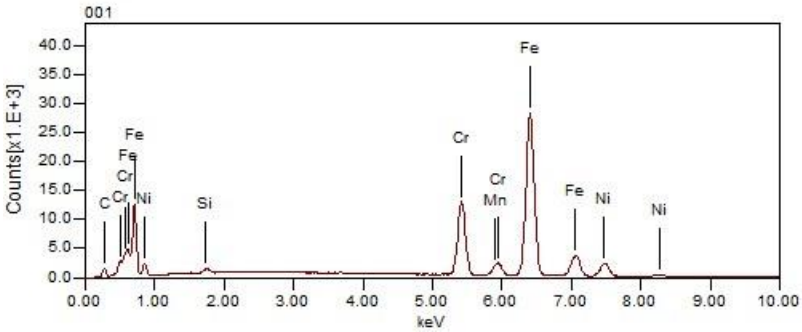

Figure 83. EDX spectra of cross section of stainless steel plate

Figure 84. SEM image of cross section of stainless steel weld

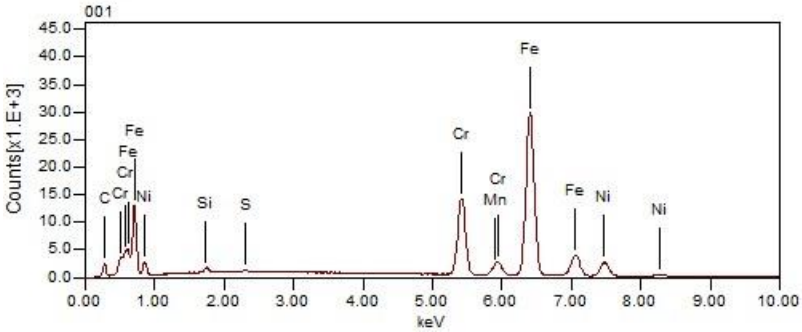

Figure 85. EDX spectra image of cross section of stainless steel weld

SAMPLE 3

Figure 86. Sample 3

Figure 87. Sample 3

Figure 88. Sample 3

Figure 89. Sample 3

Figure 90. Sample 3

Figure 91. Sample 3

Figure 92. Sample 3

Figure 93. Sample 3

Figure 94. Sample 3

Figure 95. Sample 3

Figure 96. Sample 3 (Scale=1/32”)

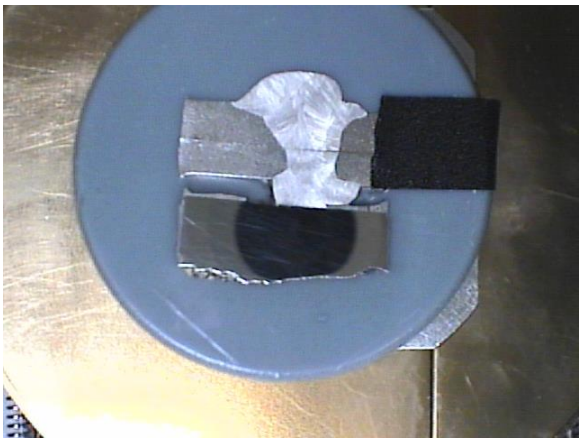

Figure 97. Overall etched cross section

Figure 98. Etched cross section

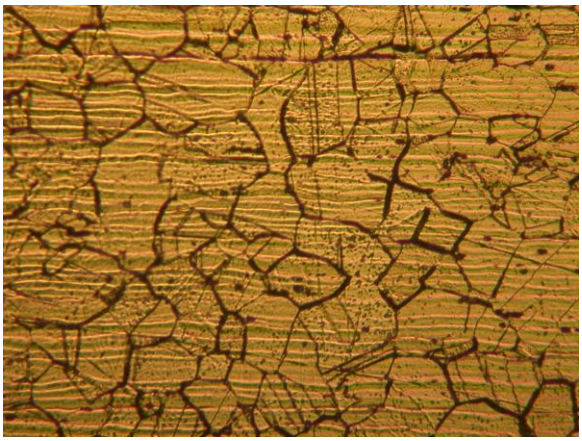

Figure 99. Optical micrograph, etched condition showing plate (256x)

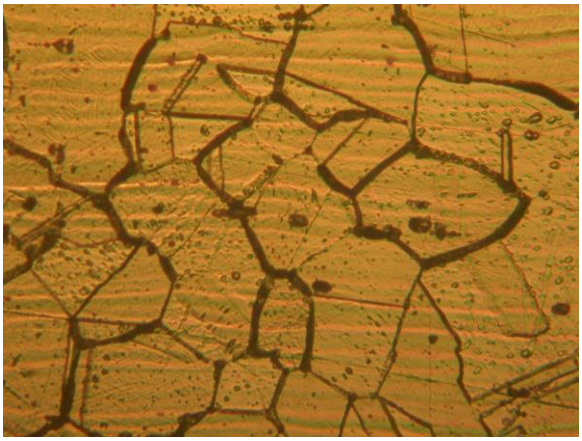

Figure 100. Optical micrograph, etched condition showing plate (517x)

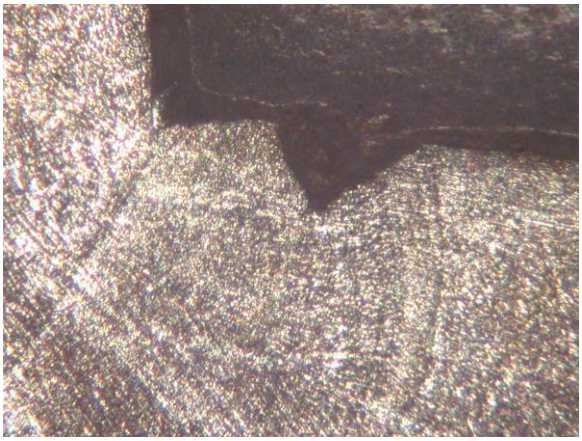

Figure 101. Optical micrograph etched condition showing a notch in the outside weld surface (122x)

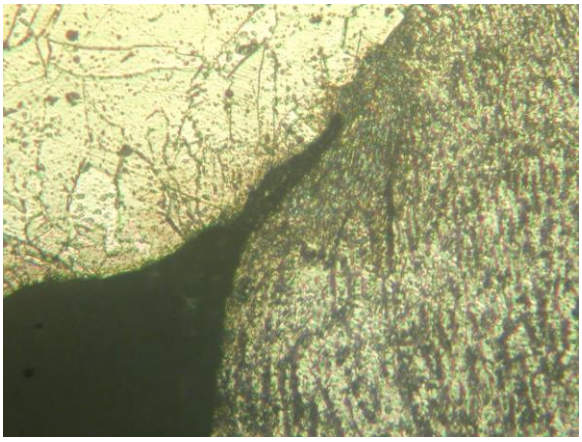

Figure 102. Optical micrograph, etched condition showing shallow undercut where the weld metal and base metal meet (517x)

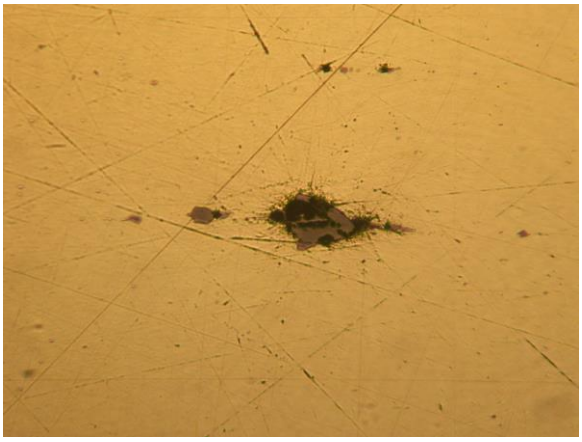

Figure 103. Optical micrograph, plate inclusion, as-polished condition (256x)

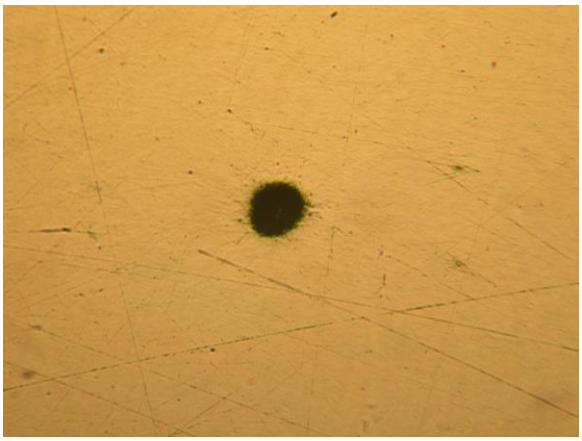

Figure 104. Optical micrograph, weld void, approximate diameter 0.004", shown as-polished condition

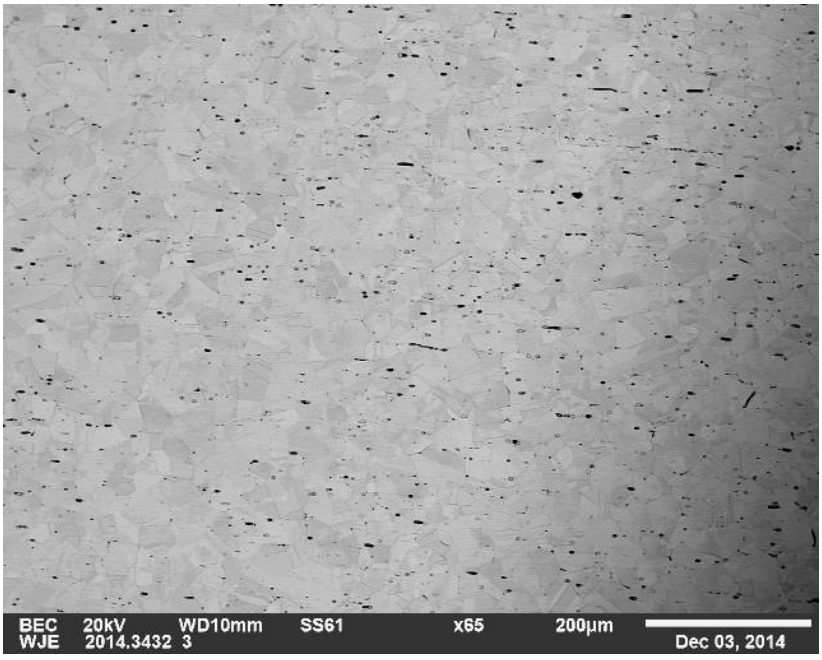

Figure 105. SEM image of cross section of stainless steel plate

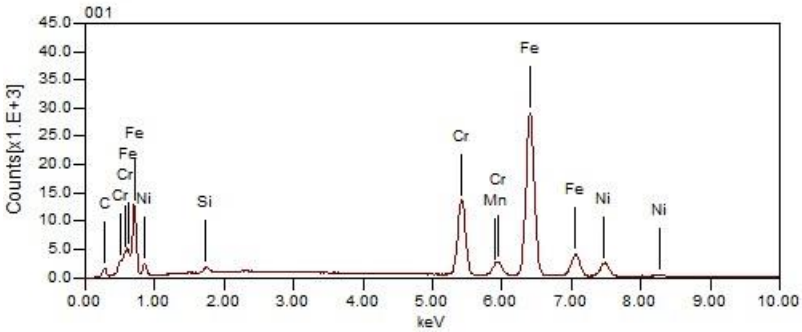

Figure 106. EDX spectra of cross section of stainless steel plate

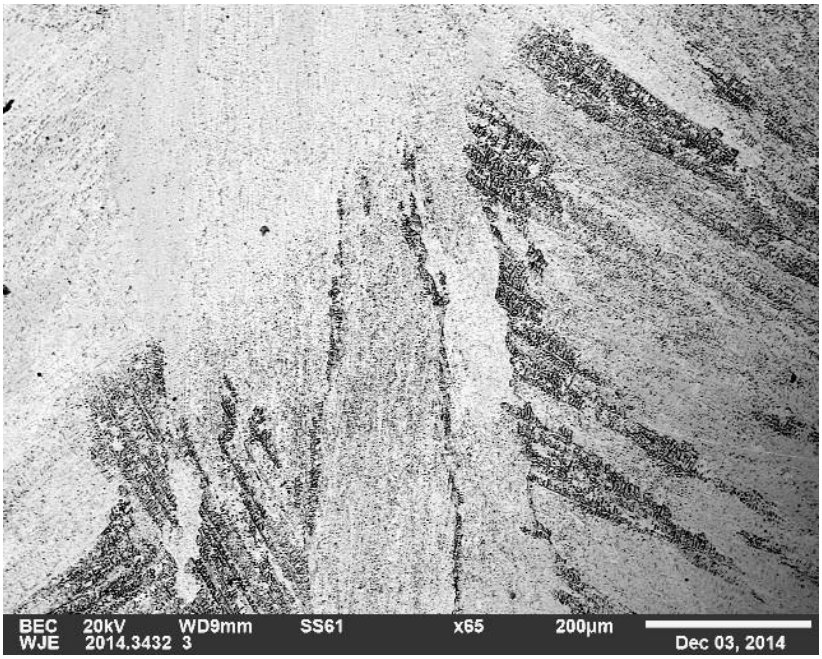

Figure 107. SEM image of cross section of stainless steel weld

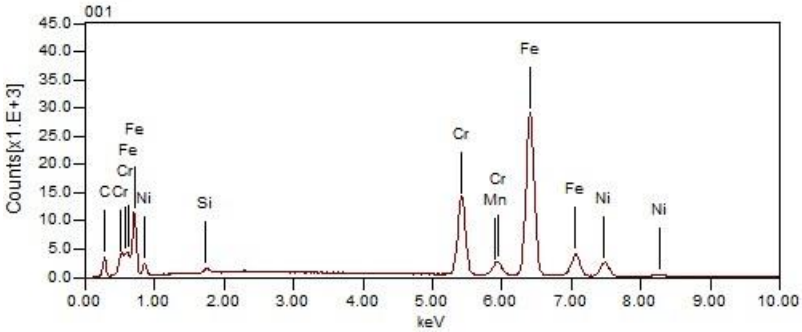

Figure 108. EDX spectra of cross section of stainless steel weld

SAMPLE 4

Figure 109. Sample 4 before

Figure 110. Sample 4 before

Figure 111. Sample 4 before

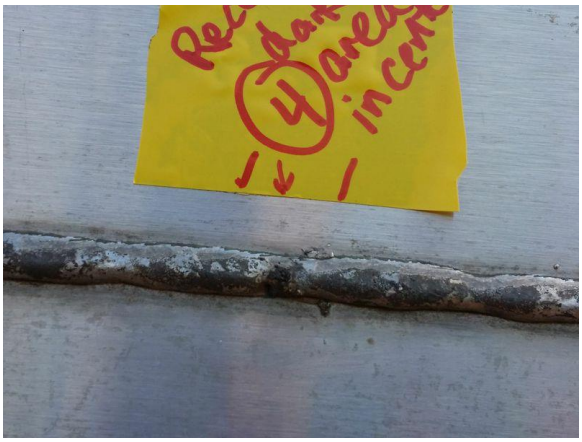

Figure 112. Sample 4 before

Figure 113. Sample 4 before

Figure 114. Sample 4 before

Figure 115. Sample 4

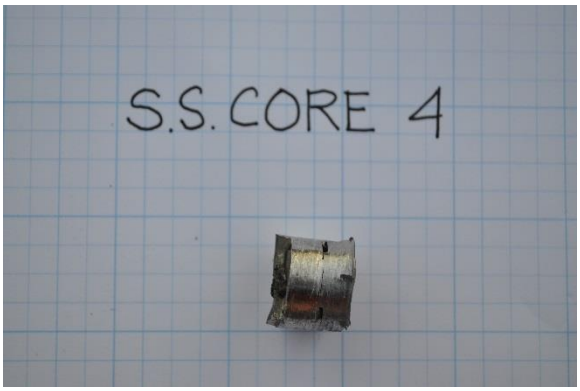

Figure 116. Sample 4

Figure 117. Sample 4

Figure 118. Sample 4

Figure 119. Sample 4 (Scale=1/32")

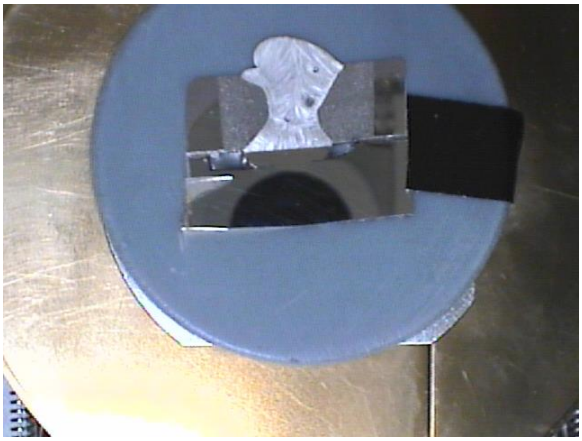

Figure 120. Overall etched cross section

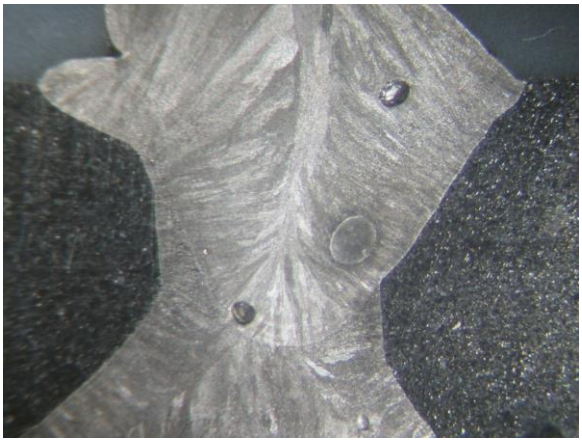

Figure 121. Macrograph, etched condition, showing weld porosity─the largest void located near mid thickness has an approximate diameter of 0.04"

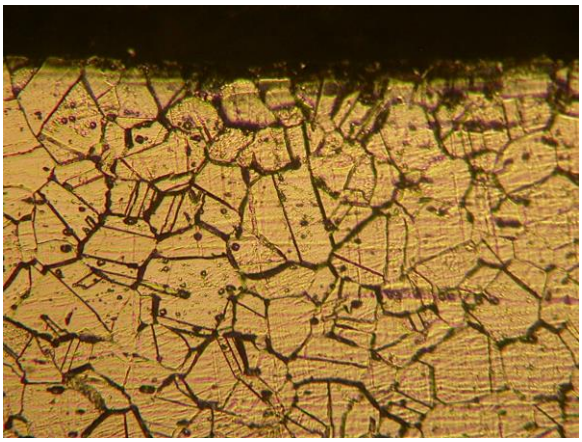

Figure 122. Optical micrograph, etched condition (256x)

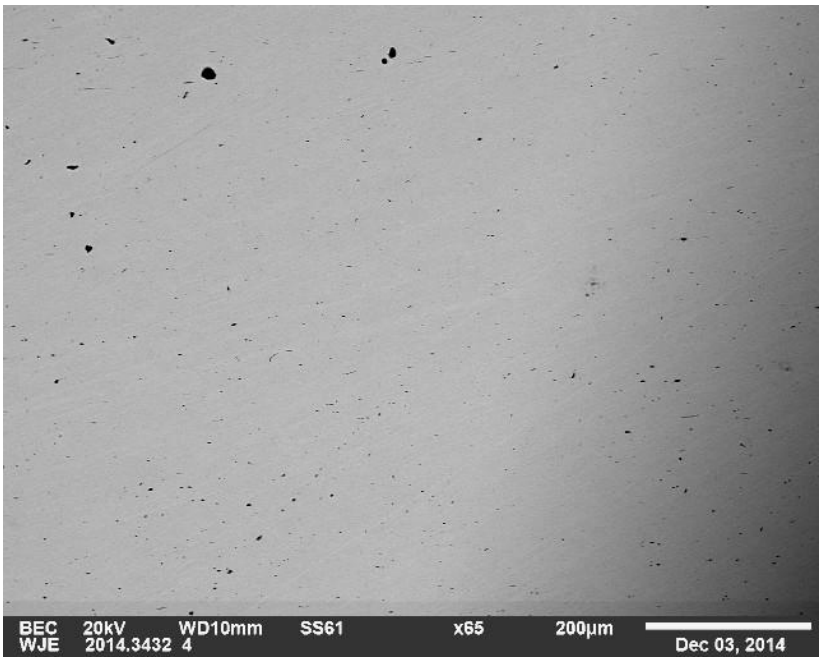

Figure 123. SEM image of cross section of stainless steel plate

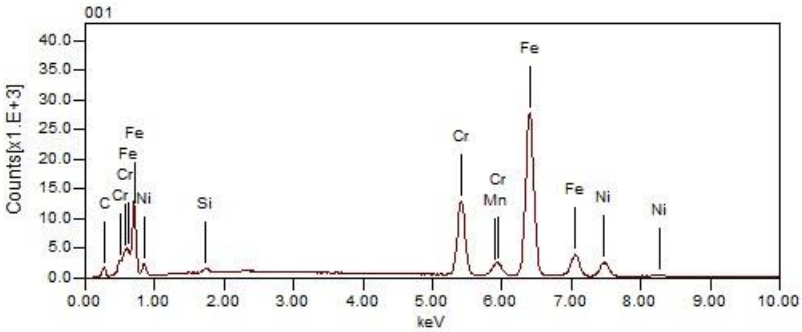

Figure 124. EDX spectra of cross section of stainless steel plate

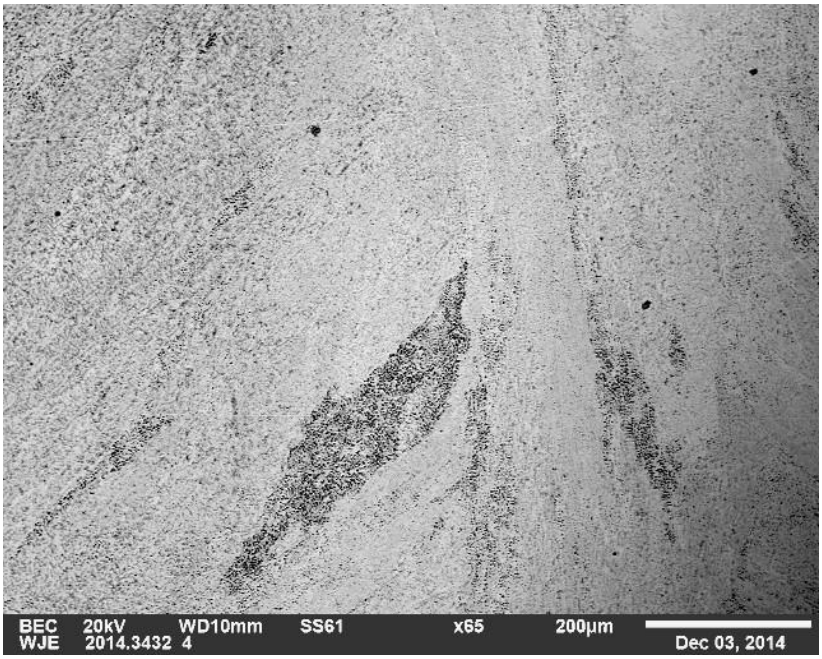

Figure 125. SEM image of cross section of stainless steel weld

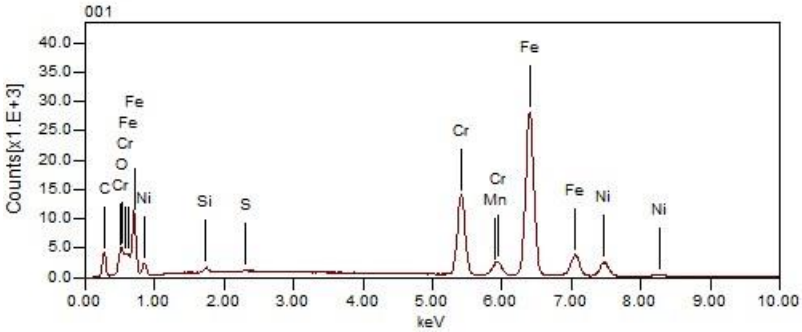

Figure 126. EDX spectra of cross section of stainless steel weld

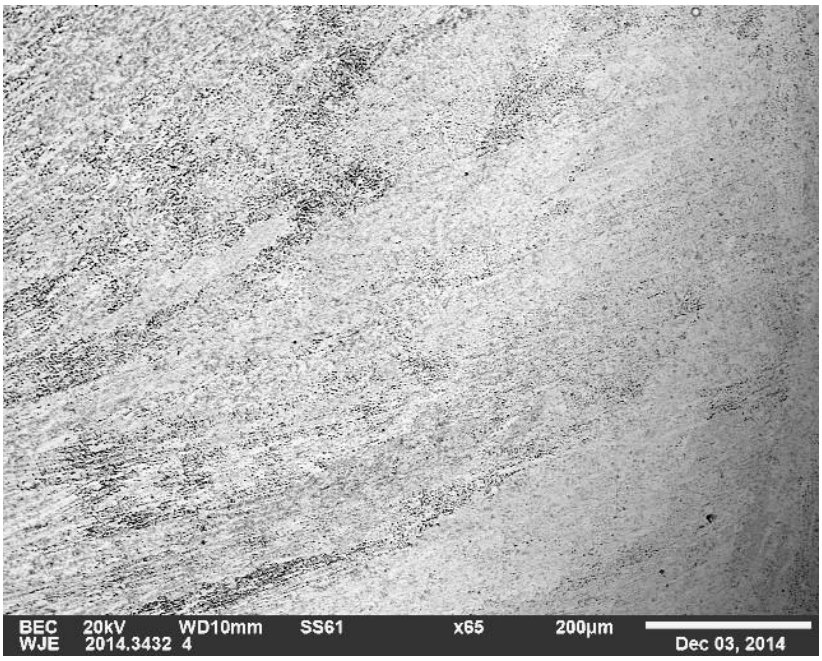

Figure 127. SEM image of cross section of stainless steel weld

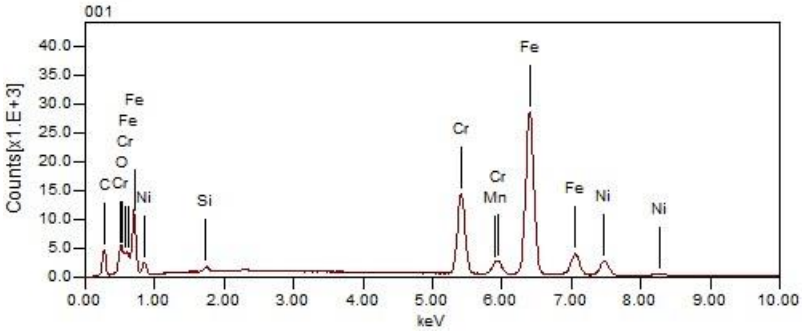

Figure 128. EDX spectra of cross section of stainless steel weld

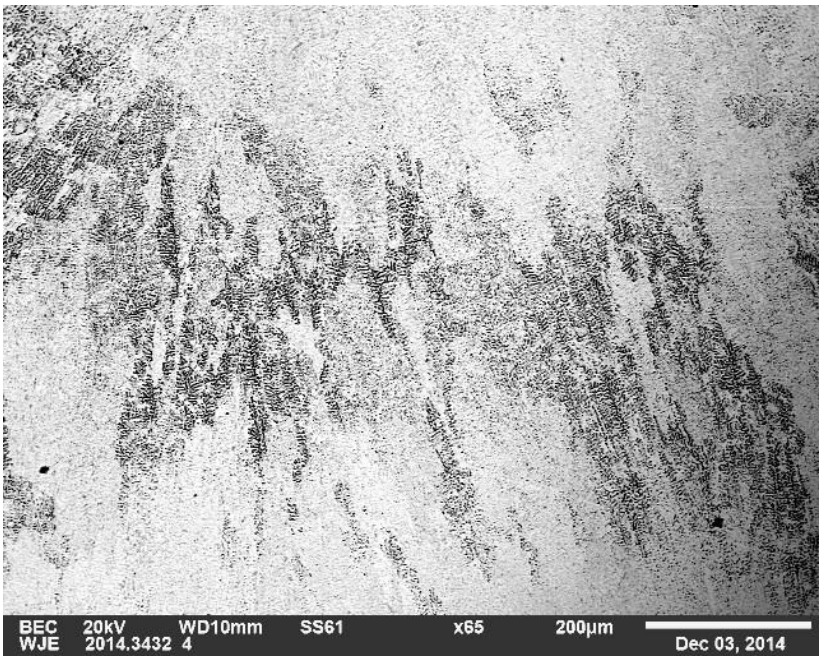

Figure 129. SEM image of cross section of stainless steel weld

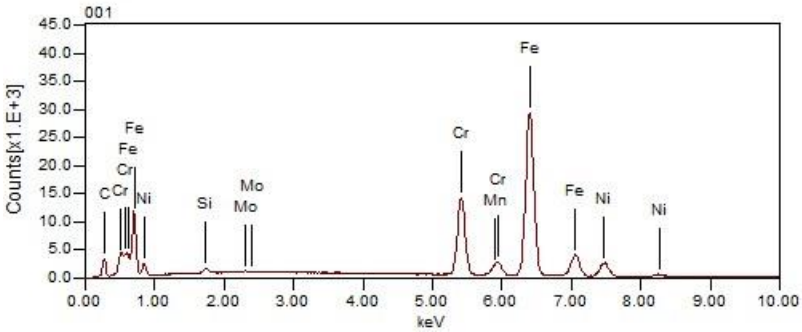

Figure 130. EDX spectra of cross section of stainless steel weld

SAMPLE 5

Figure 131. Sample 5 before

Figure 132. Sample 5 before

Figure 133. Sample 5 before

Figure 134.Sample 5 before

Figure 135. Sample 5 before

Figure 136. Sample 5 before

Figure 137. Sample 5 before

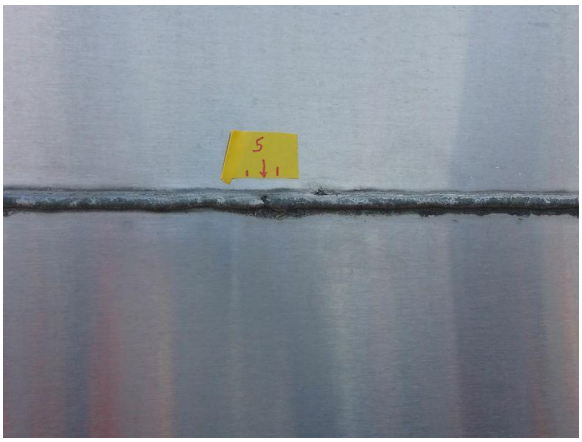

Figure 138. Sample 5 before

Figure 139. Sample 5 before

Figure 140. Sample 5 before

Figure 141. Sample 5 before

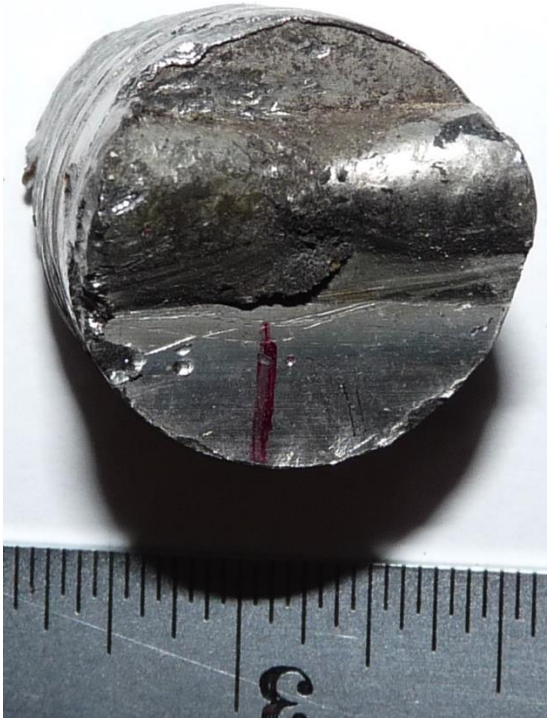

Figure 142. Sample 5 (Scale=1/32")

Figure 143. Sample 5

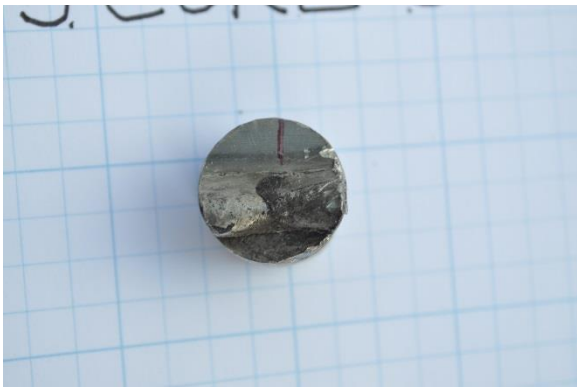

Figure 144. Sample 5

Figure 145. Sample 5

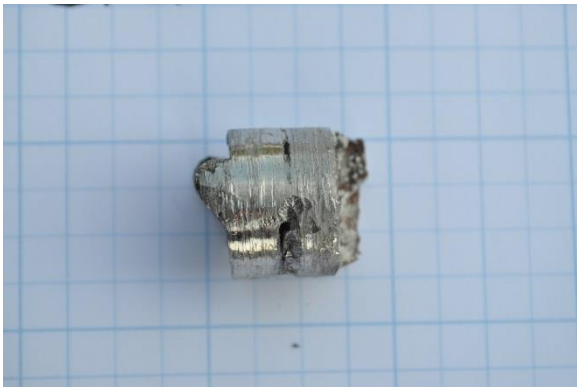

Figure 146. Sample 5

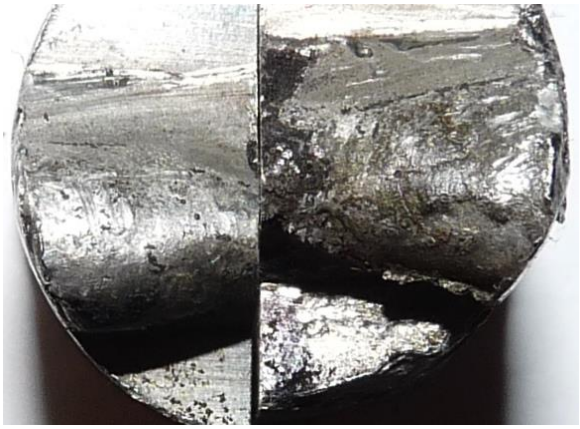

Figure 147. Sample 5 after sectioning and a corresponding micrograph of section #5 at the weld crown (256x)

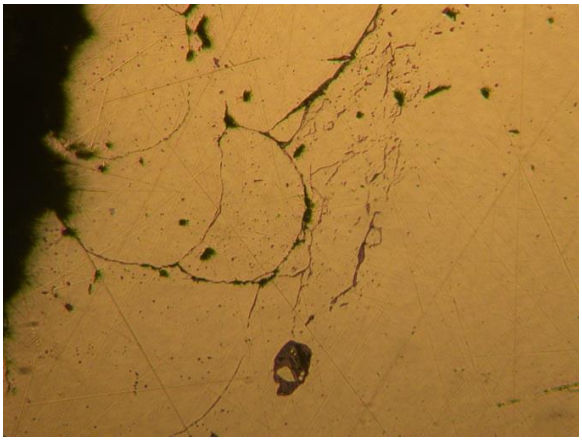

Figure 148. Optical micrograph at the weld crown shown in the as-polished condition. (256x)

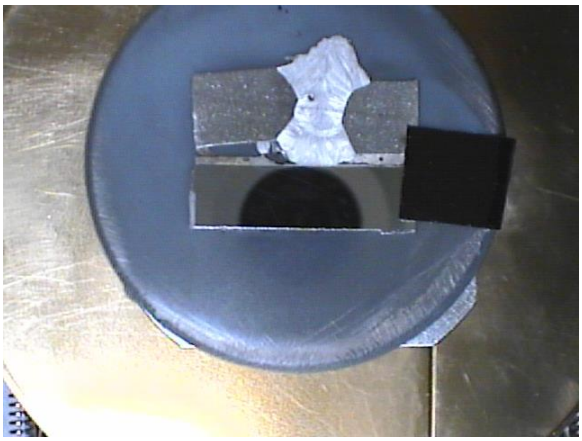

Figure 149. Overall etched cross section

Figure 150. Etched cross section

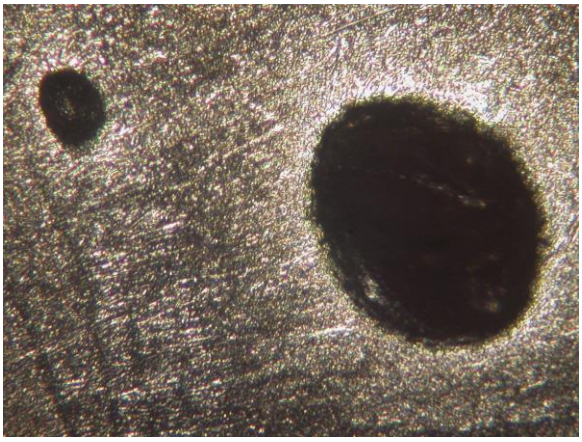

Figure 151. Optical micrograph etched condition

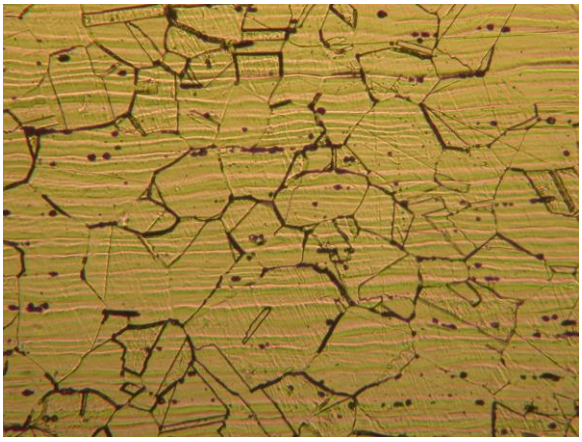

Figure 152. Optical micrograph etched condition (256x)

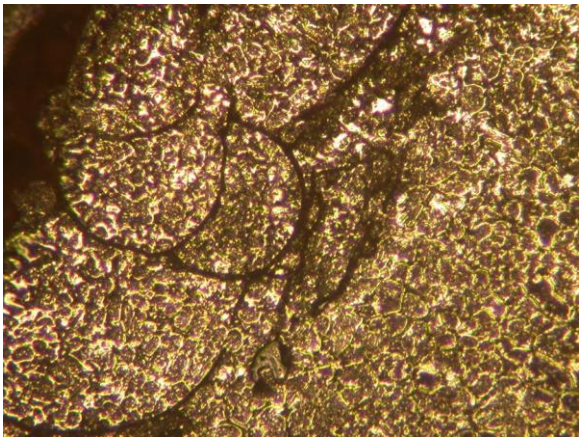

Figure 153.Optical micrograph weld crown in the etched condition (256x)

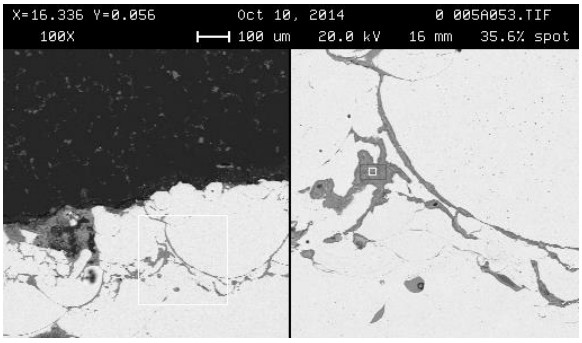

Figure 154. SEM micrograph at the weld crown (256x)

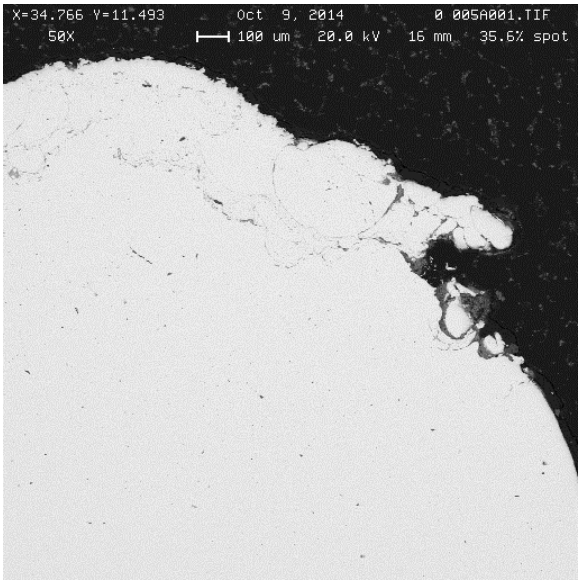

Figure 155. SEM photomicrograph

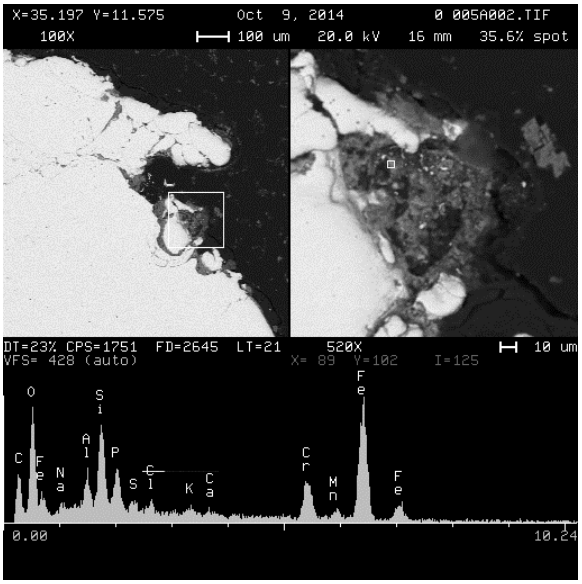

Figure 156. SEM photomicrograph

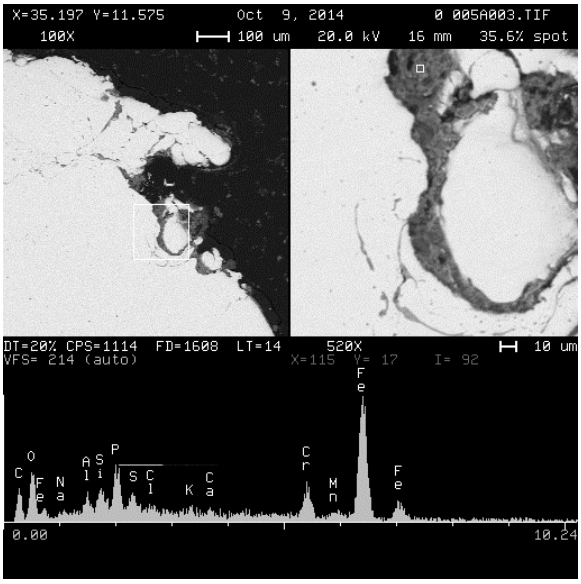

Figure 157. SEM photomicrograph

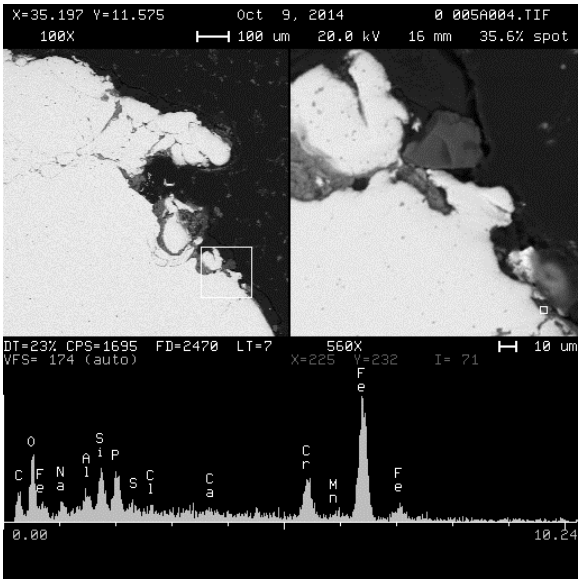

Figure 158. SEM photomicrograph

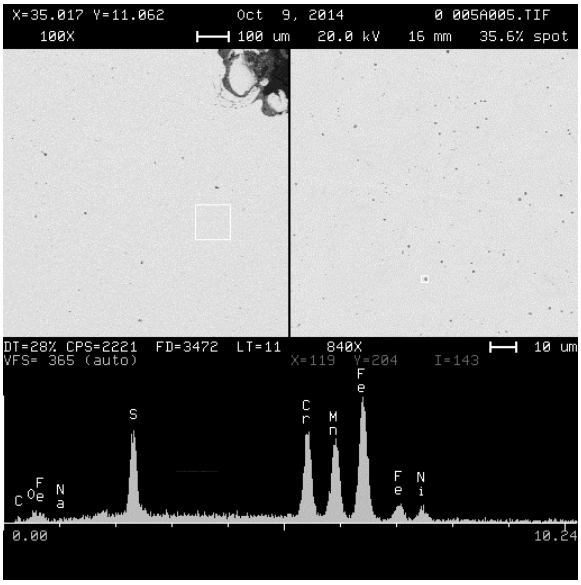

Figure 159. SEM photomicrograph

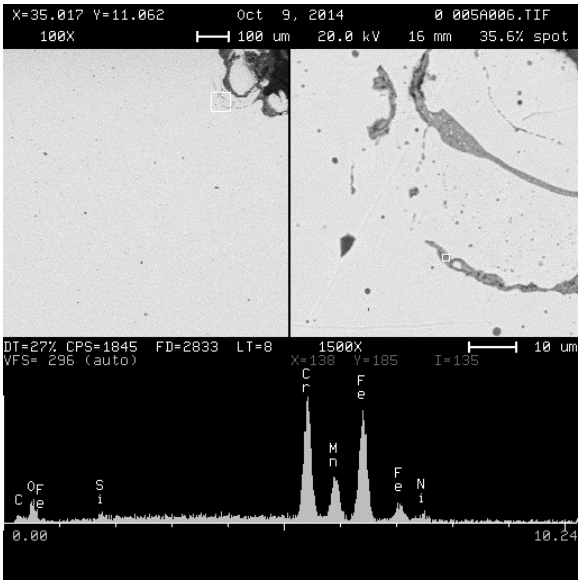

Figure 160. SEM photomicrograph

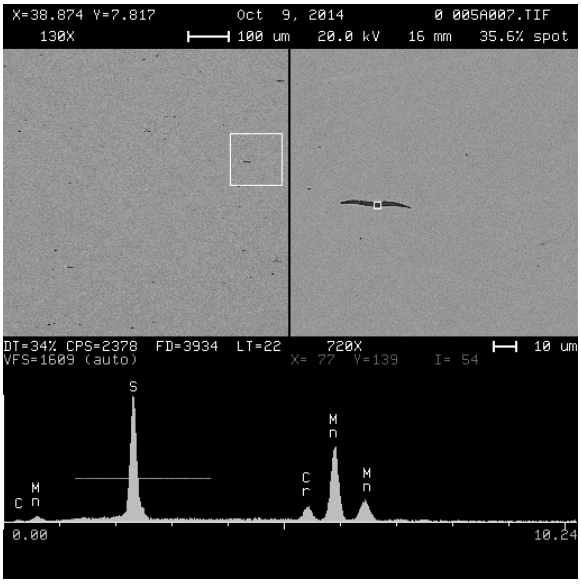

Figure 161. SEM photomicrograph

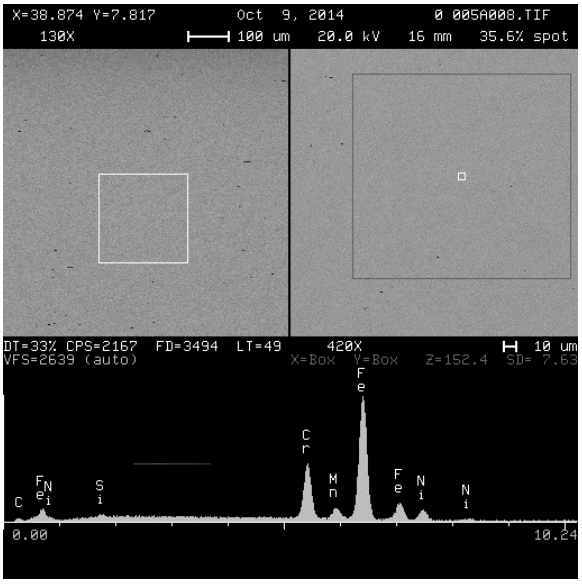

Figure 162. SEM photomicrograph

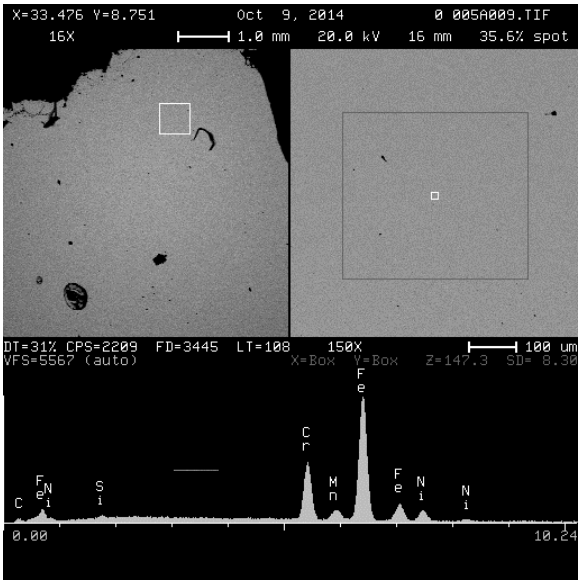

Figure 163. SEM photomicrograph

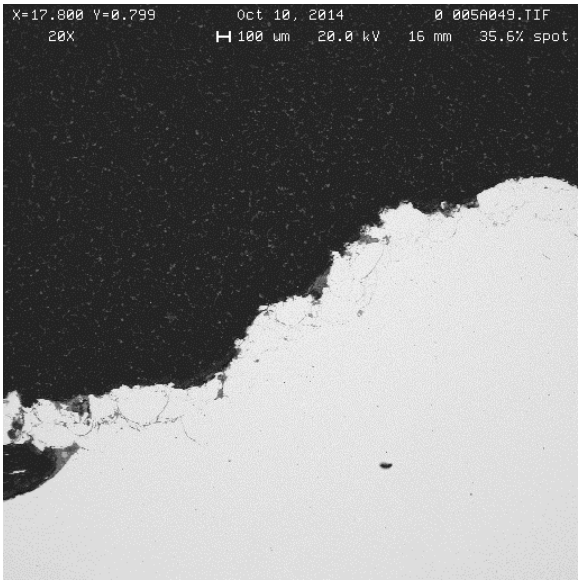

Figure 164. SEM photomicrograph

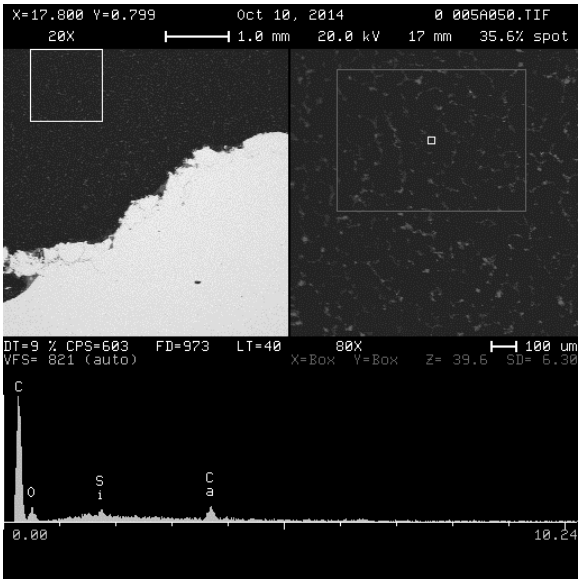

Figure 165. SEM photomicrograph

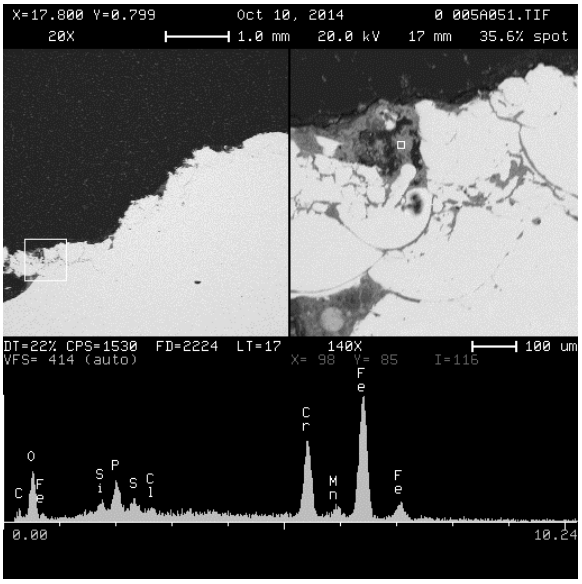

Figure 166. SEM photomicrograph

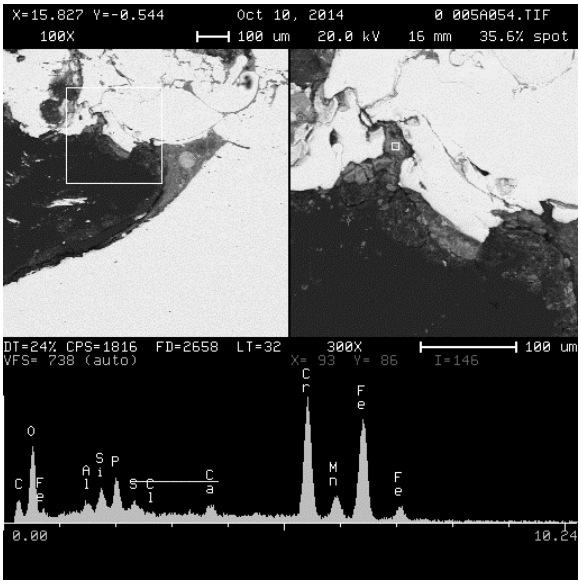

Figure 167. SEM photomicrograph

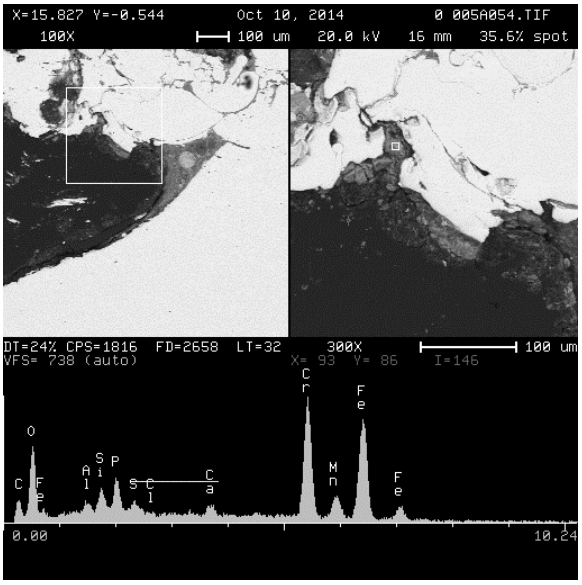

Figure 168. SEM photomicrograph

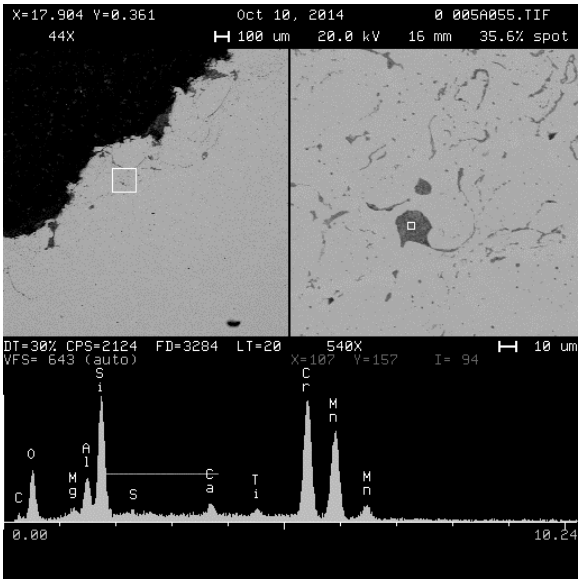

Figure 169. SEM photomicrograph

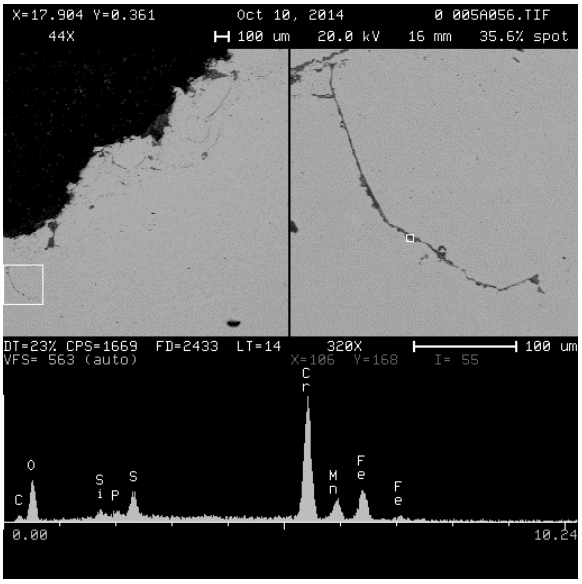

Figure 170. SEM photomicrograph

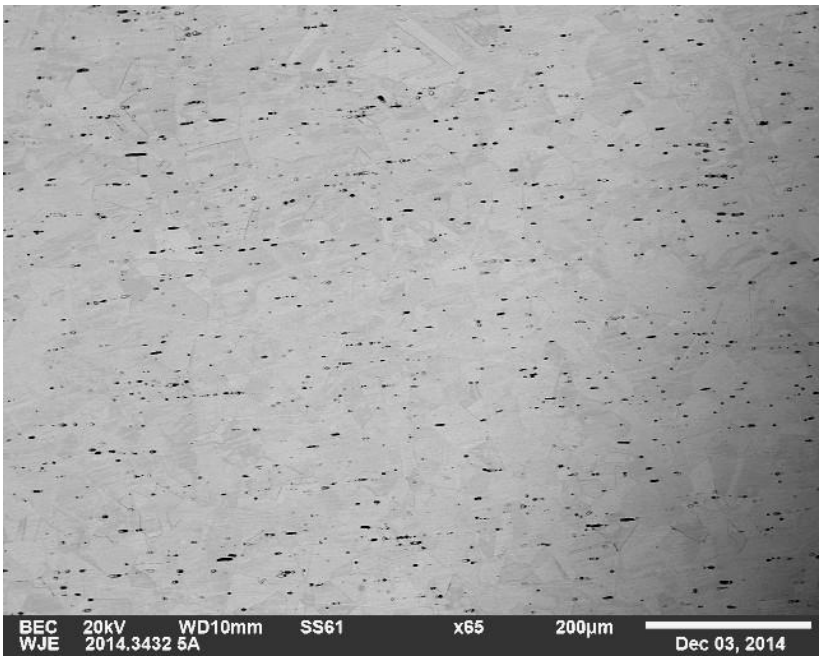

Figure 171. SEM image of cross section of stainless steel plate

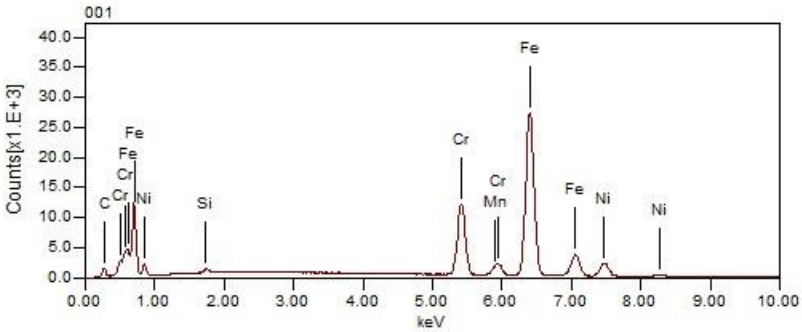

Figure 172. EDX spectra of cross section of stainless steel plate

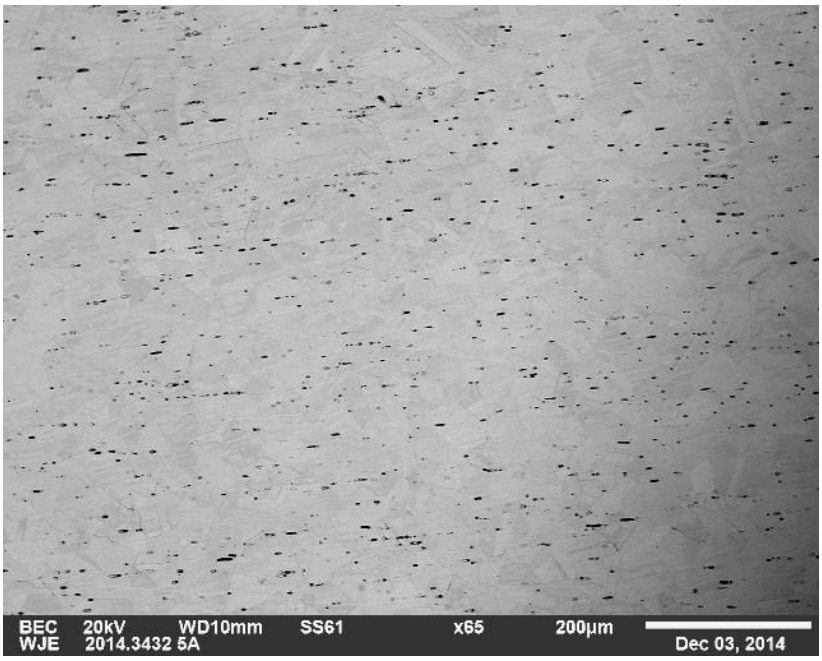

Figure 173. SEM image of cross section of stainless steel plate

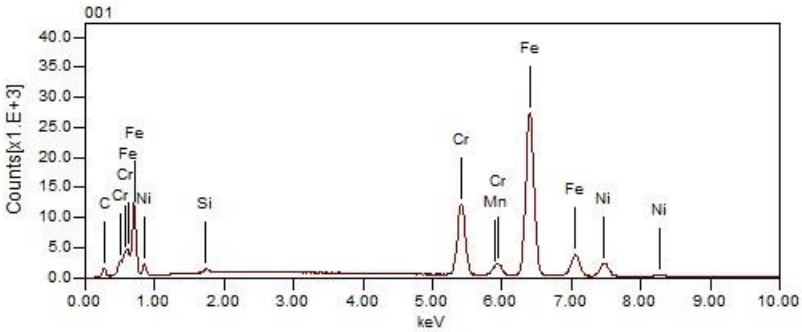

Figure 174. EDX spectra of cross section of stainless steel plate

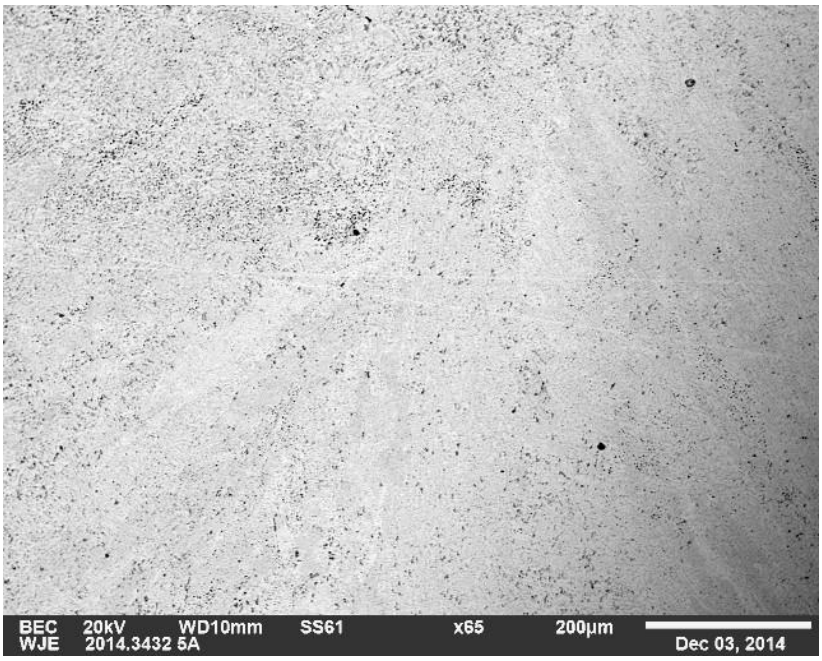

Figure 175. SEM image of cross section of stainless steel weld

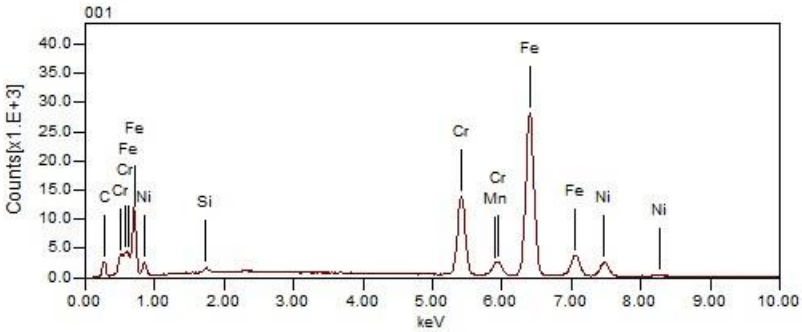

Figure 176. EDX spectra of cross section of stainless steel weld

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APPENDIX H -
LABORATORY ANALYSIS OF REMOVED DEPOSITS

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Sample 1B

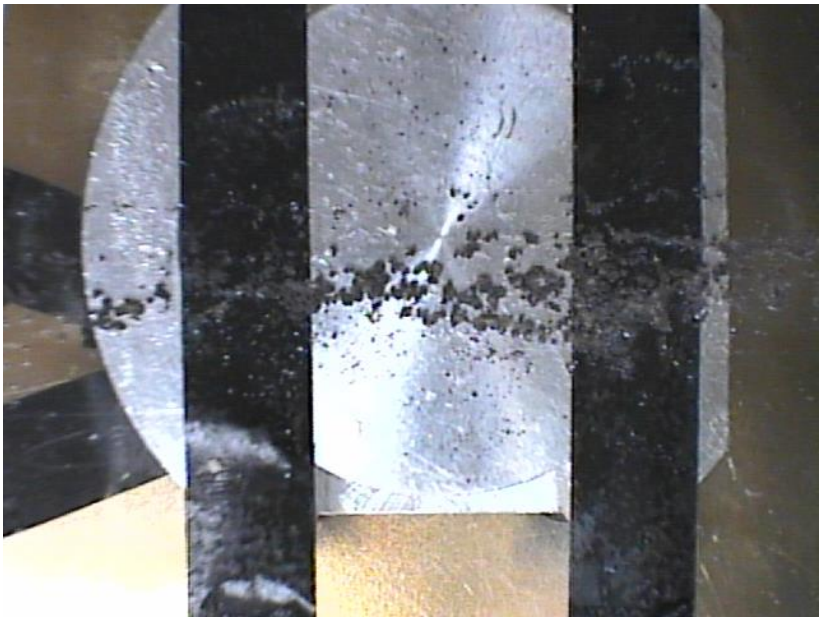


Figure 1

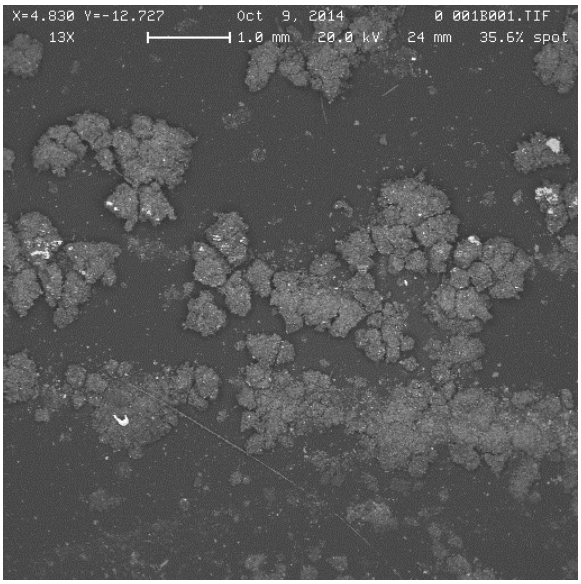


Figure 2

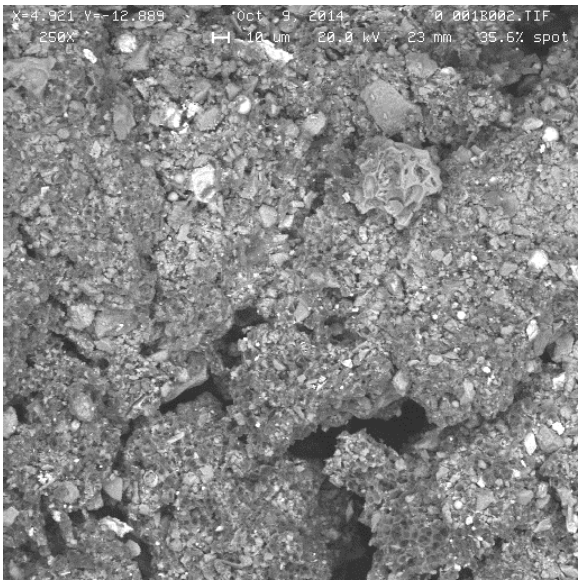


Figure 3

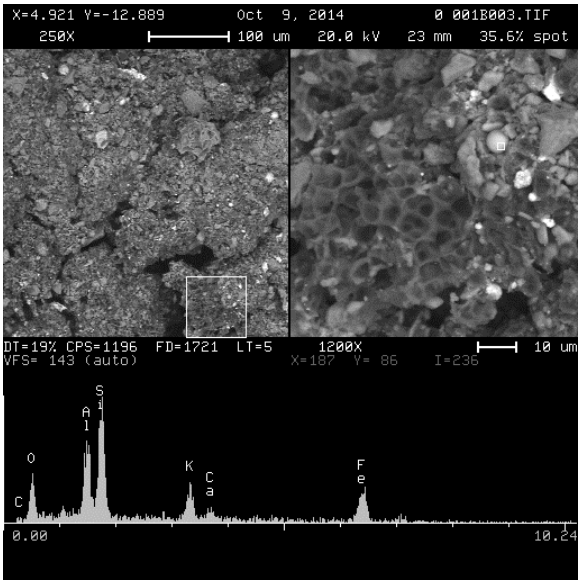


Figure 4

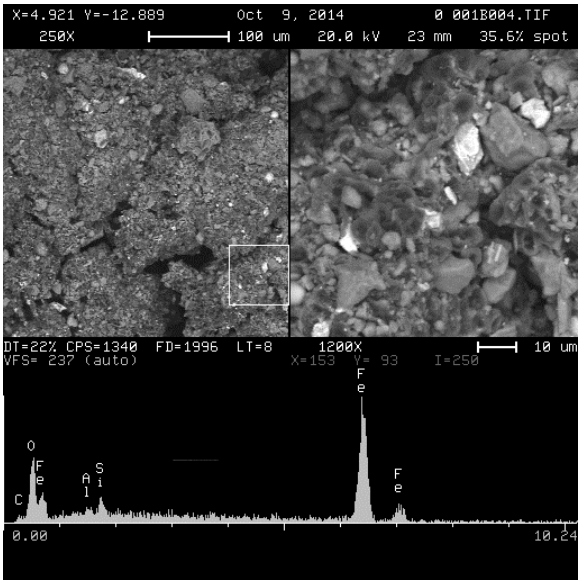


Figure 5

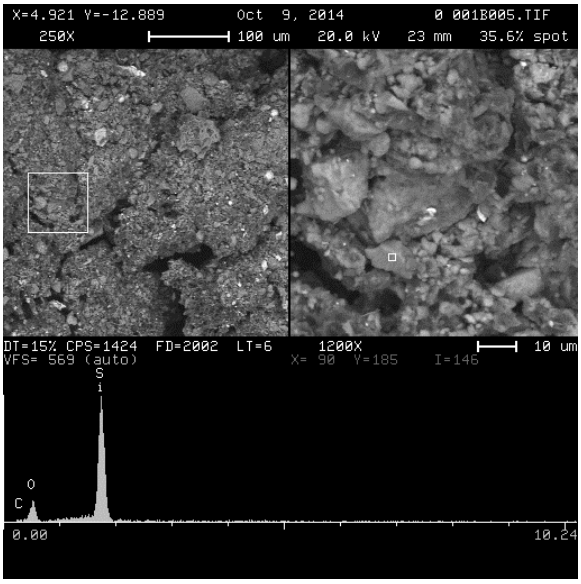


Figure 6

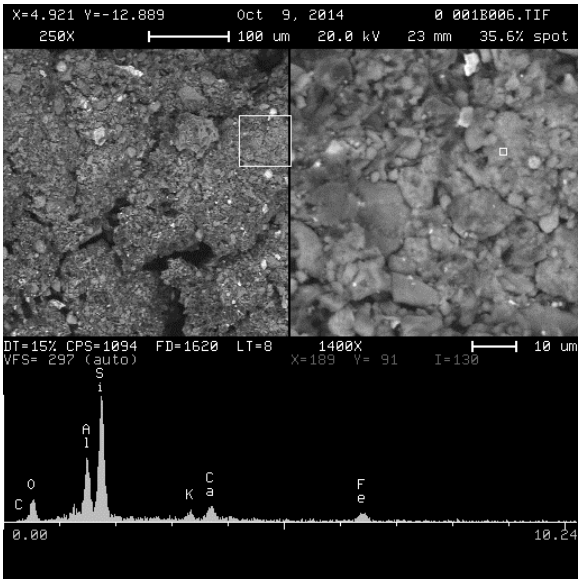


Figure 7

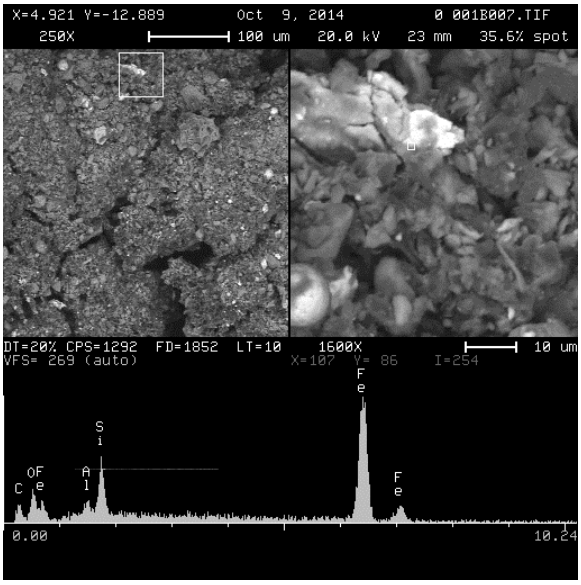


Figure 8

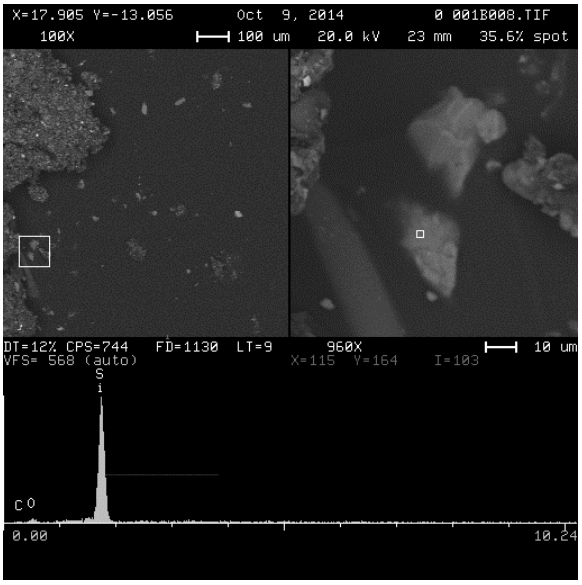


Figure 9

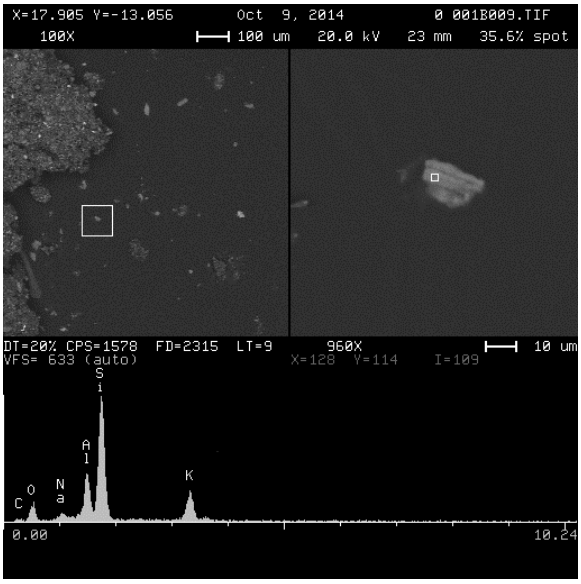


Figure 10

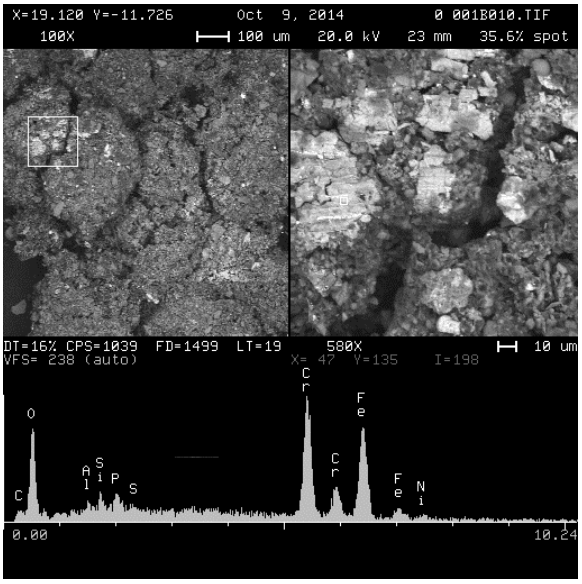


Figure 11

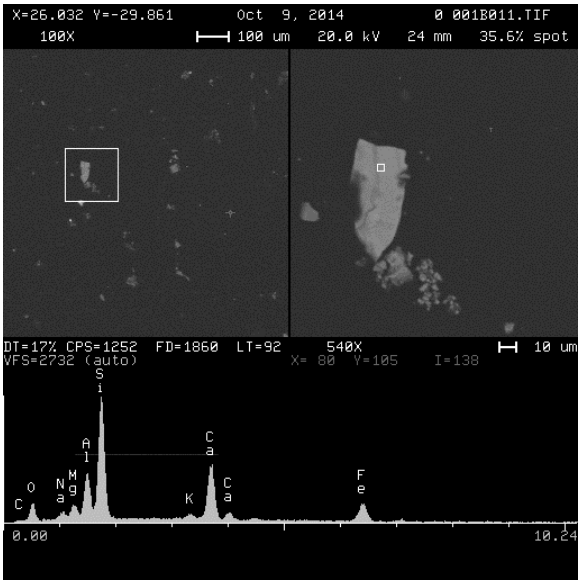


Figure 12

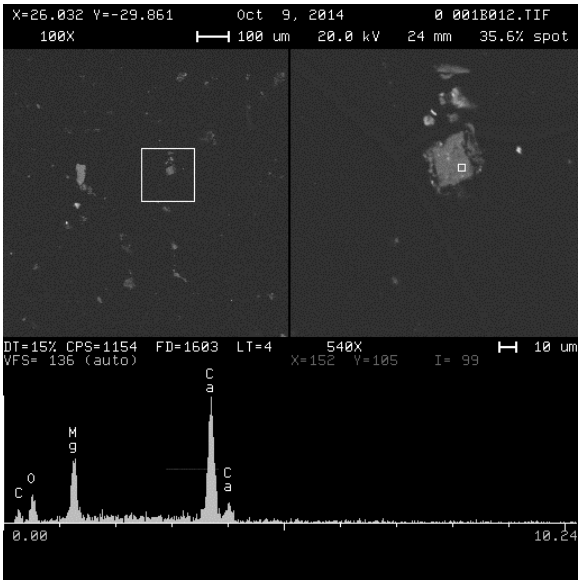


Figure 13

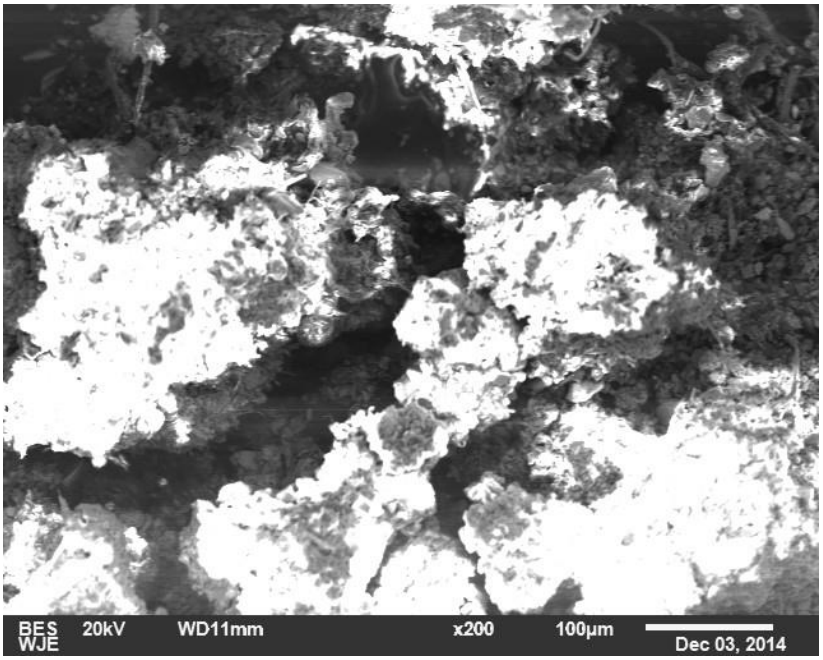


Figure 14

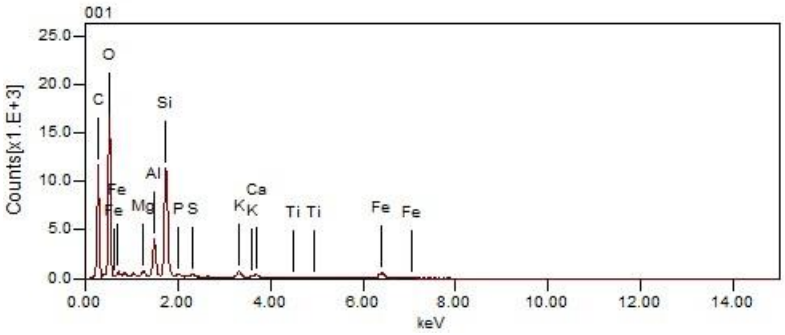


Figure 15. EDS spectra

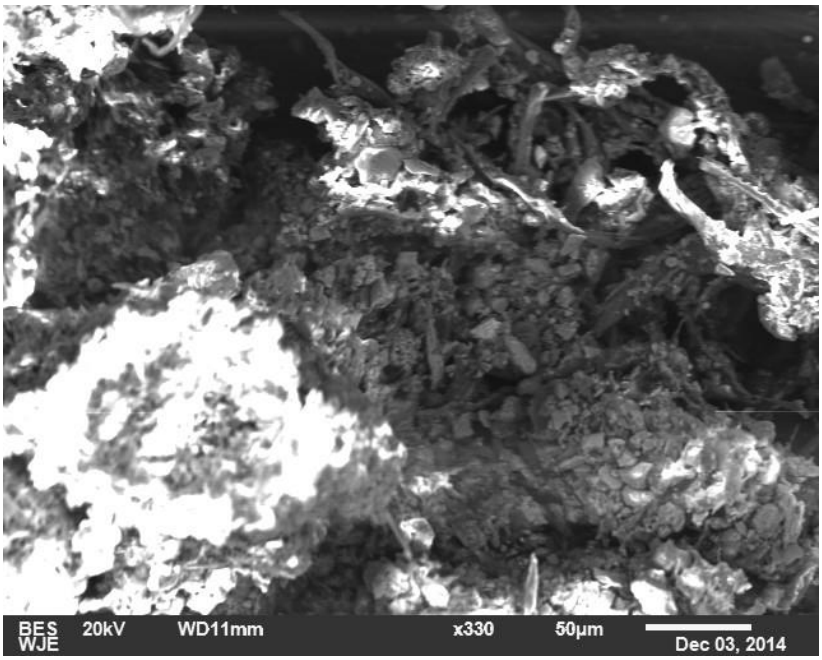


Figure 16

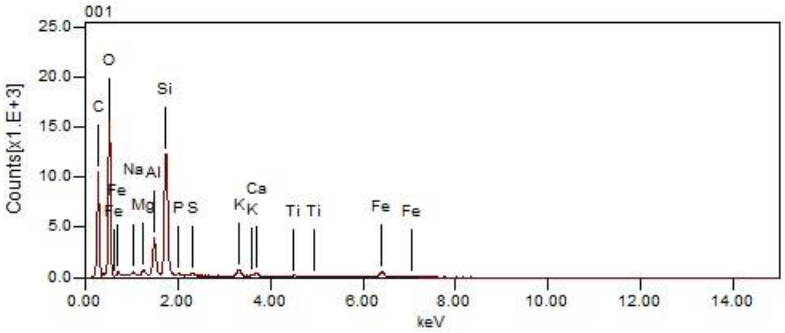


Figure 17. EDS spectra

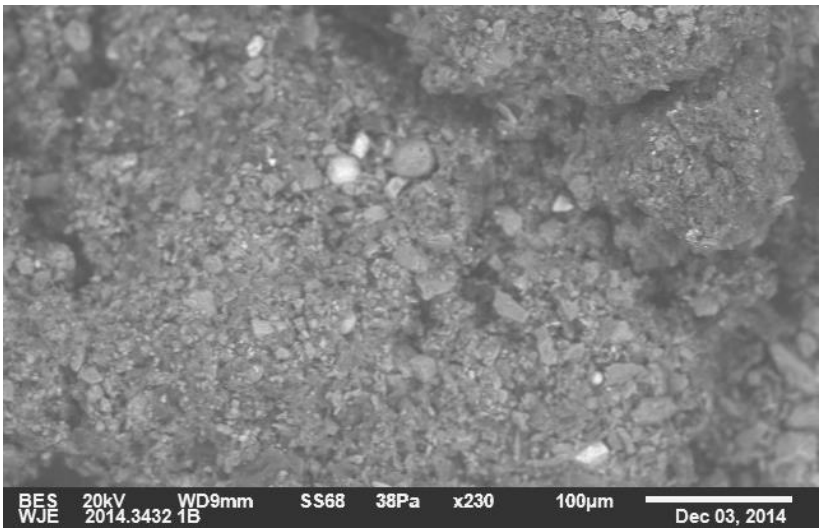


Figure 18

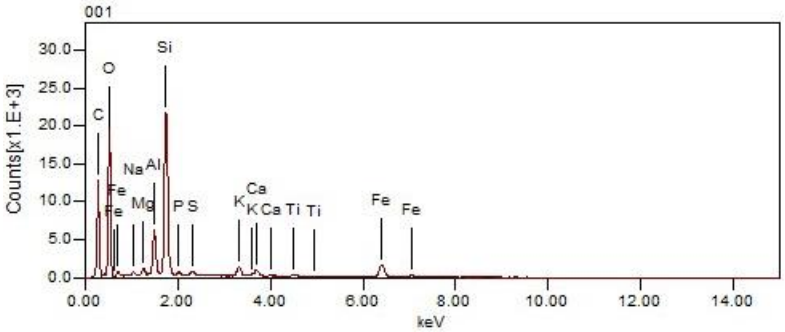


Figure 19. EDS spectra

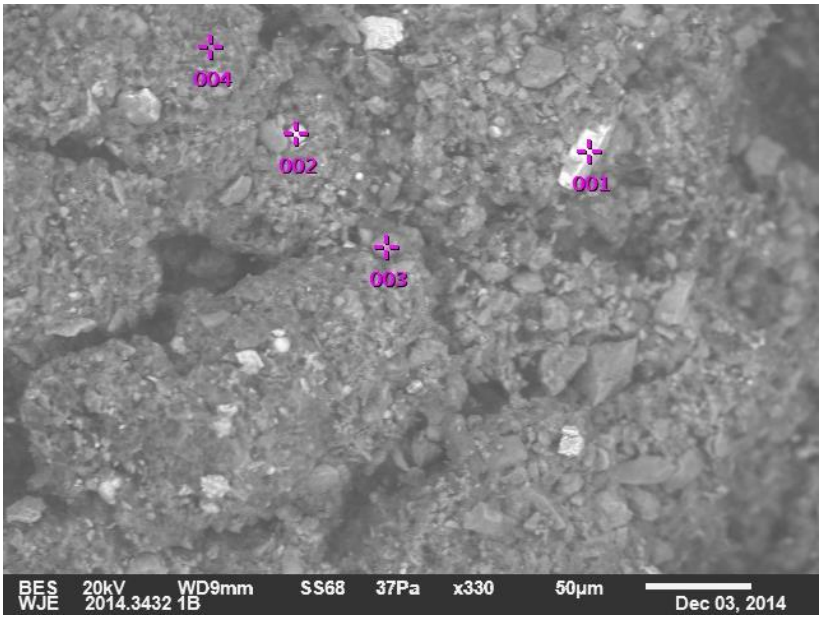


Figure 20

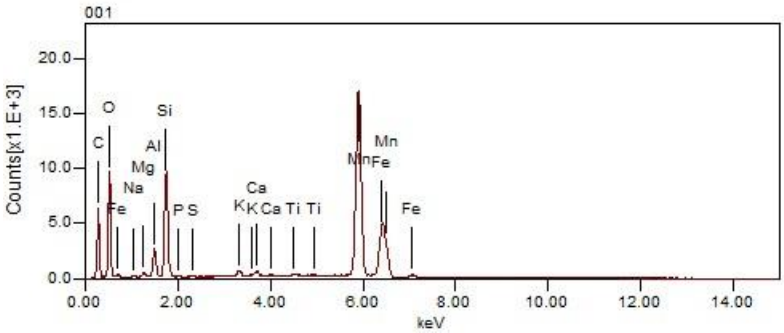


Figure 21. EDS spectra location 1

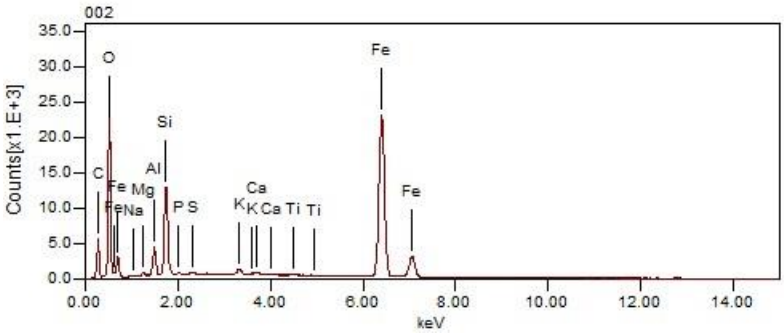


Figure 22. EDS spectra location 2

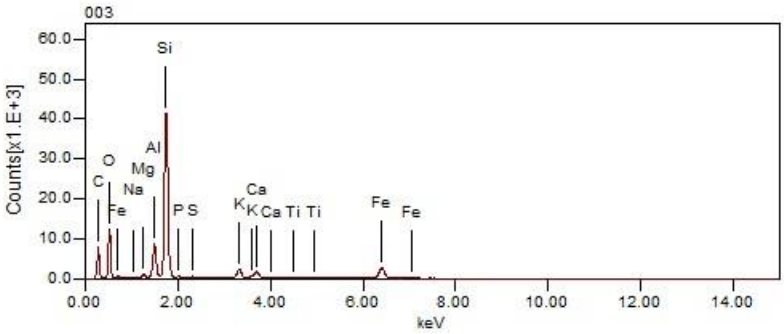


Figure 23. EDS spectra location 3

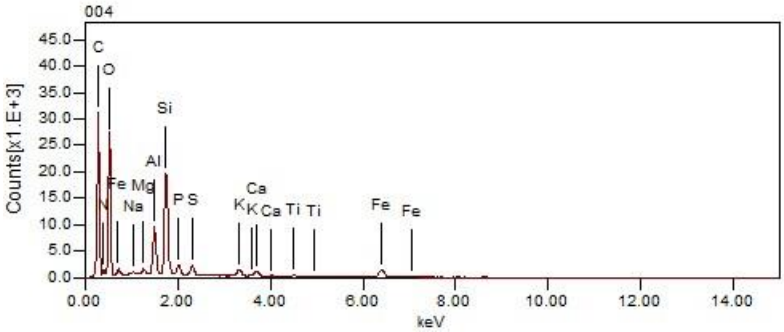


Figure 24. EDS spectra location 4

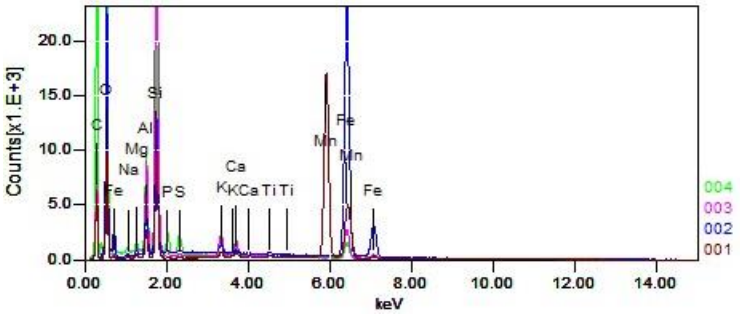


Figure 25. Composite EDS spectra

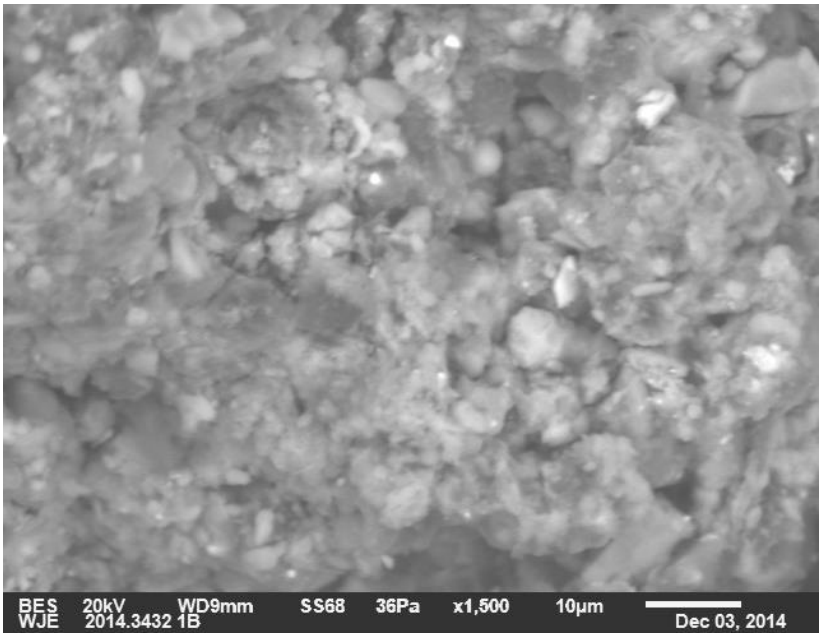


Figure 26

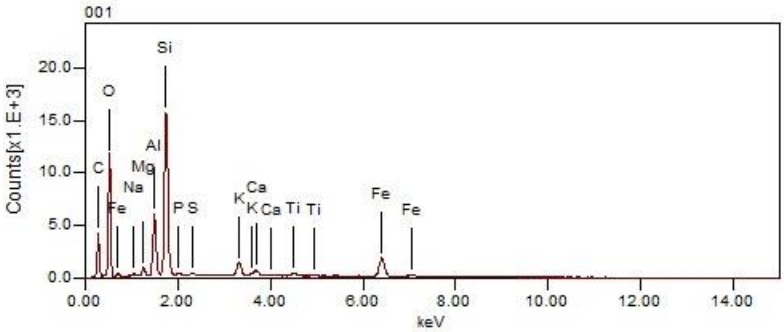


Figure 27. EDS spectra location 1

Sample 2B

Figure 28

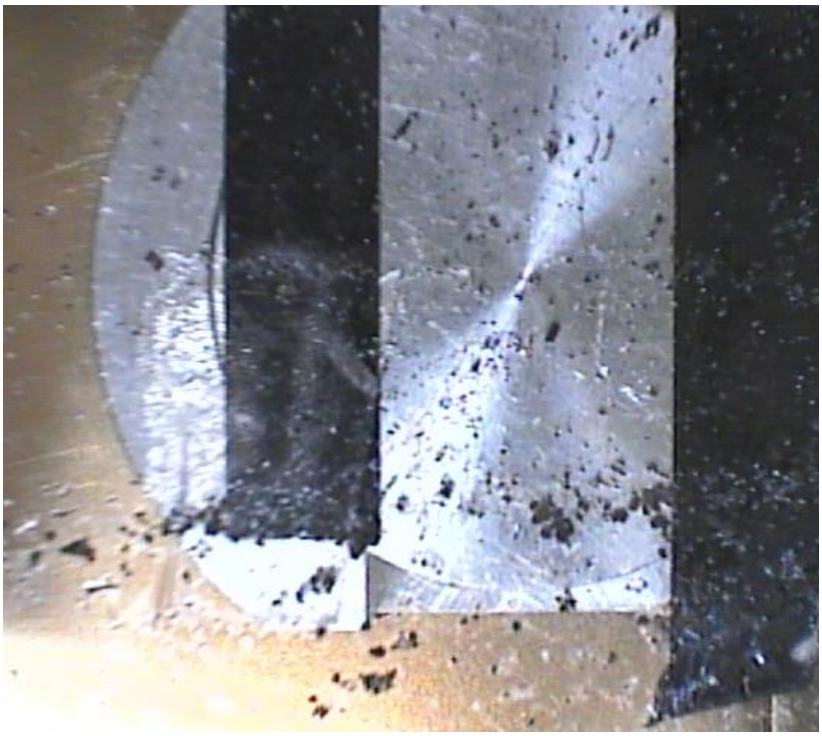


Figure 29

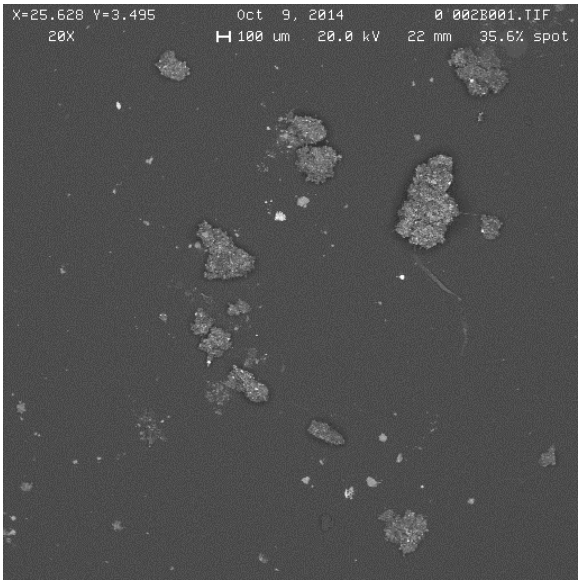


Figure 30

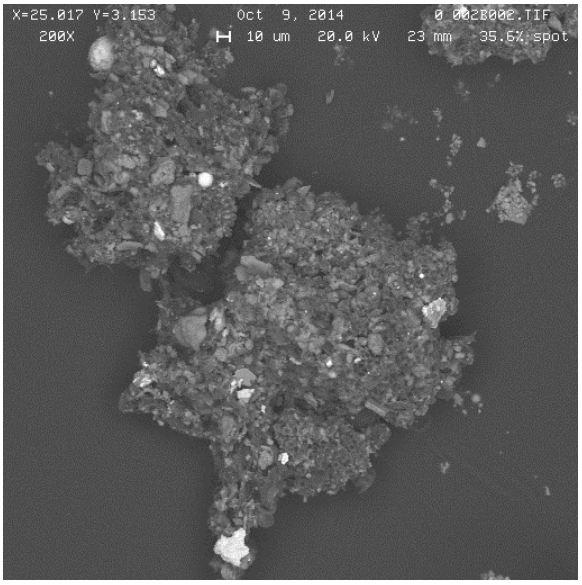


Figure 31

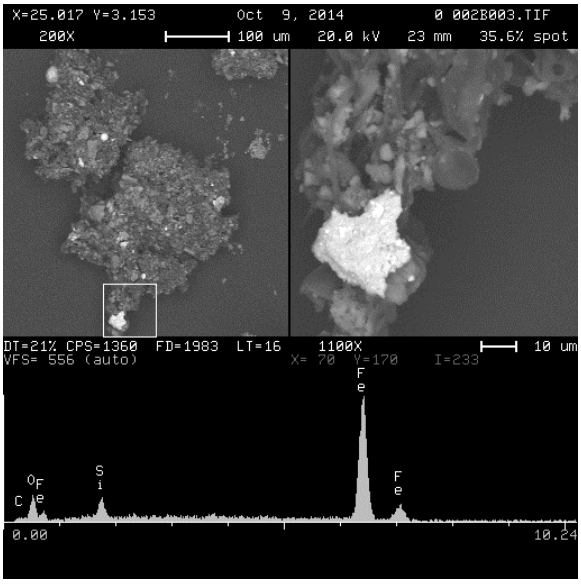


Figure 32

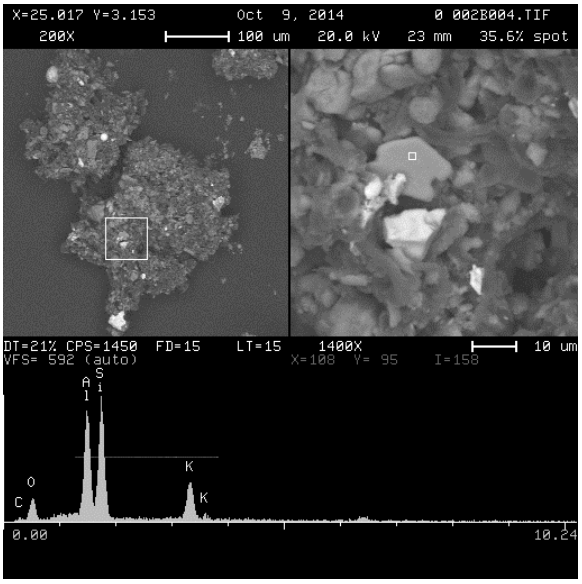


Figure 33

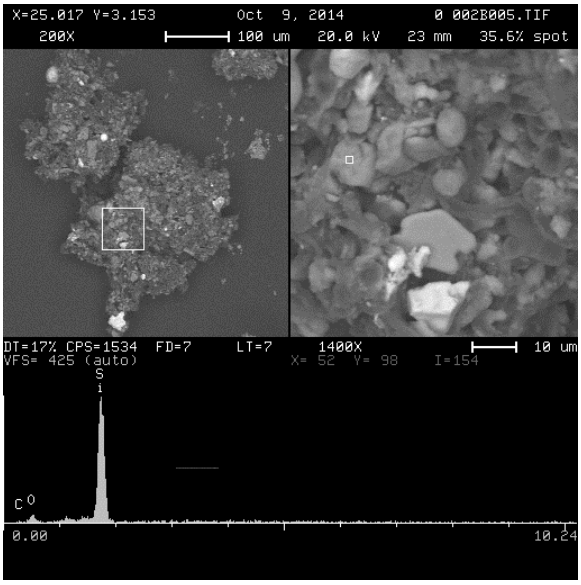


Figure 34

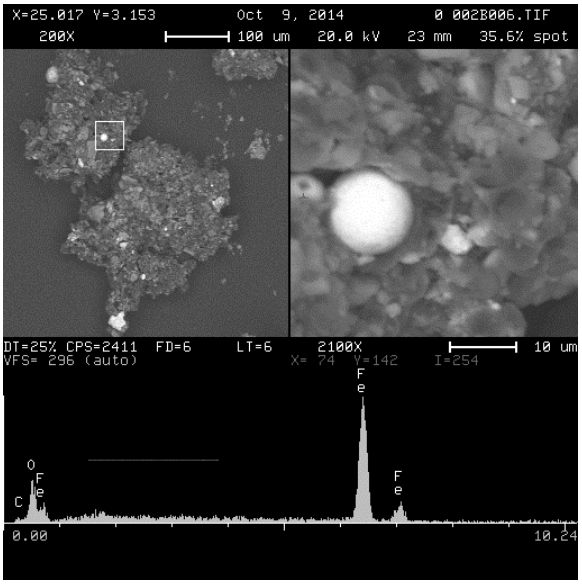


Figure 35

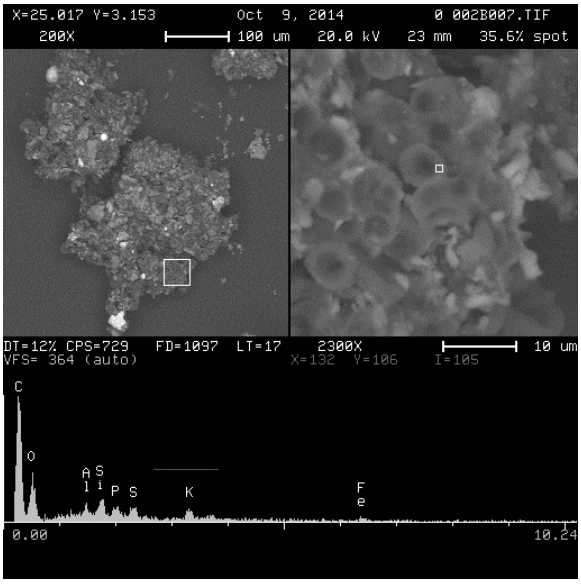


Figure 36

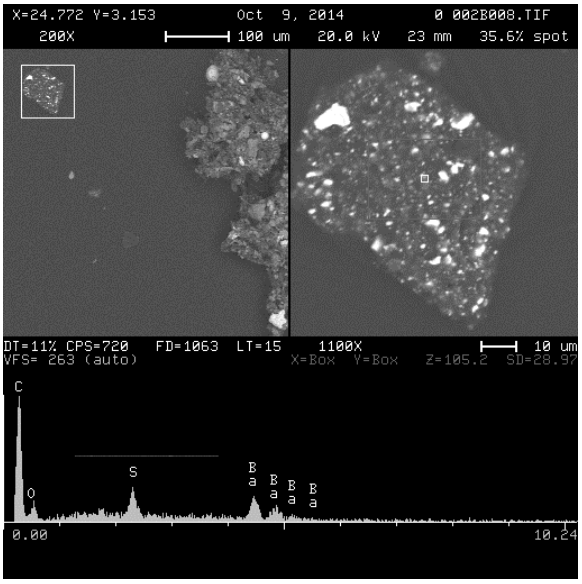


Figure 37

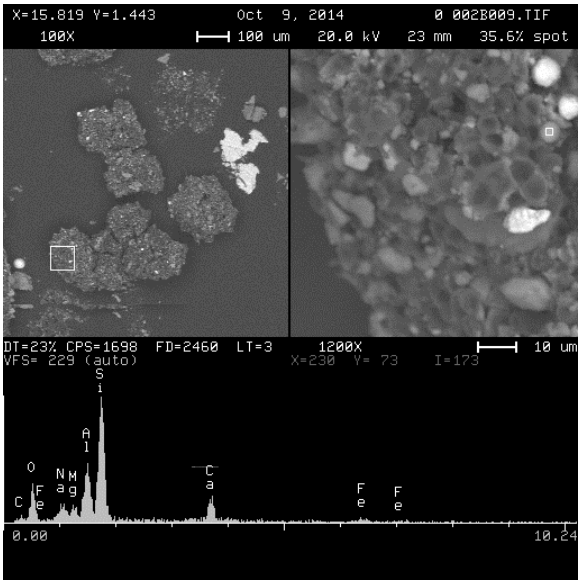


Figure 38

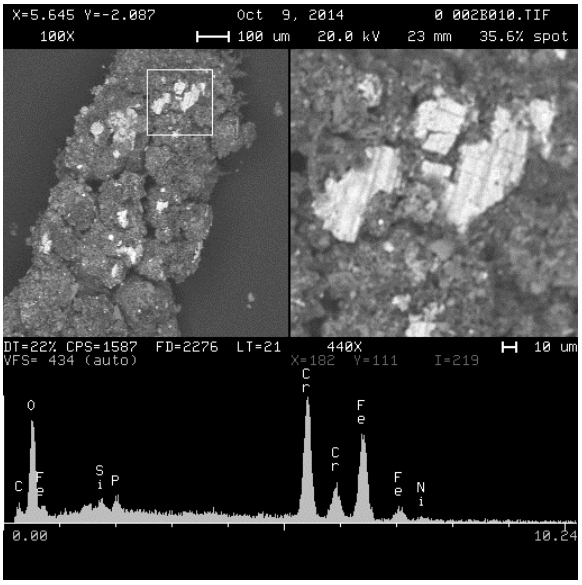


Figure 39

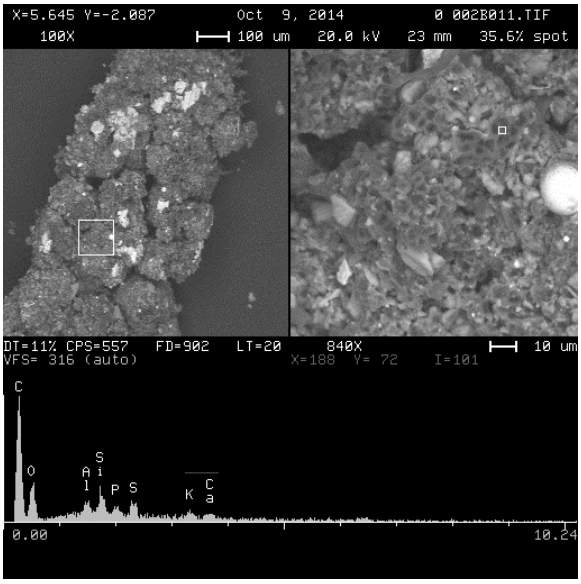


Figure 40

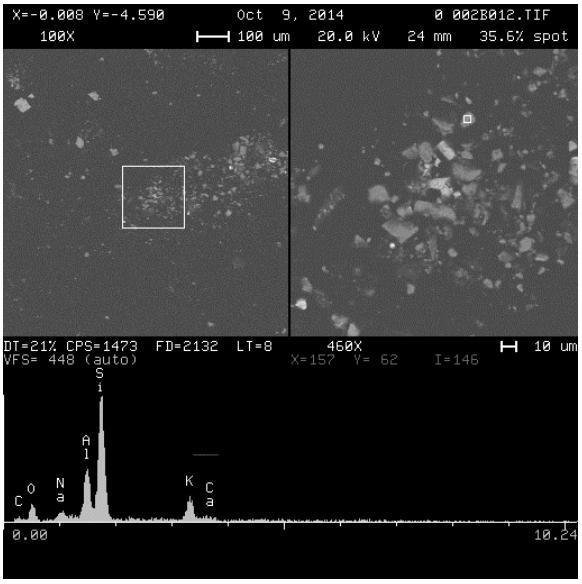


Figure 41

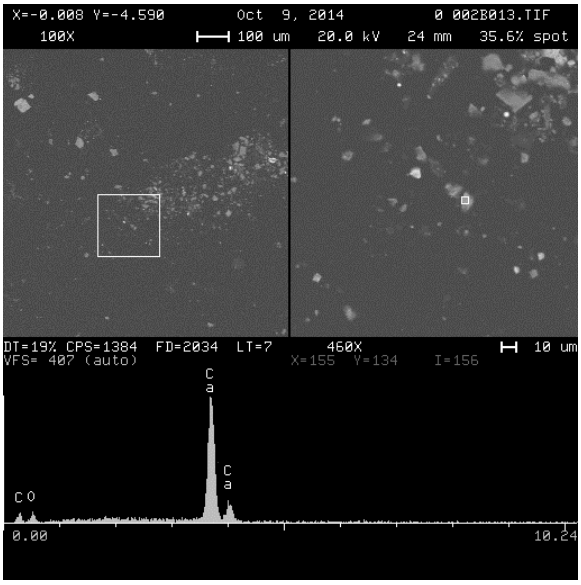


Figure 42

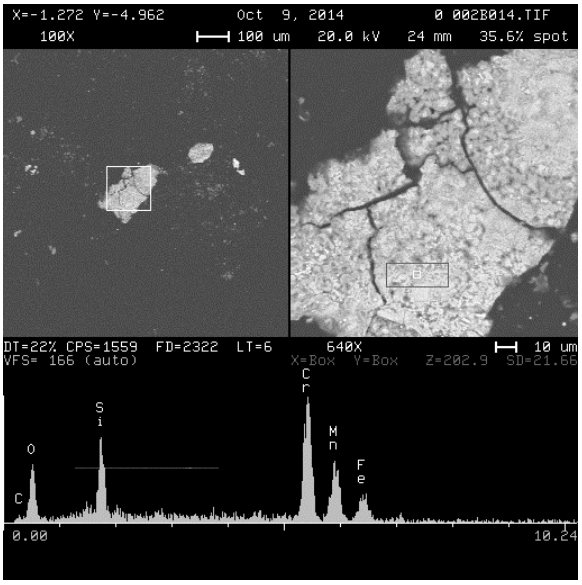


Figure 43

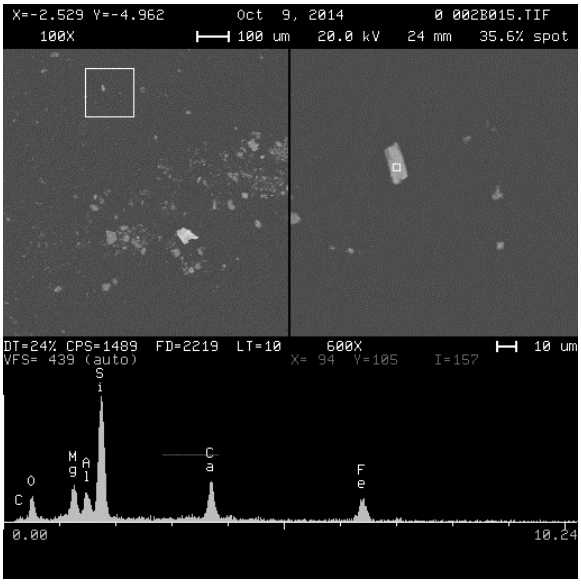


Figure 44

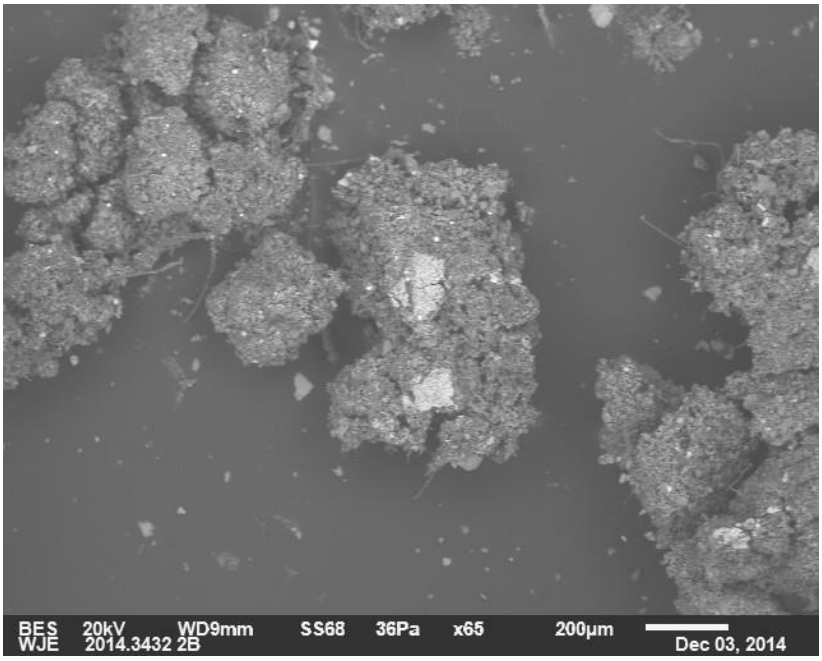


Figure 45

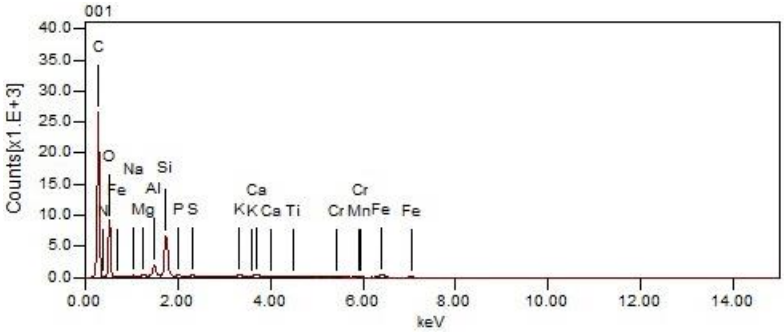


Figure 46. EDS spectra

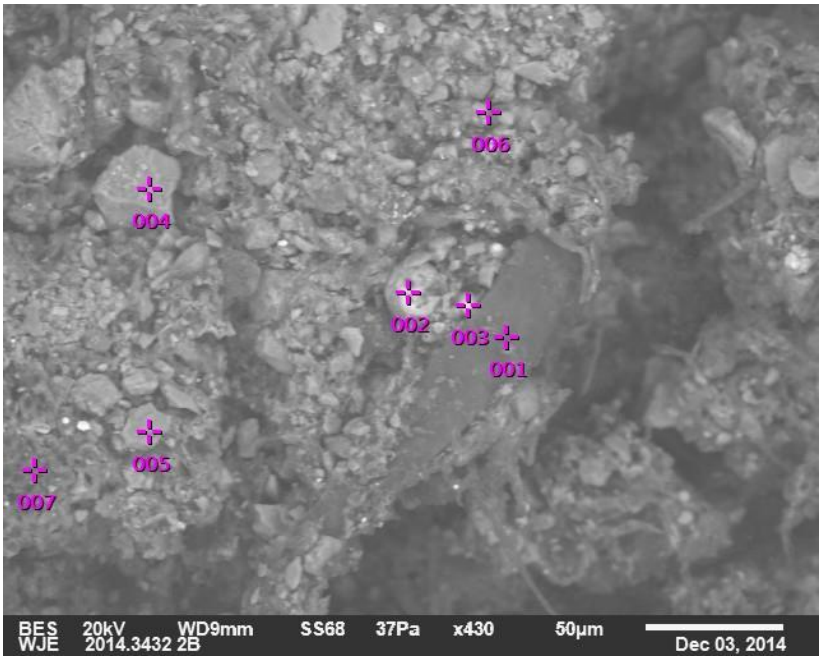


Figure 47

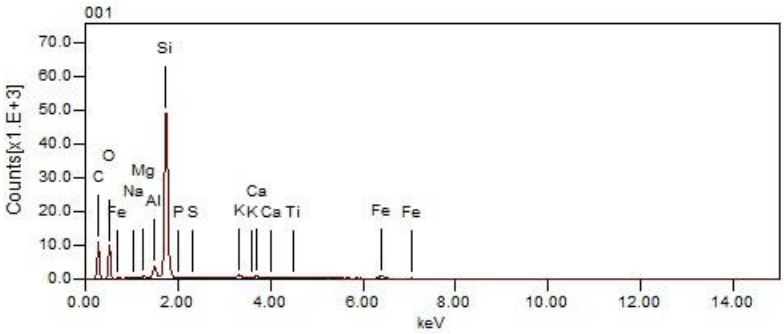


Figure 48. EDS spectra location 1

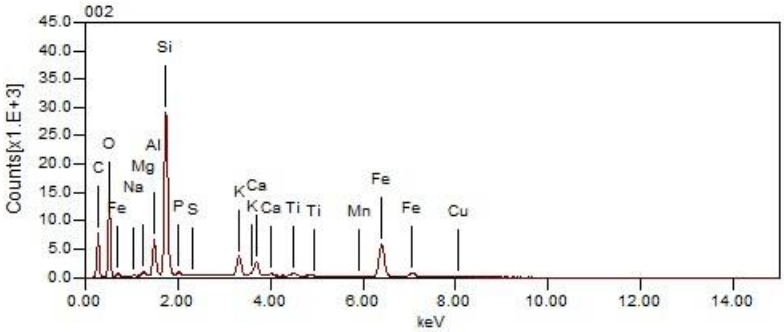


Figure 49. EDS spectra location 2

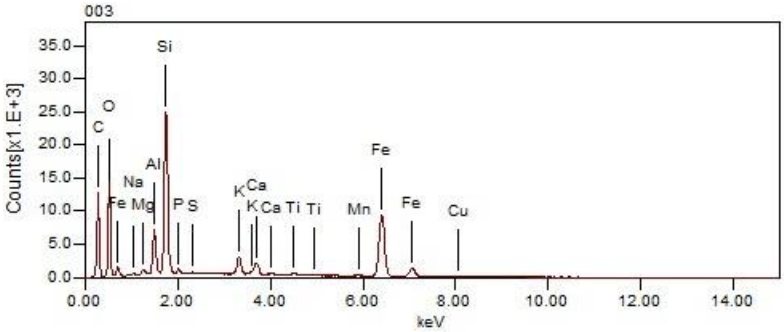


Figure 50. EDS spectra location 3

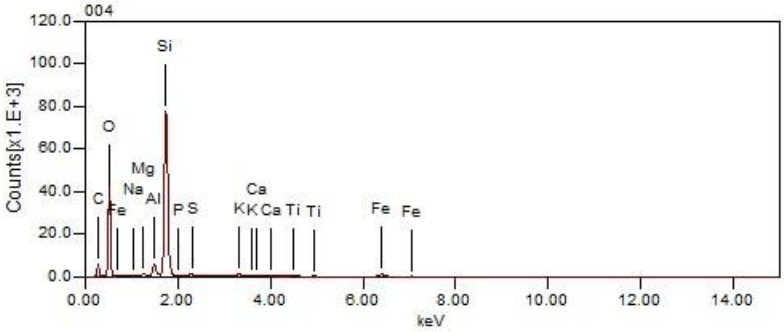


Figure 51. EDS spectra location 4

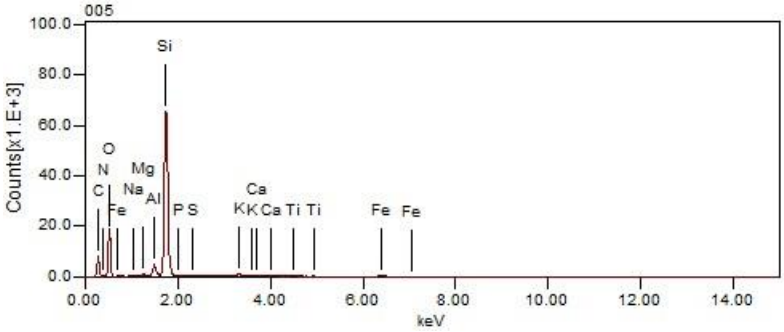


Figure 52. EDS spectra location 5

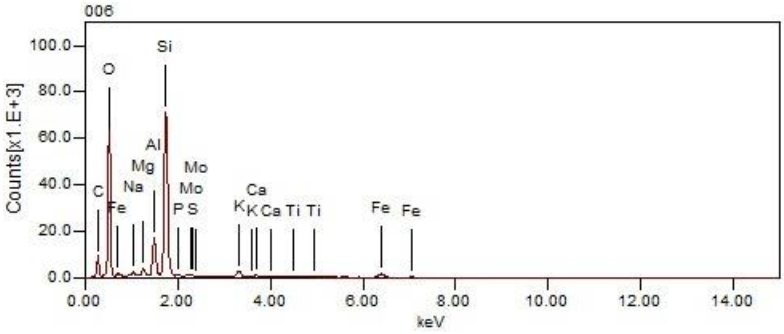


Figure 53. EDS spectra location 6

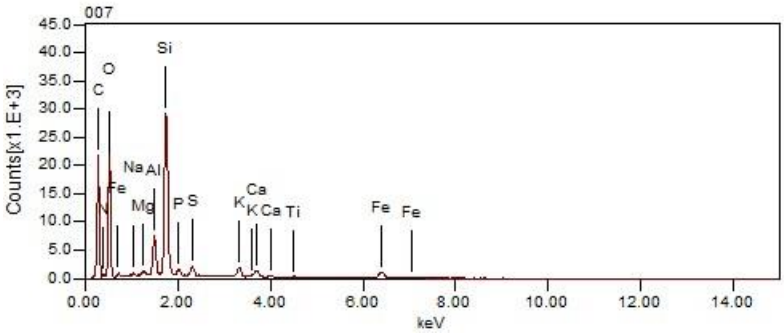


Figure 54. EDS spectra location 7

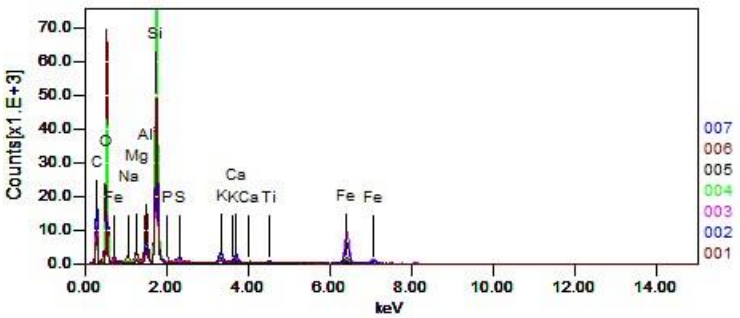


Figure 55. Composite EDS spectra

Sample 3B

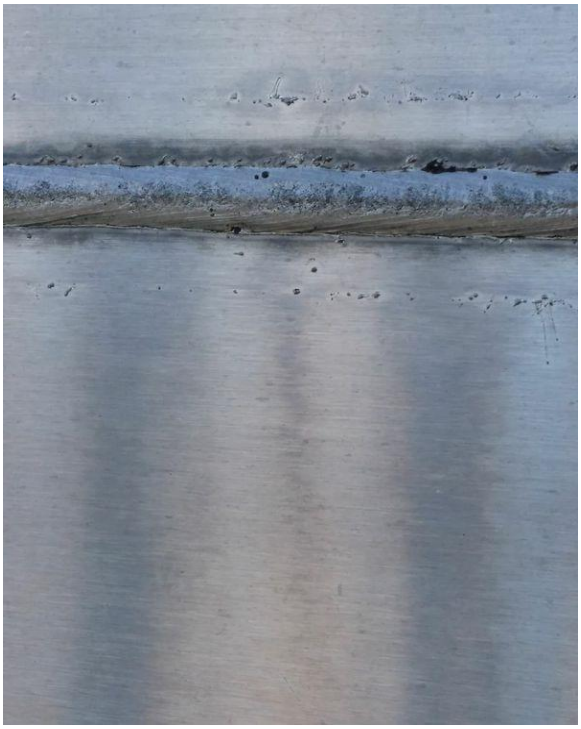


Figure 56

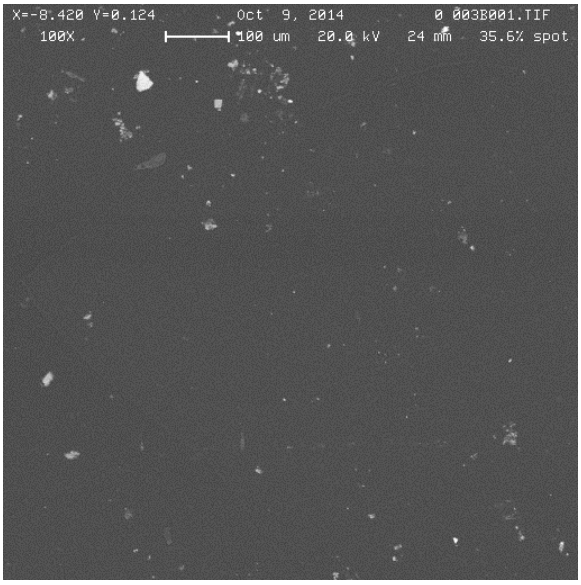


Figure 57

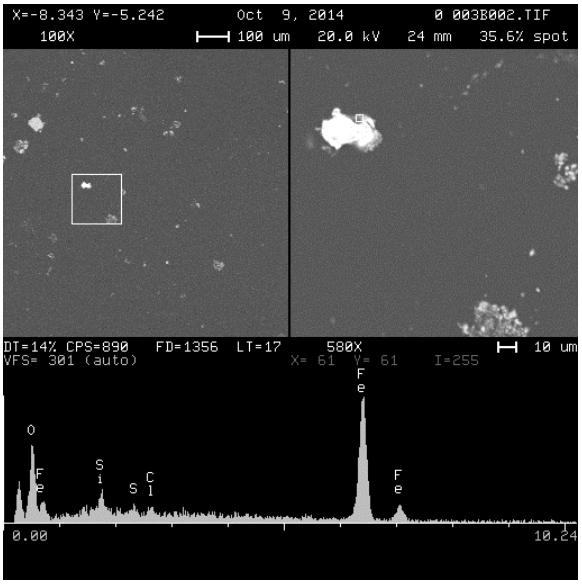


Figure 58

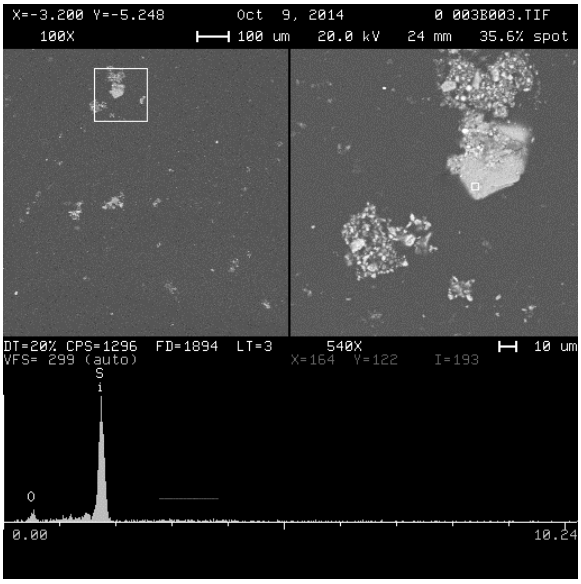


Figure 59

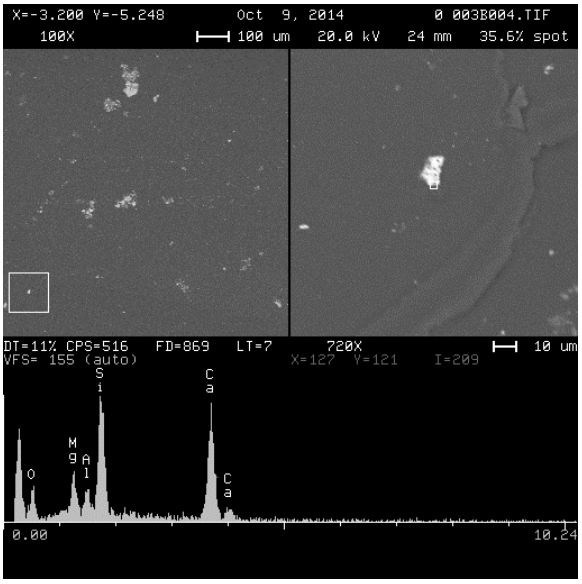


Figure 60

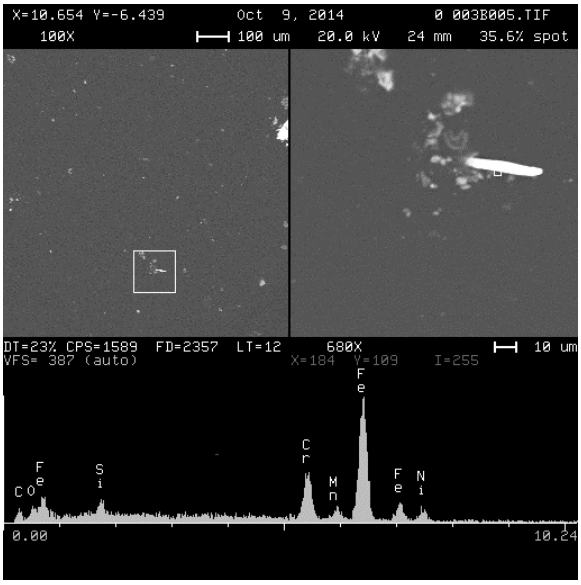


Figure 61

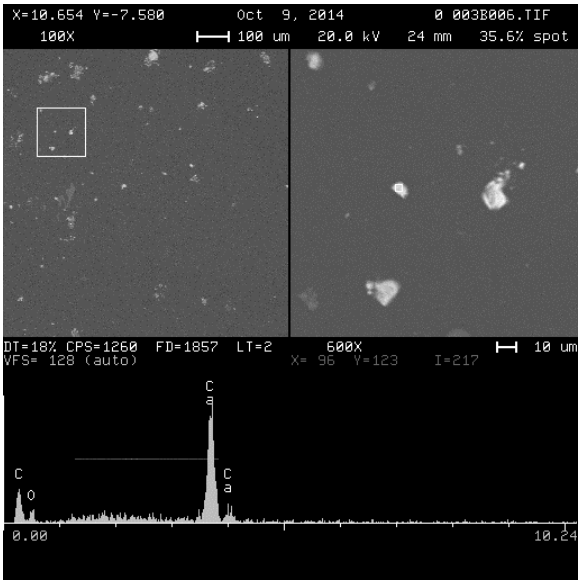


Figure 62

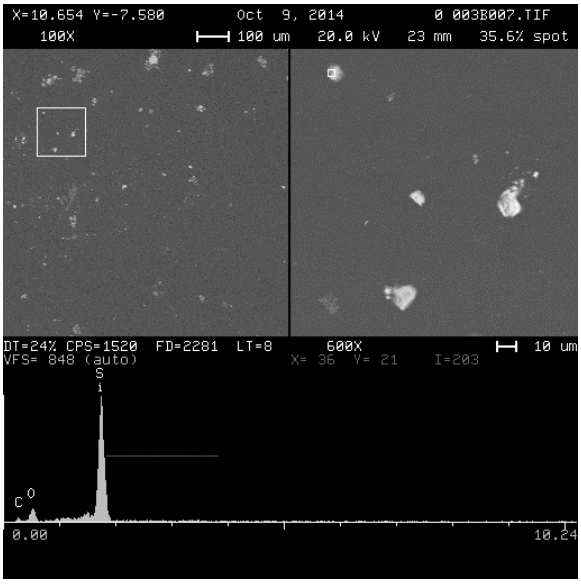


Figure 63

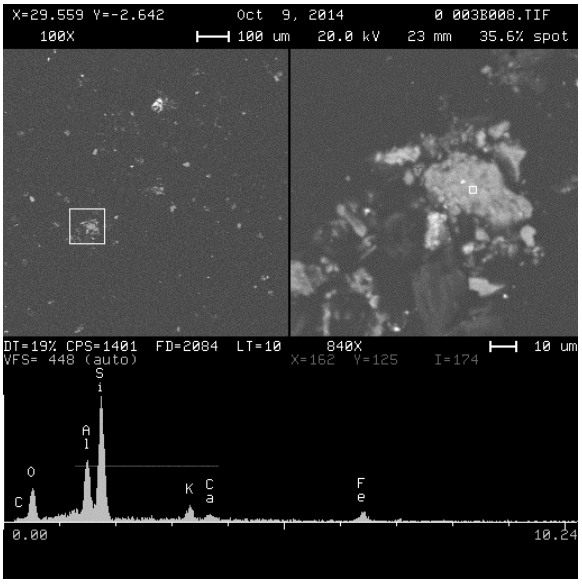


Figure 64

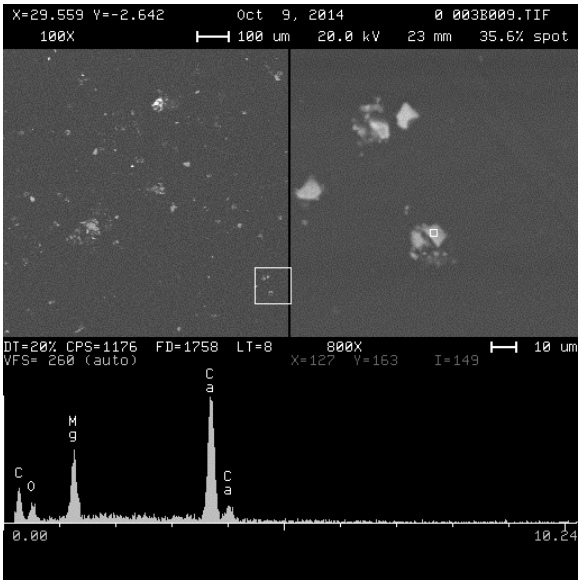


Figure 65

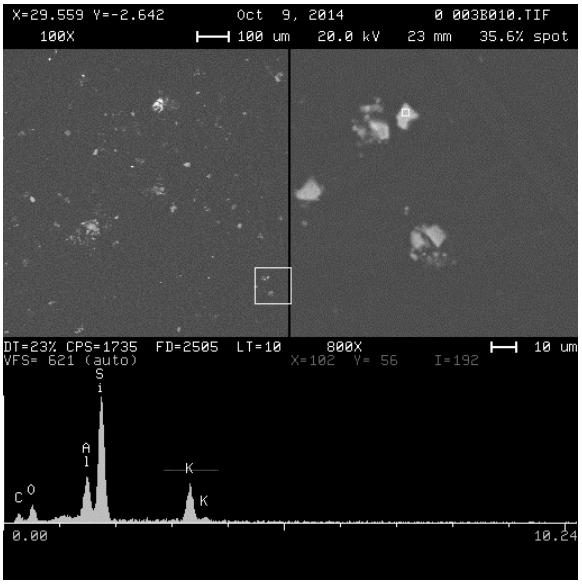


Figure 66

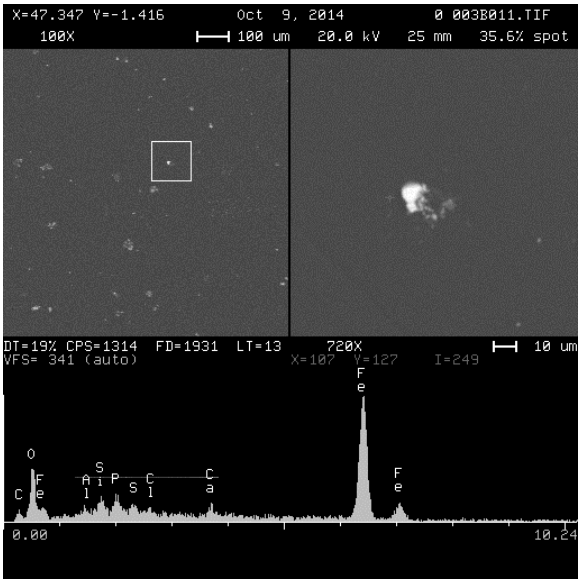


Figure 67

Sample 4B

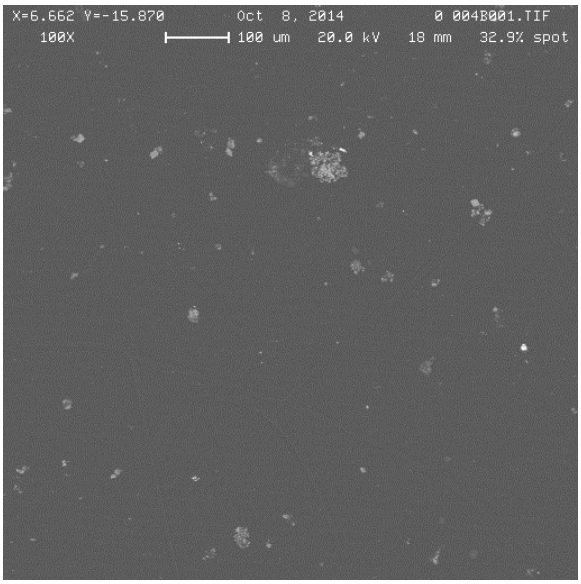


Figure 68

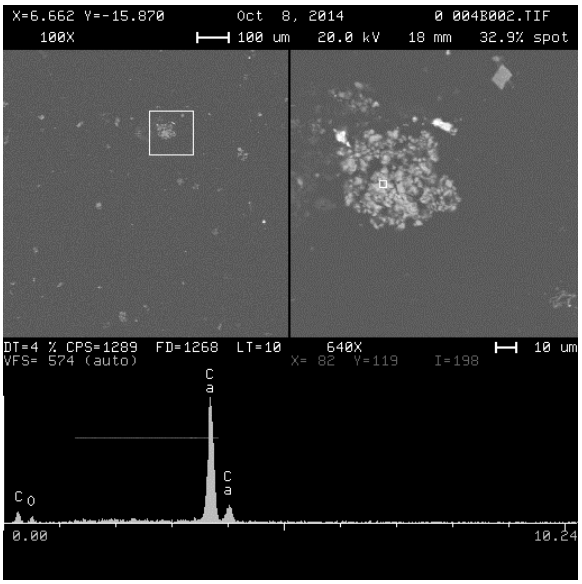


Figure 69

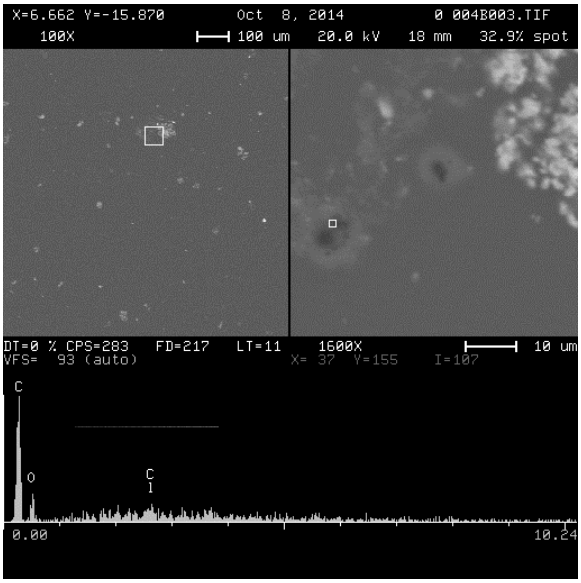


Figure 70

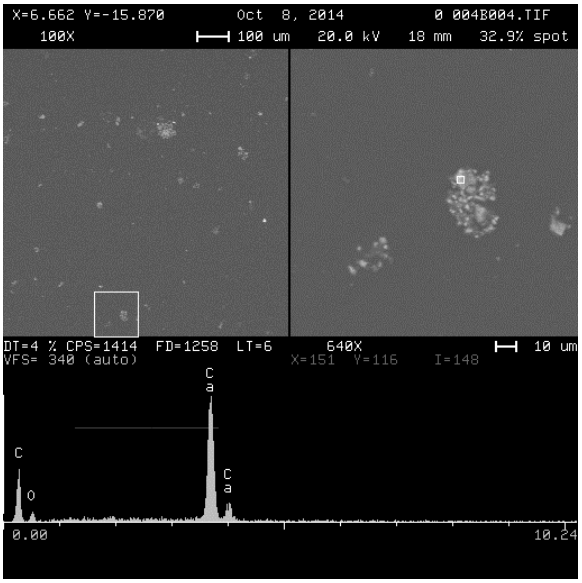


Figure 71

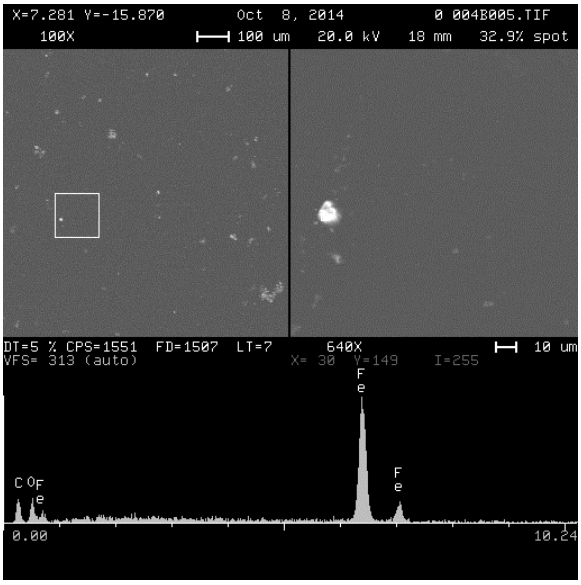


Figure 72

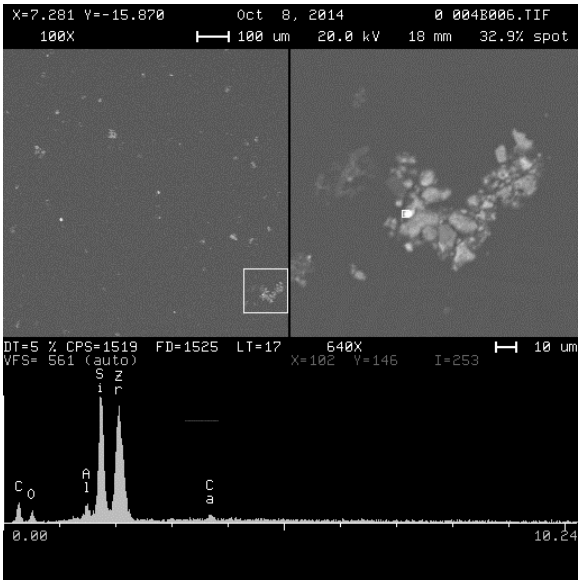


Figure 73

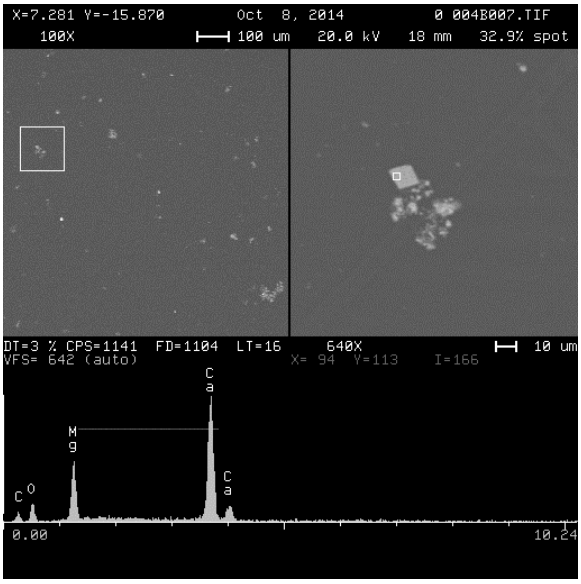


Figure 74

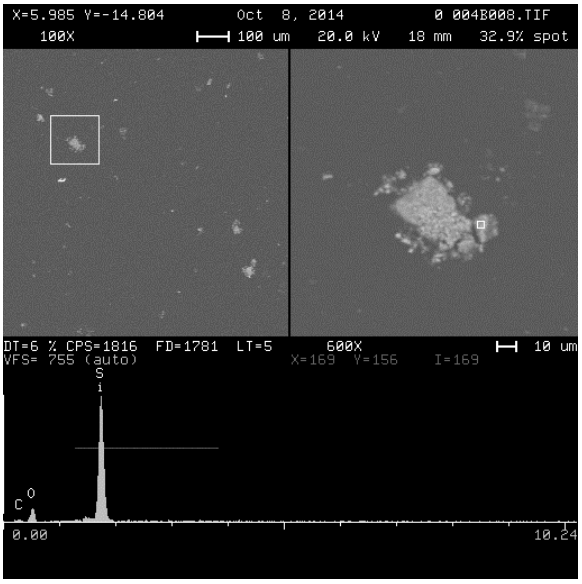


Figure 75

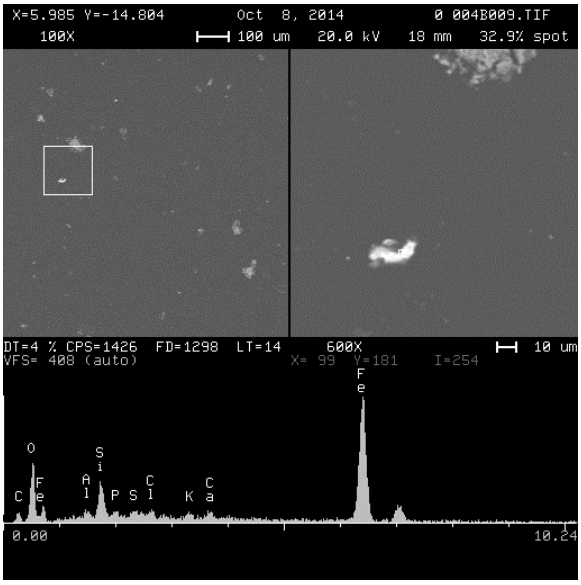


Figure 76

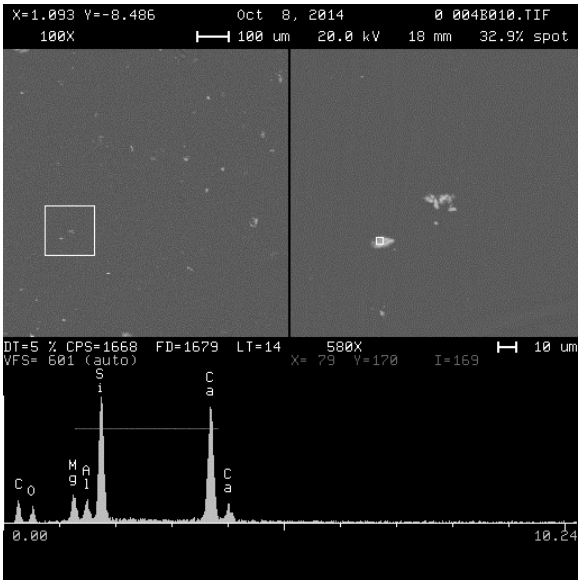


Figure 77

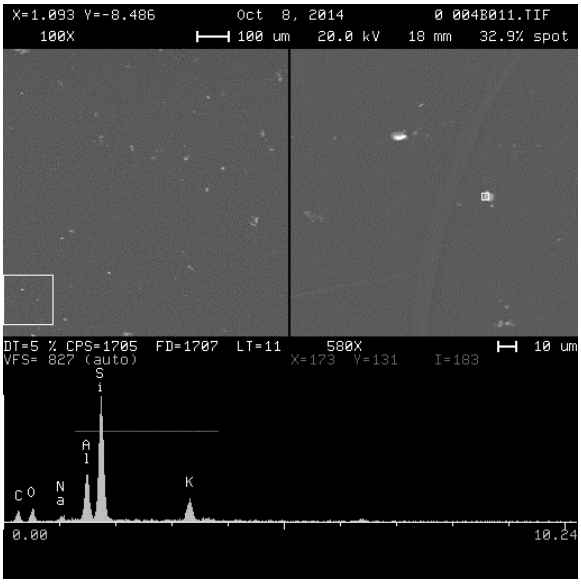


Figure 78

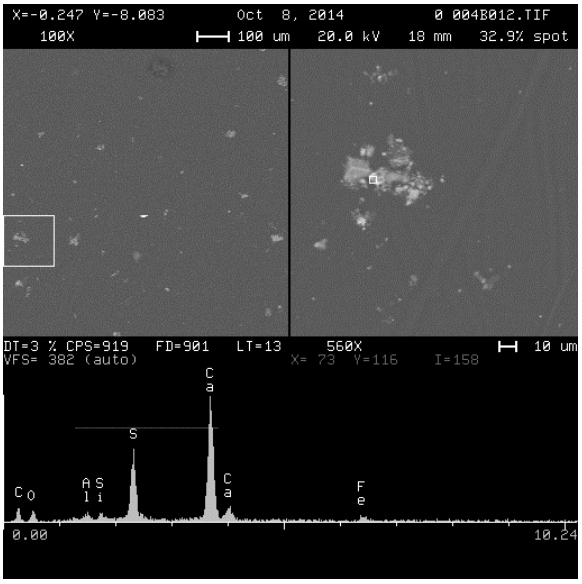


Figure 79

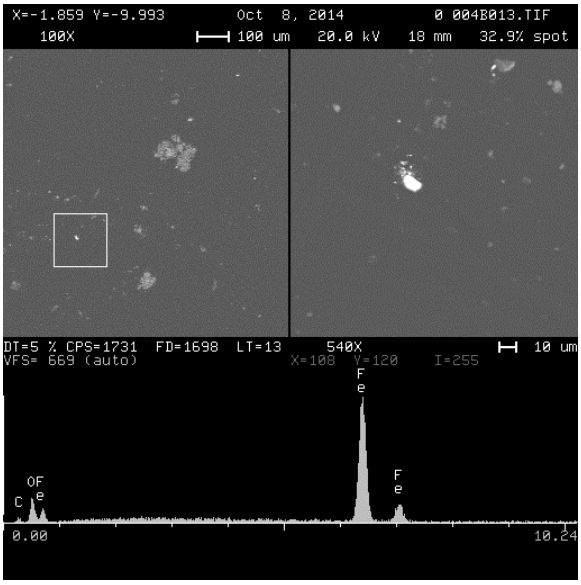


Figure 80

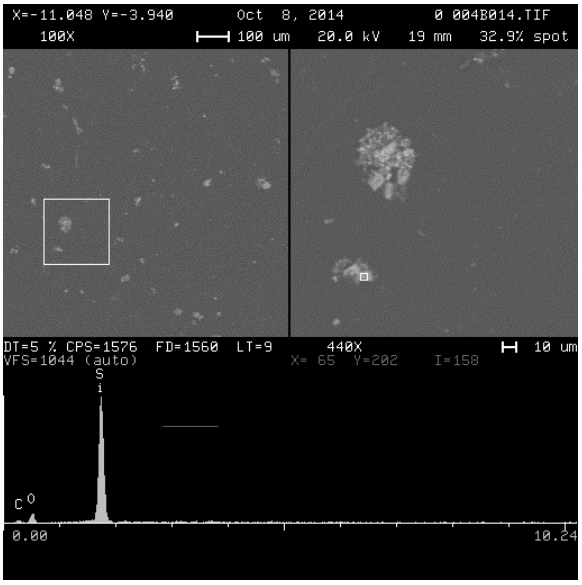


Figure 81

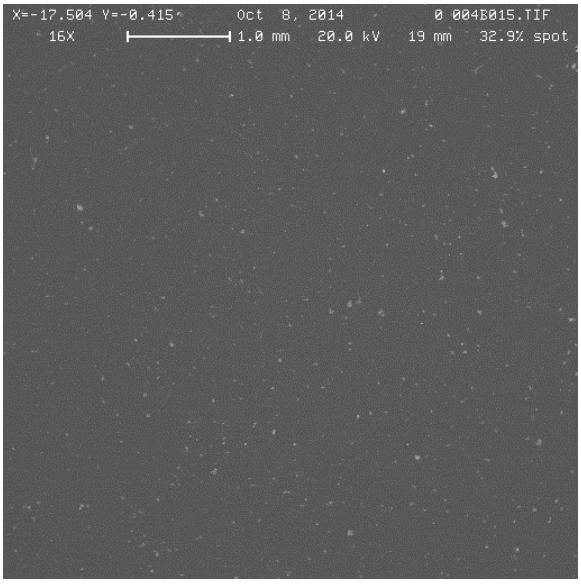


Figure 82

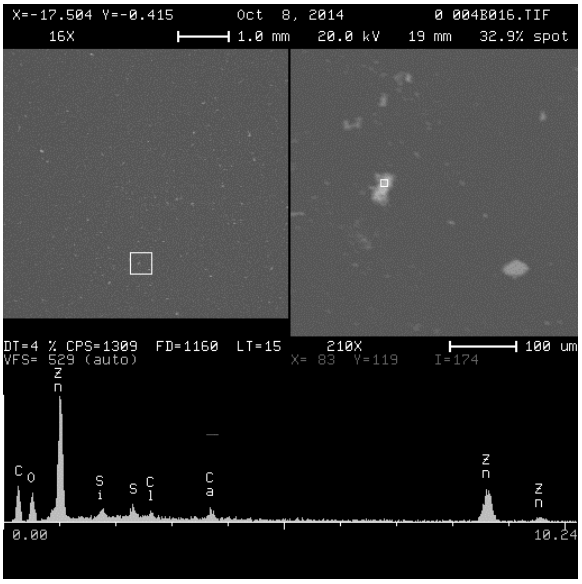


Figure 83

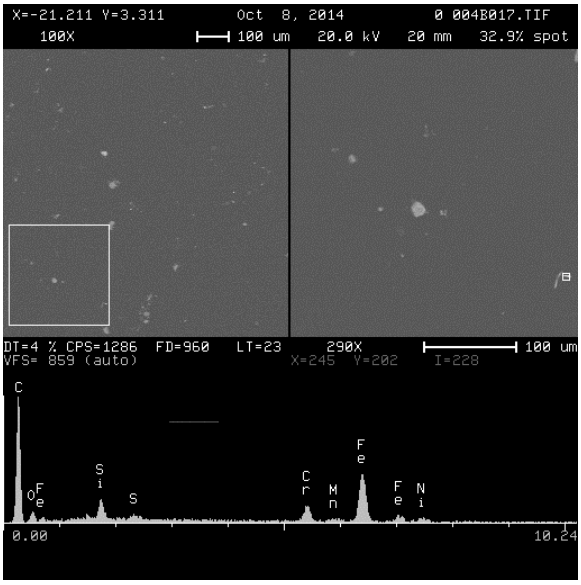


Figure 84

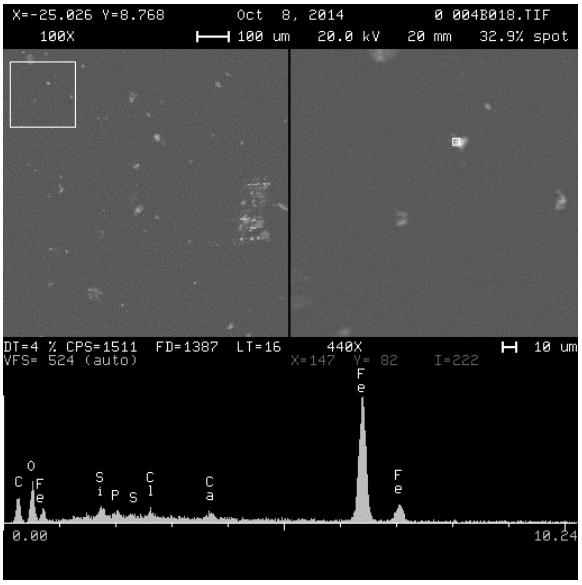


Figure 85

Sample 5B

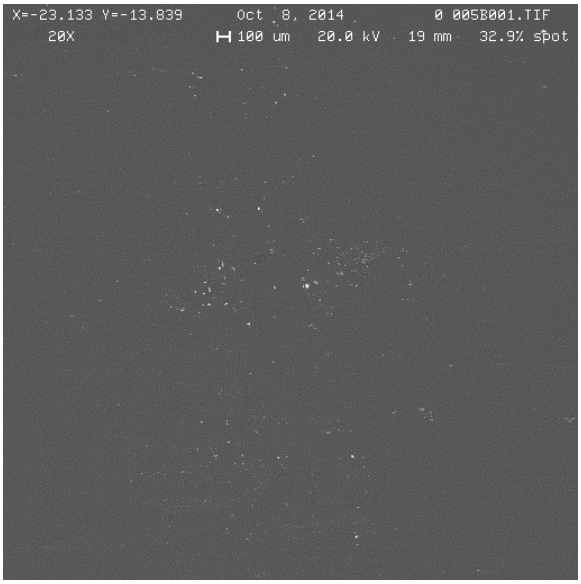
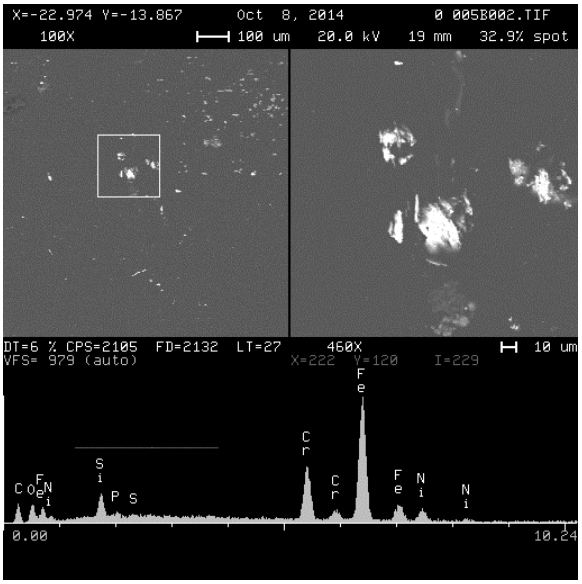


Figure 86



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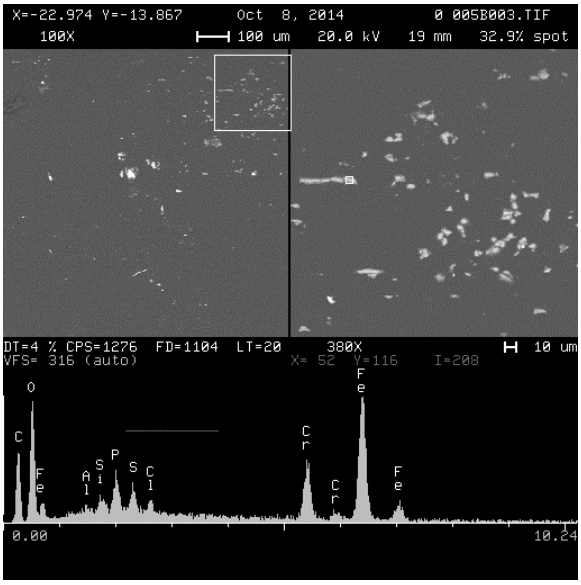

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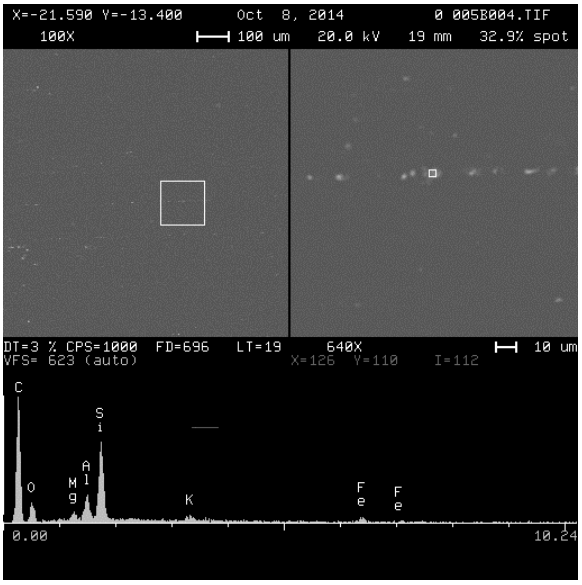

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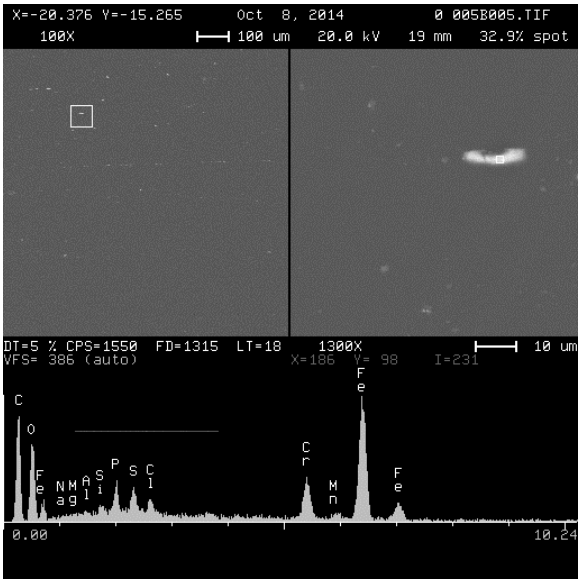

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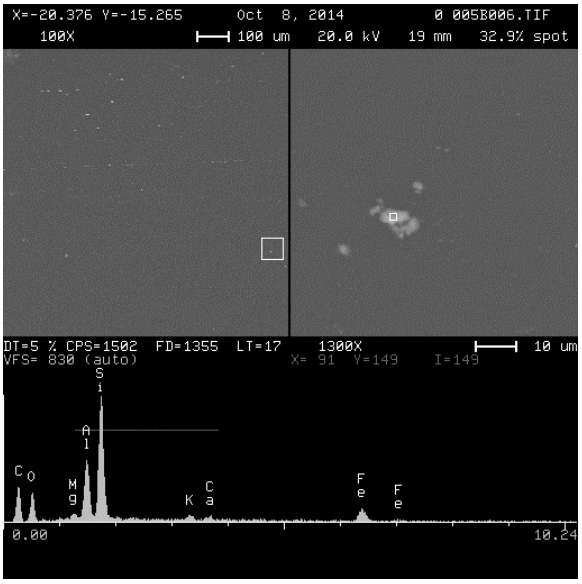

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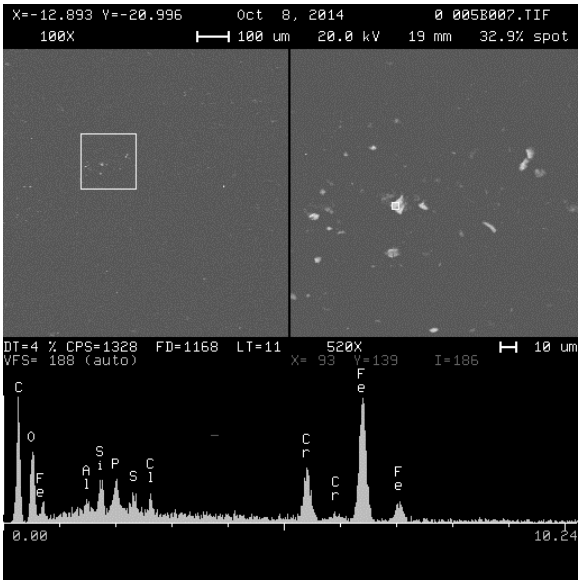

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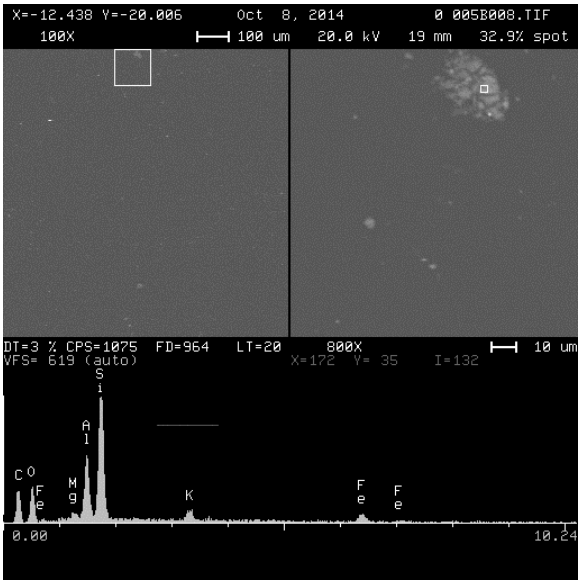

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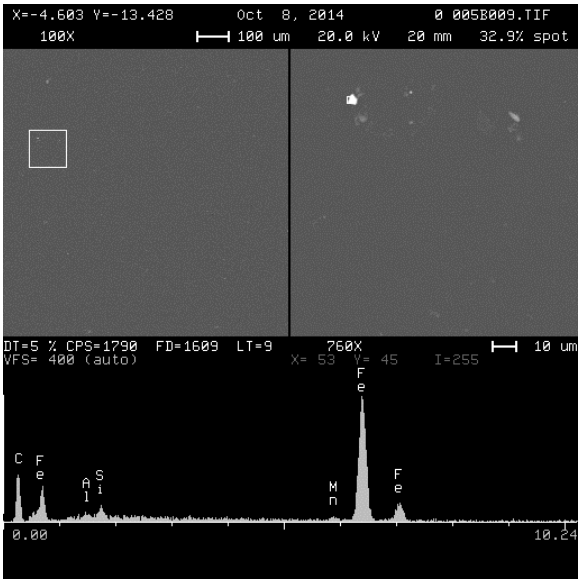
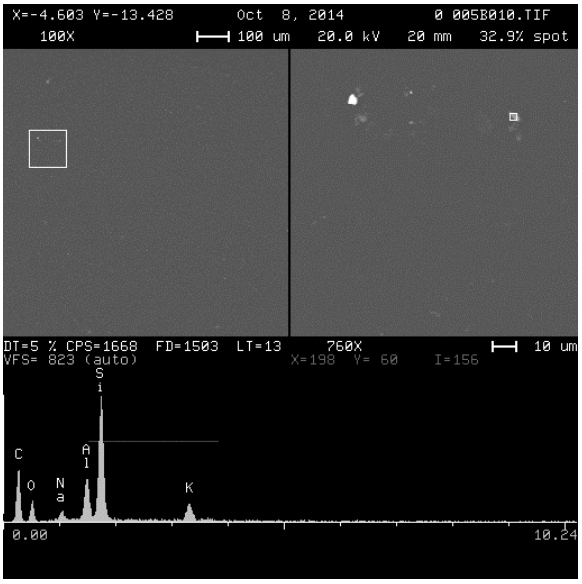


Figure 94



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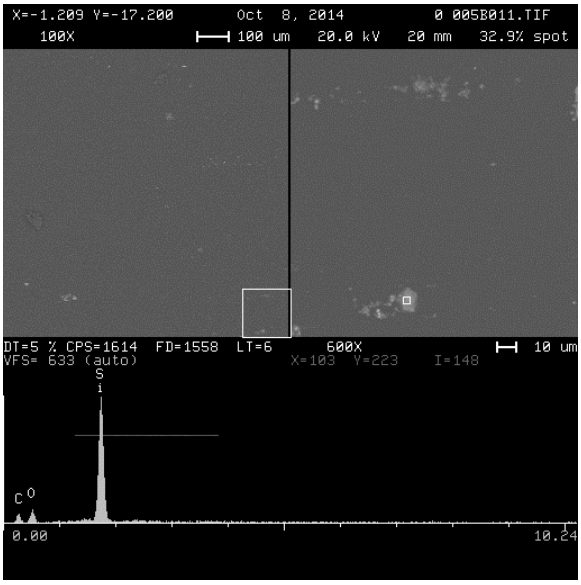

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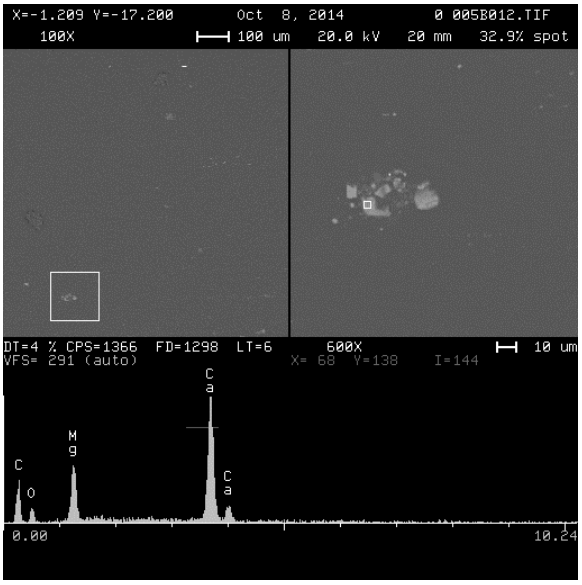

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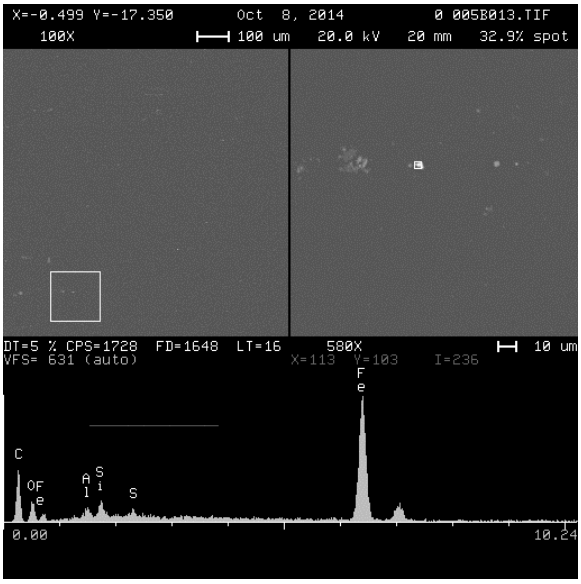

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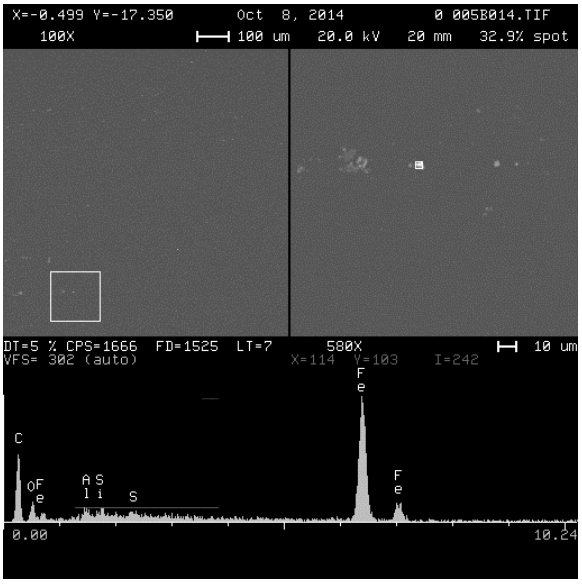

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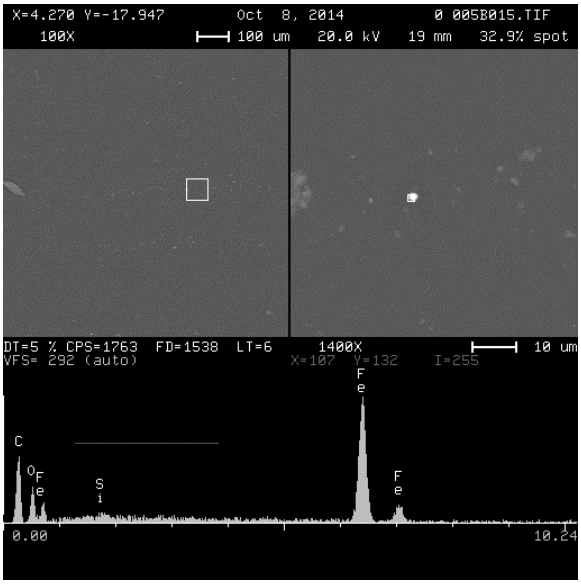

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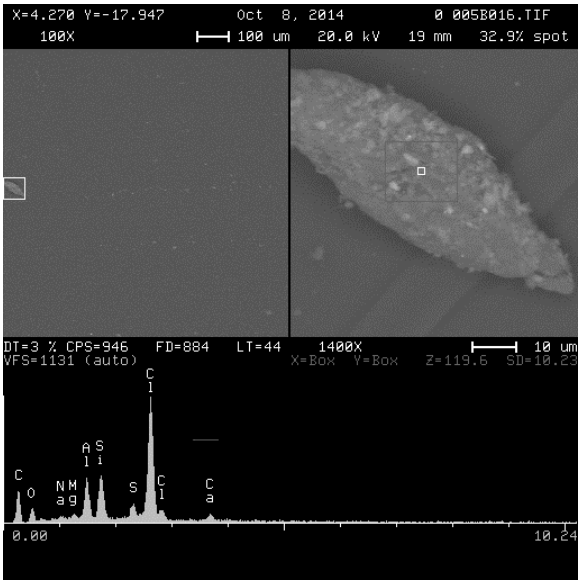
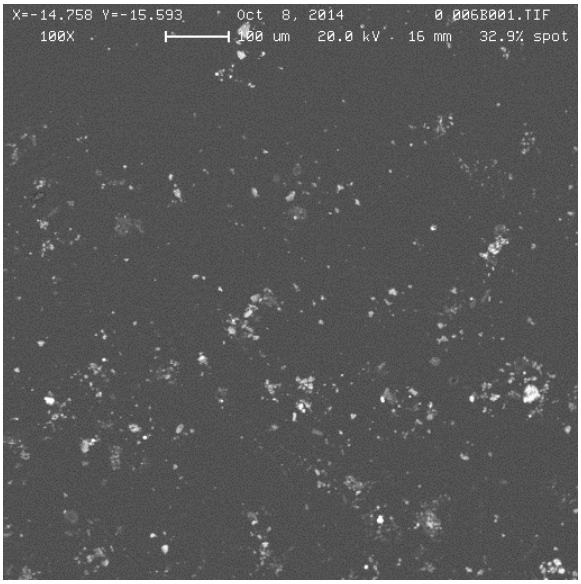


Figure 101

Sample 6B



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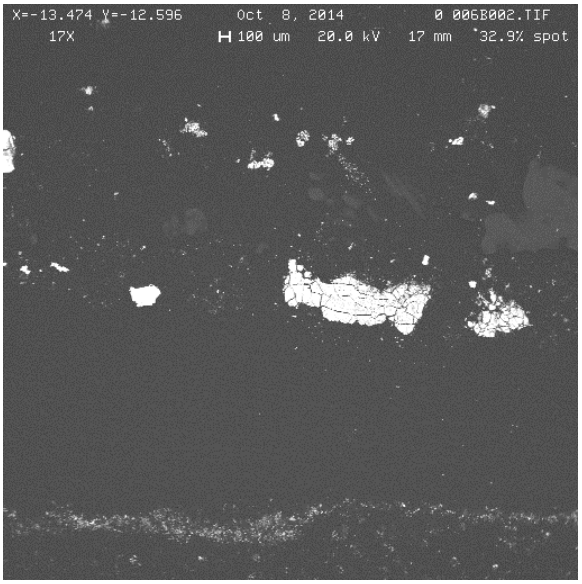

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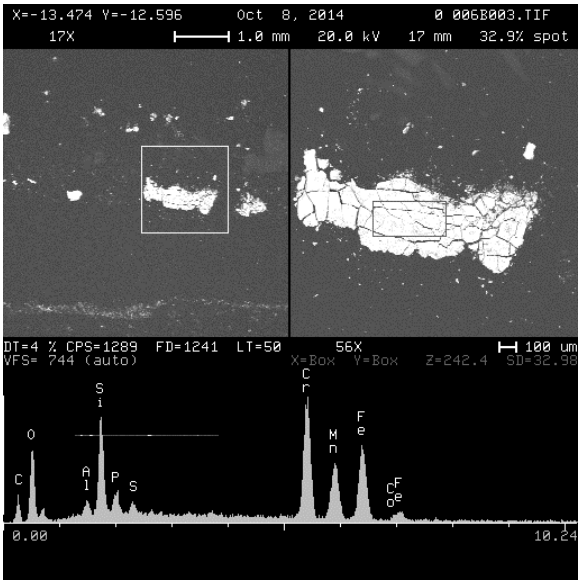
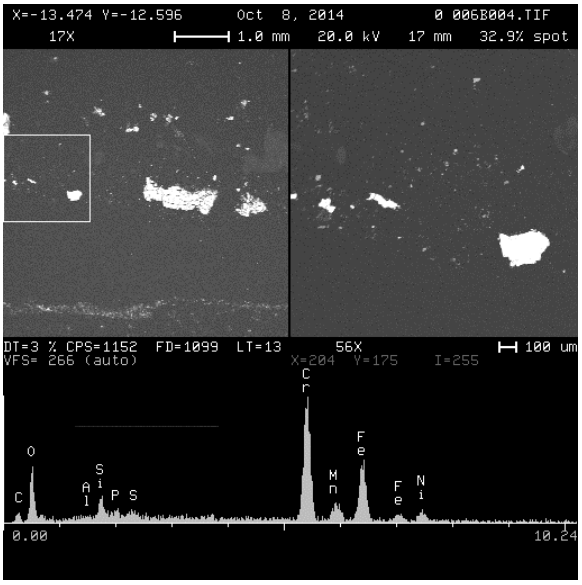


Figure 104



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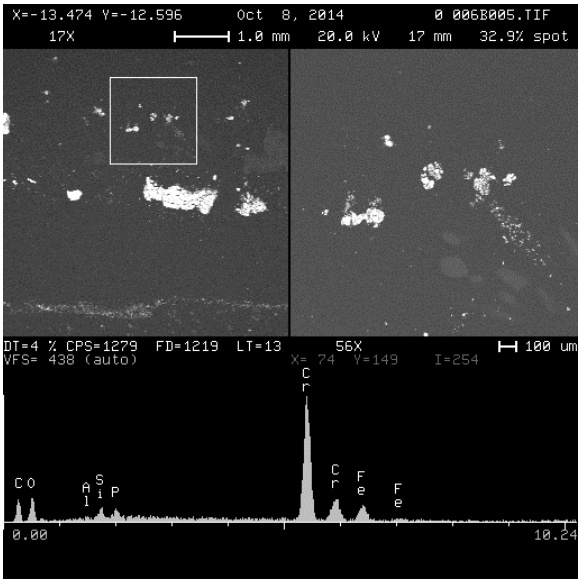
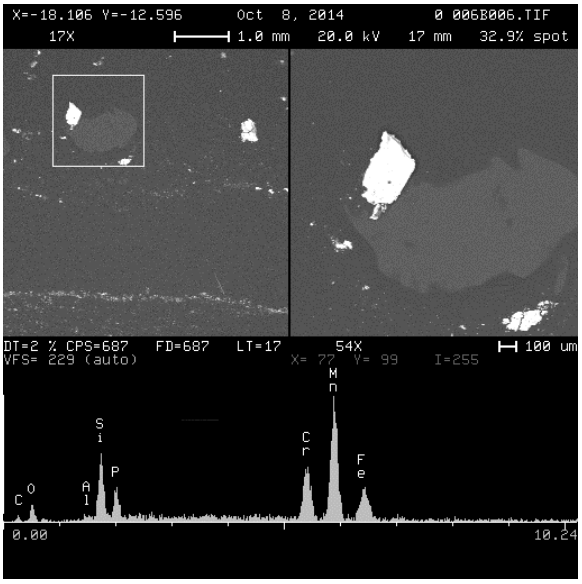


Figure 106



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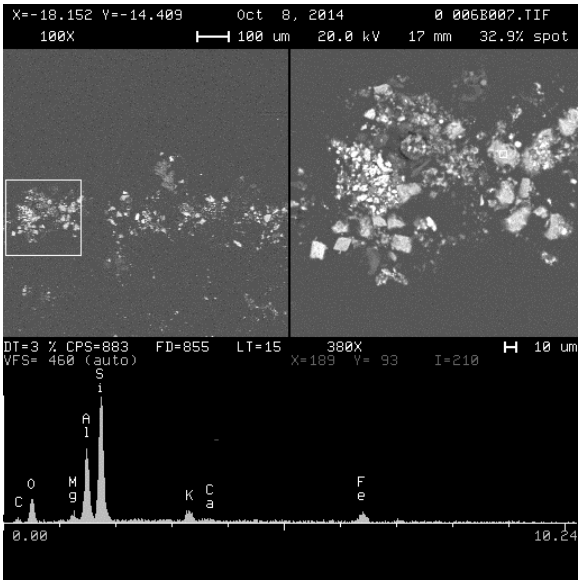

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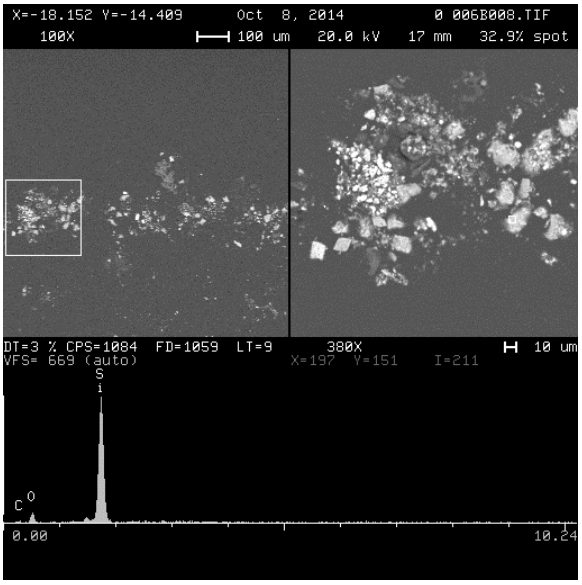

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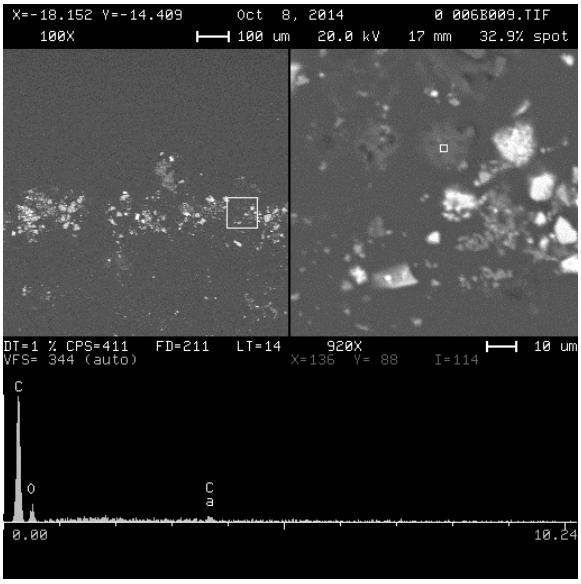

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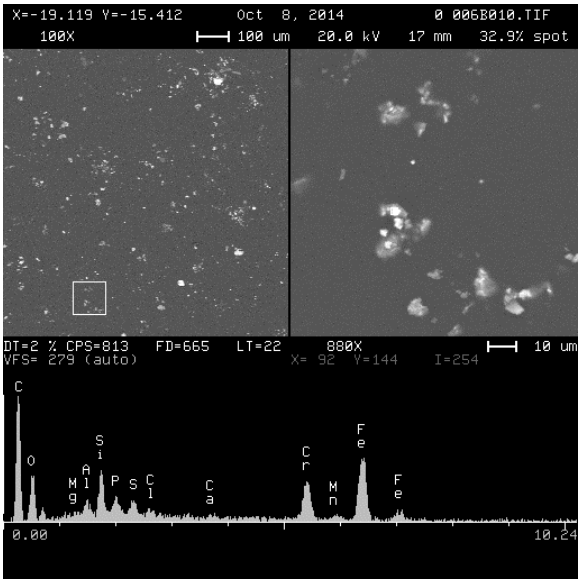

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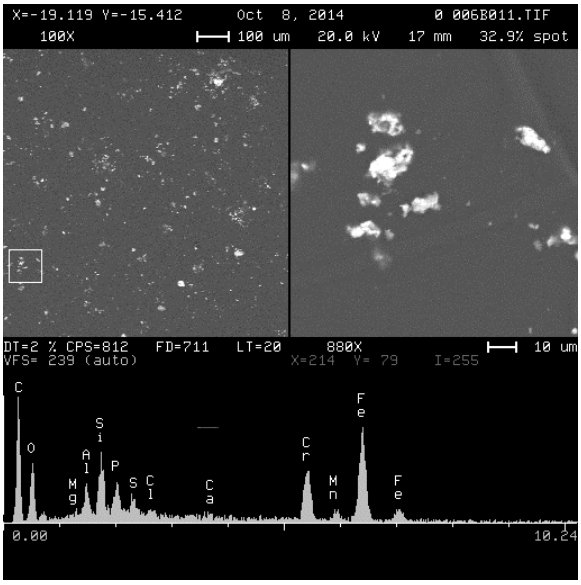

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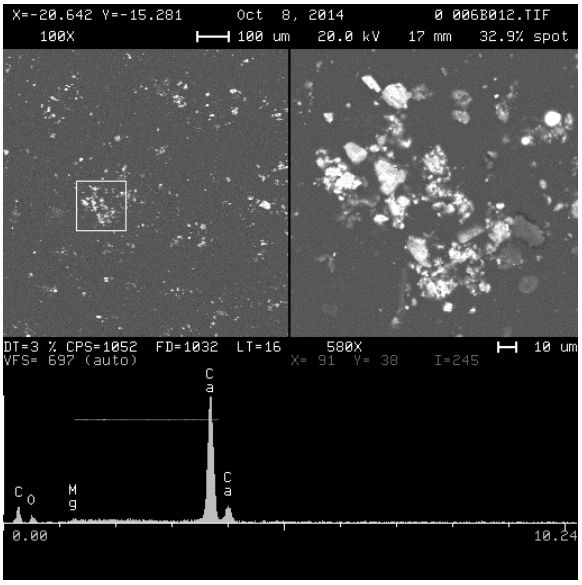

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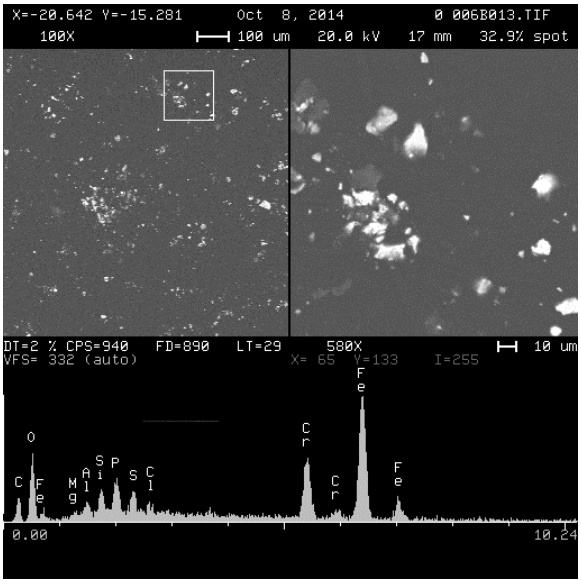

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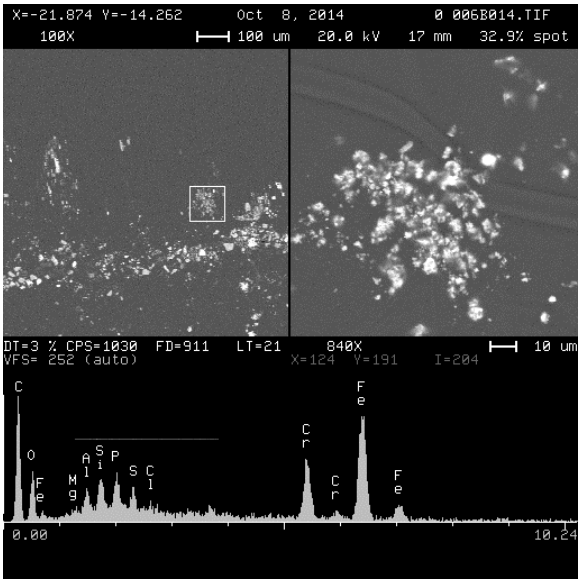

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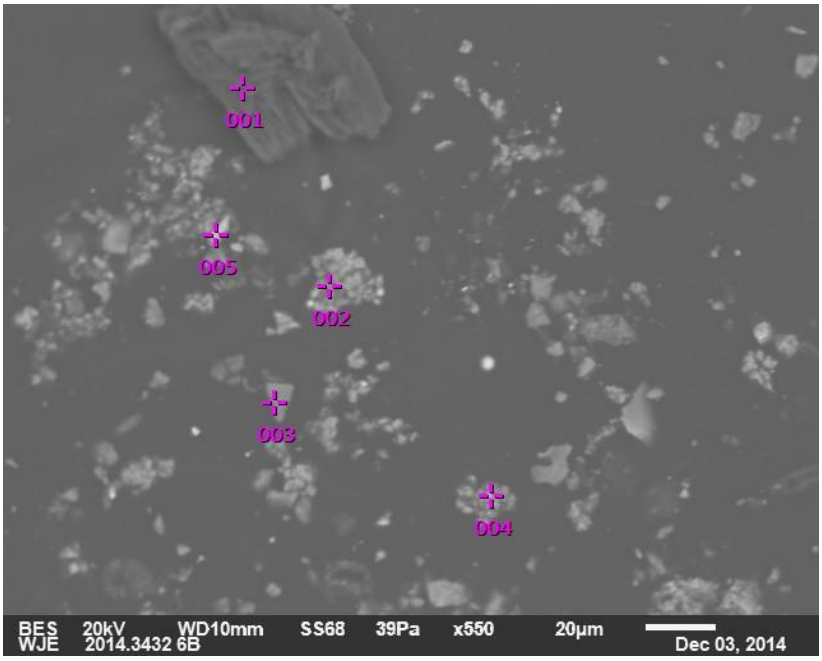

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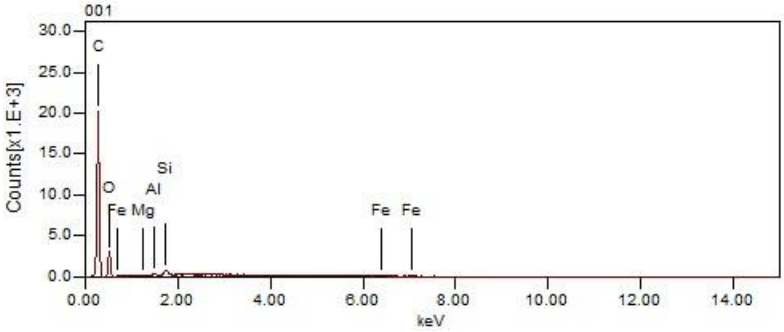


Figure 117. EDS spectra location 1

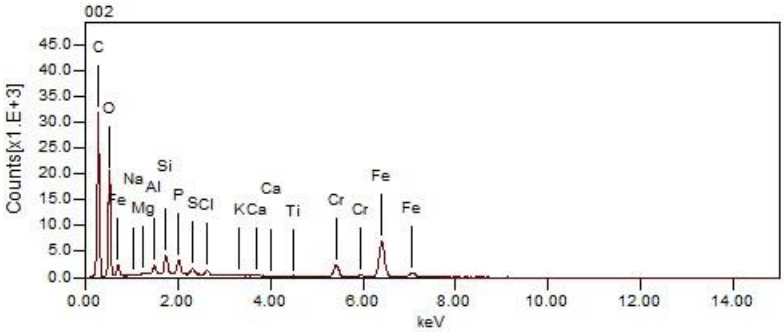


Figure 118. EDS spectra location 2

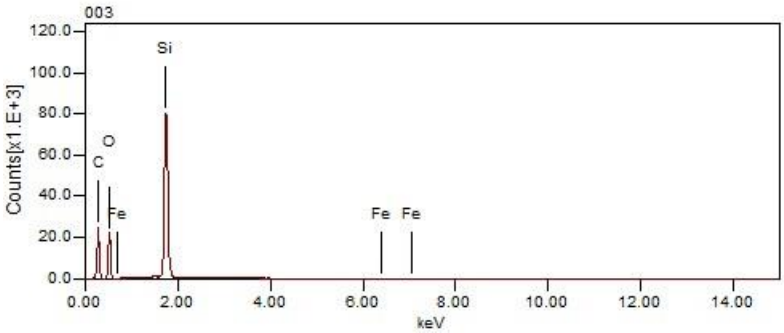


Figure 119. EDS spectra location 3

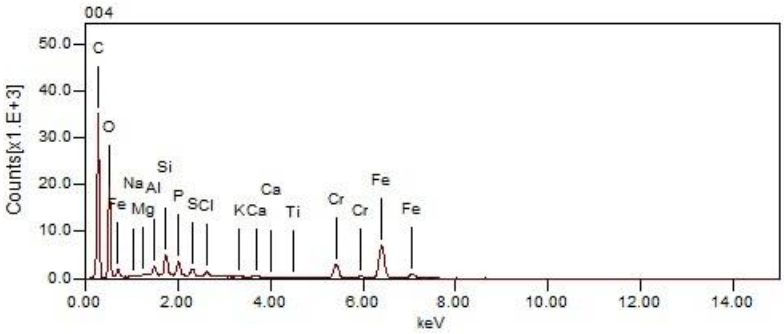


Figure 120. EDS spectra location 4

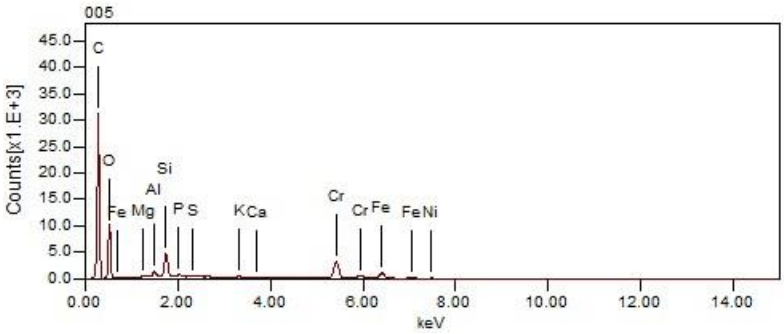


Figure 121. EDS spectra location 5

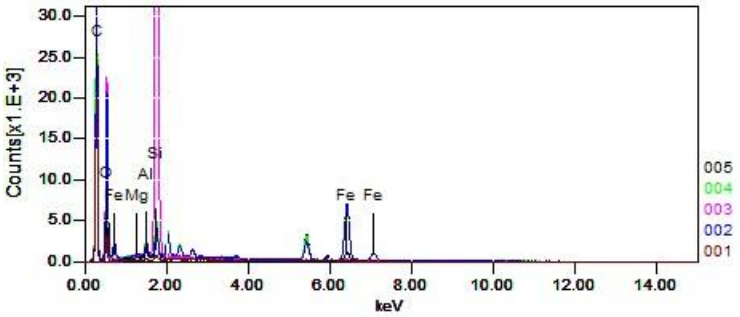


Figure 122. Composite EDS spectra

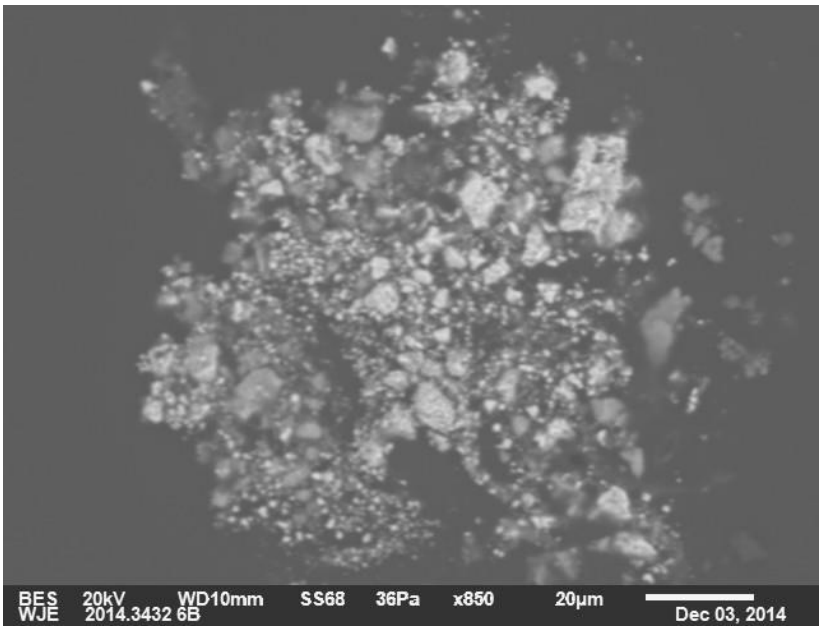


Figure 123

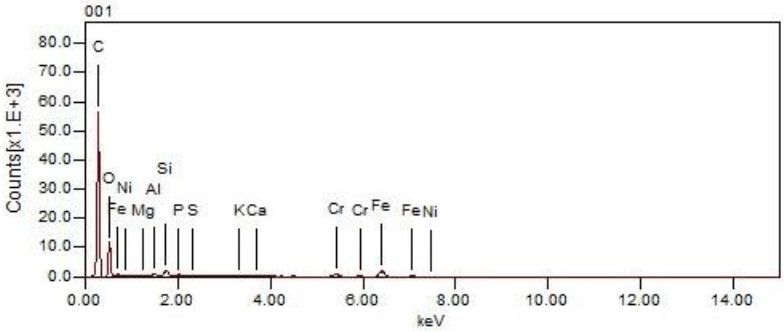


Figure 124. EDS spectra

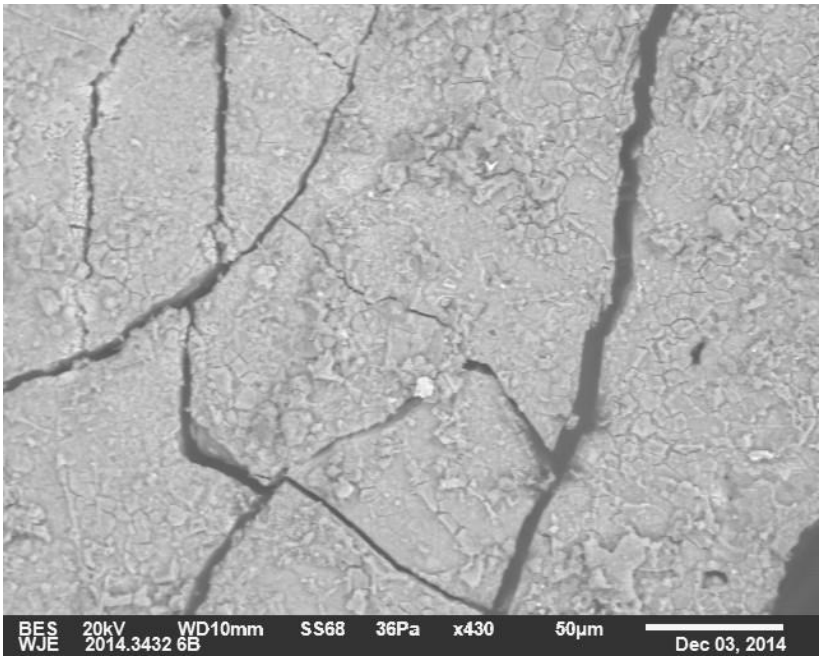


Figure 125

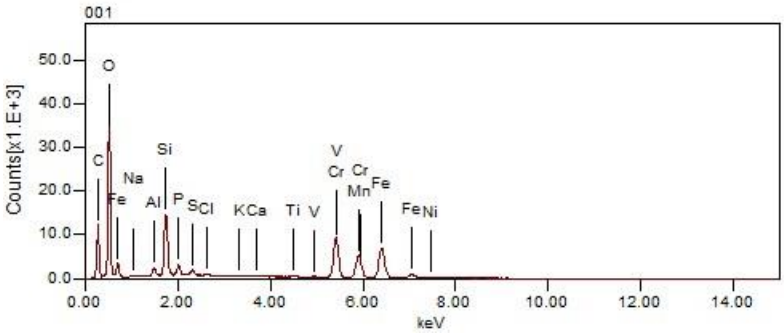


Figure 126. EDS spectra

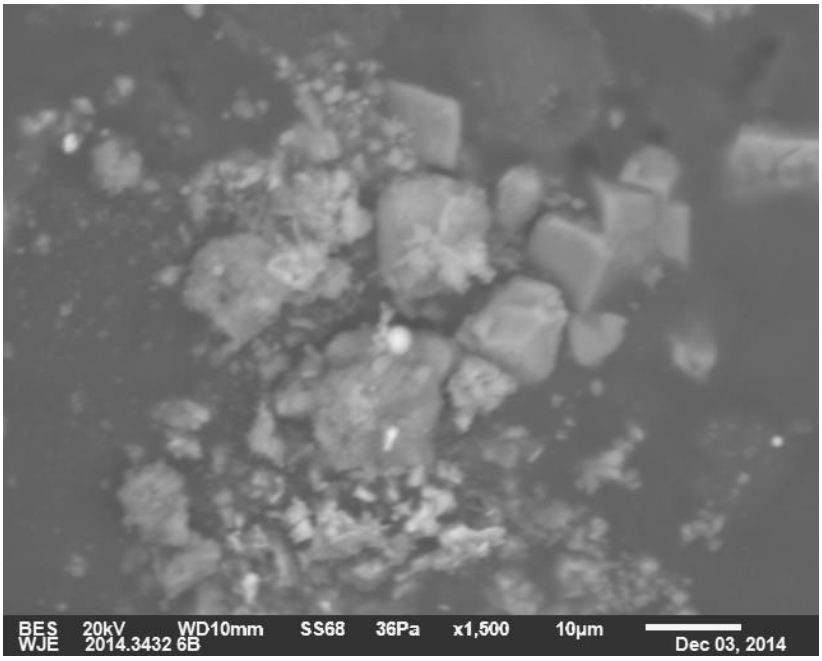


Figure 127

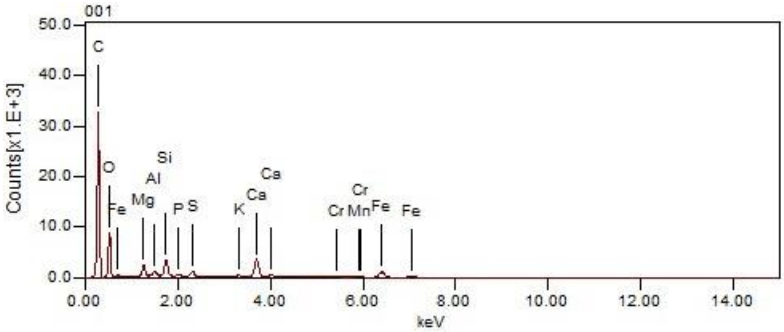


Figure 128. EDS spectra

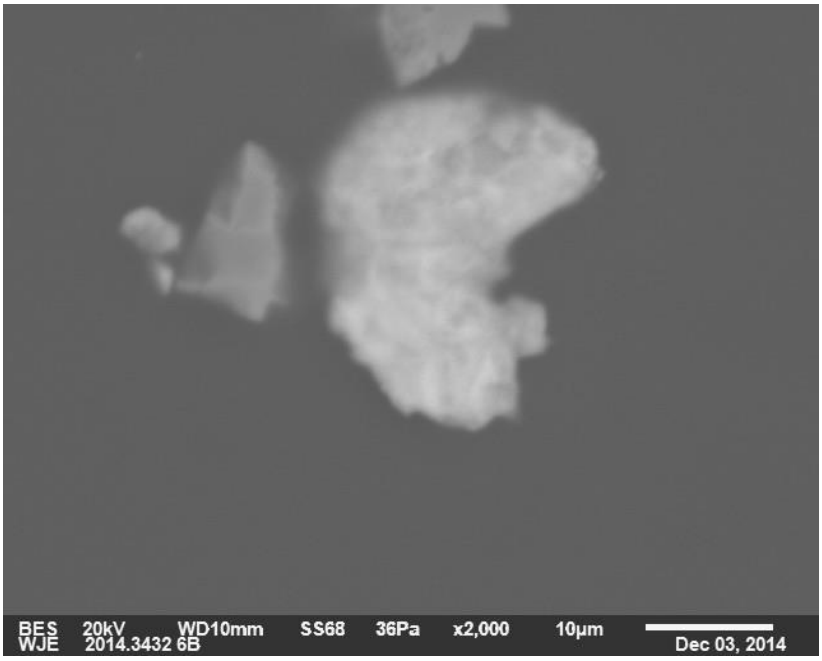


Figure 129

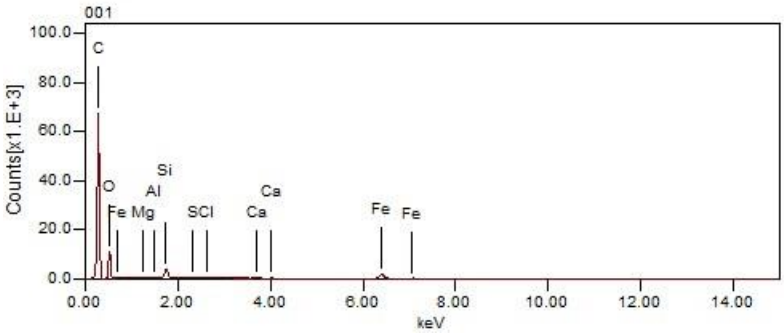


Figure 130. EDS spectra

Sample 7B

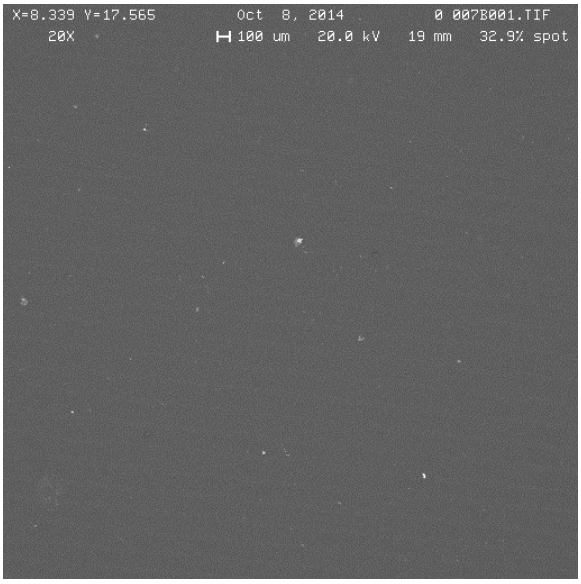


Figure 131

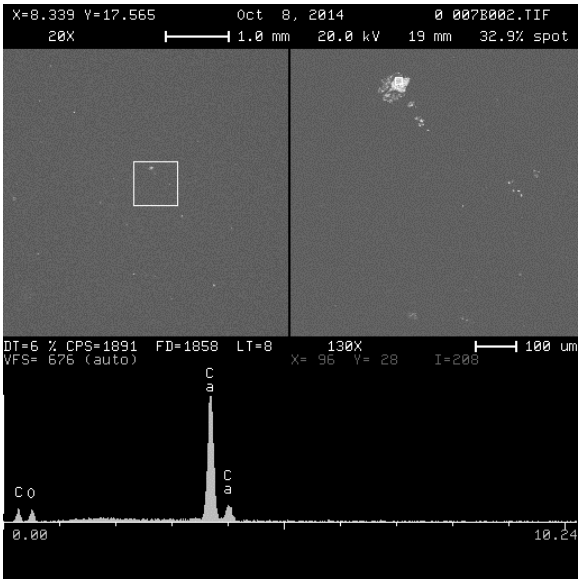


Figure 132

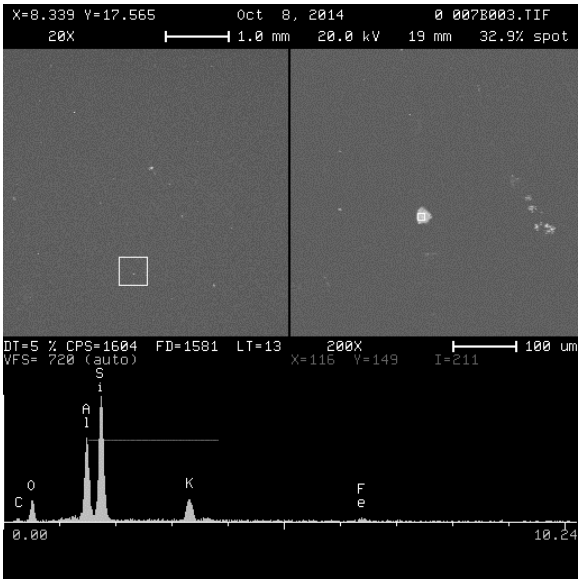


Figure 133

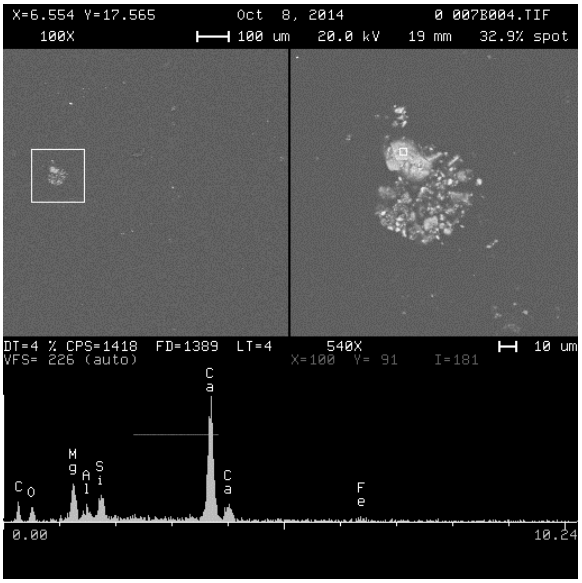


Figure 134

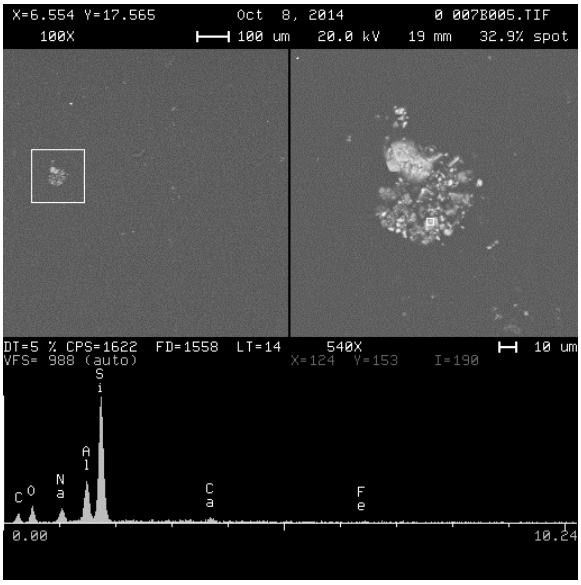


Figure 135

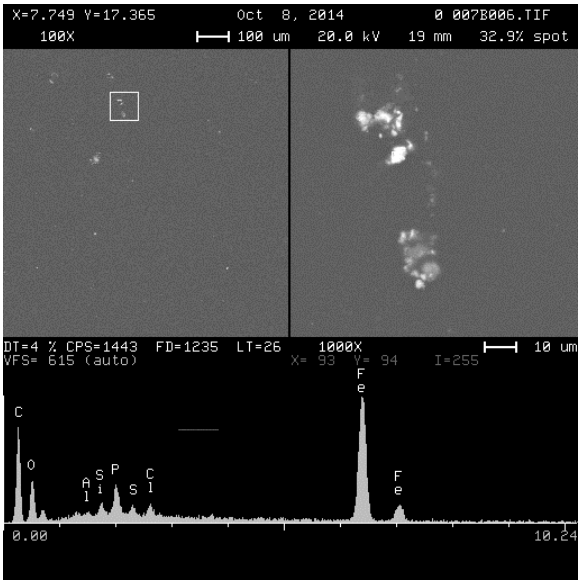
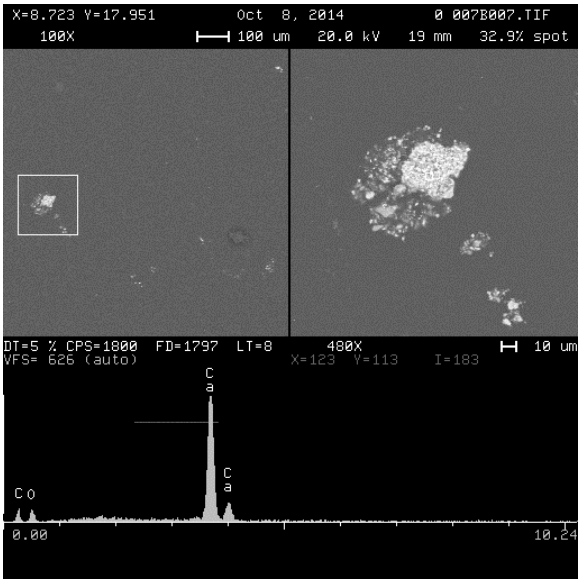


Figure 136



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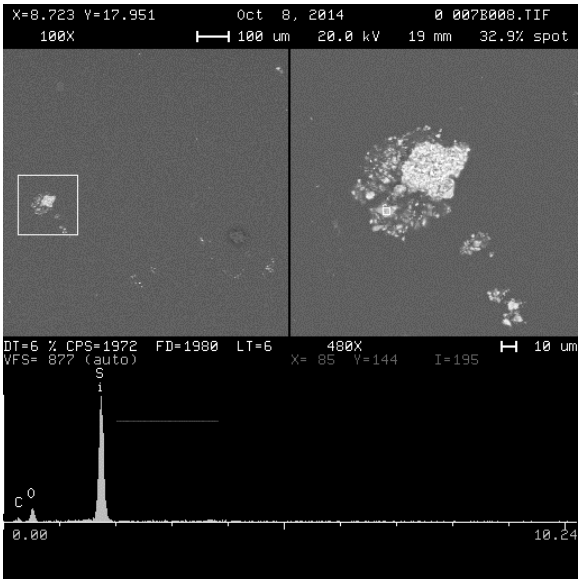


Figure 138

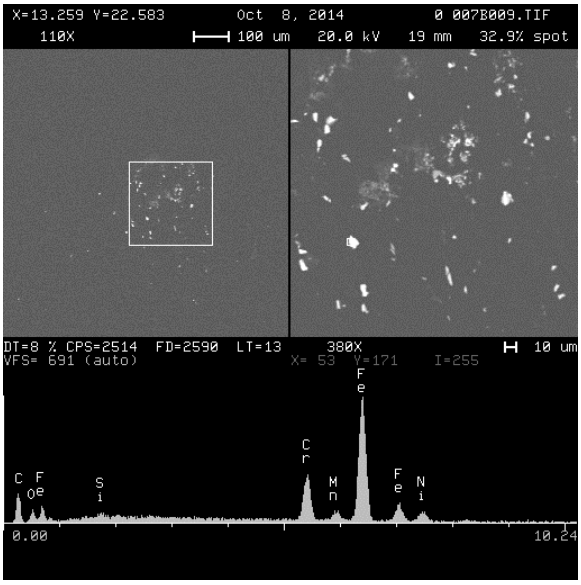


Figure 139

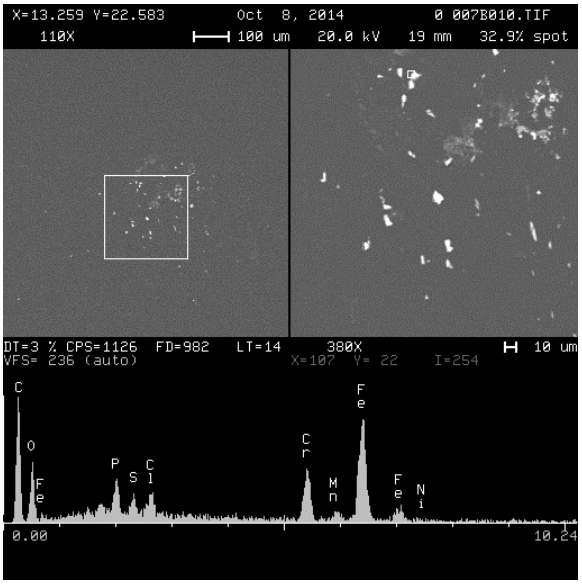


Figure 140

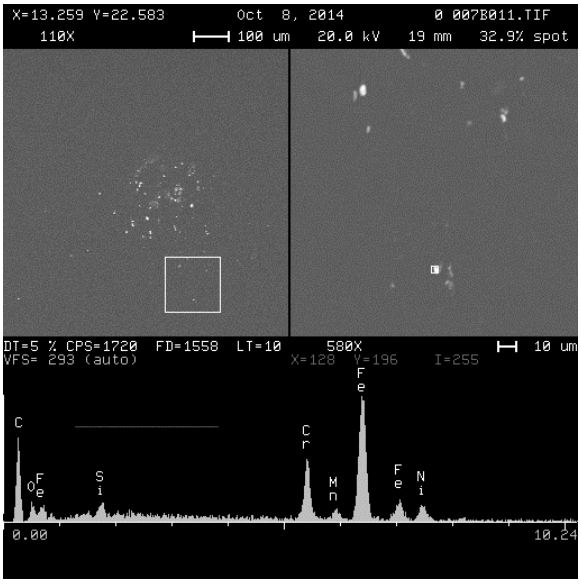


Figure 141

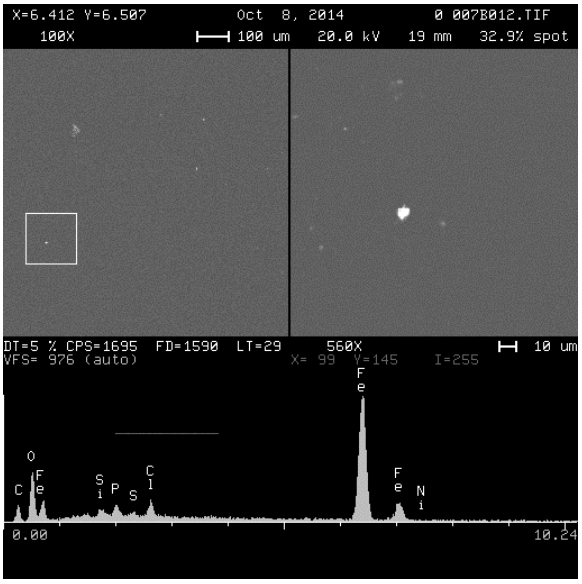


Figure 142

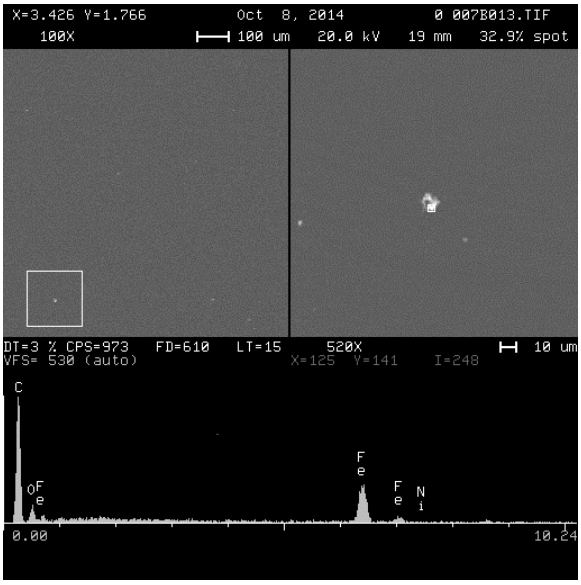


Figure 143

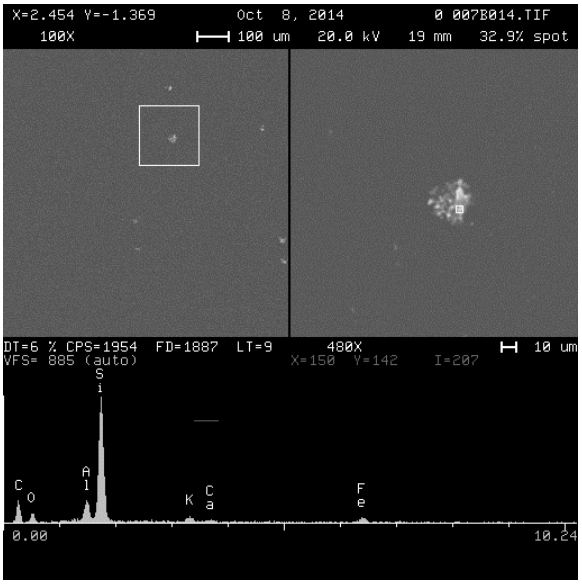
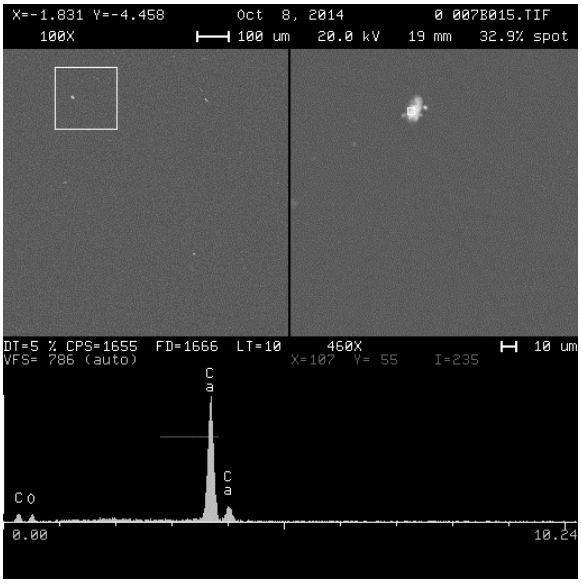


Figure 144



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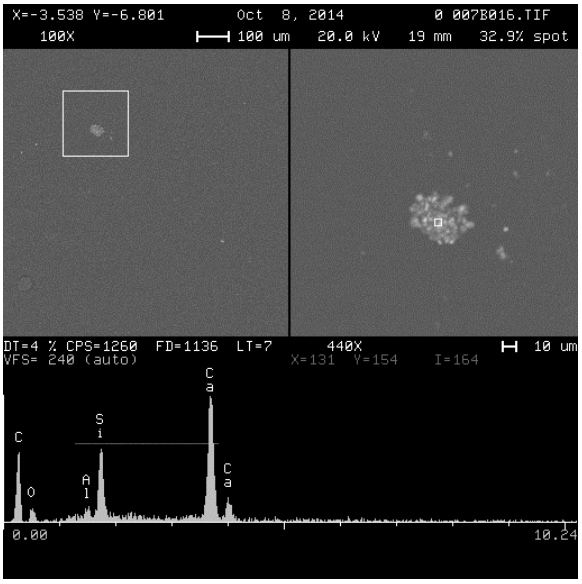


Figure 146

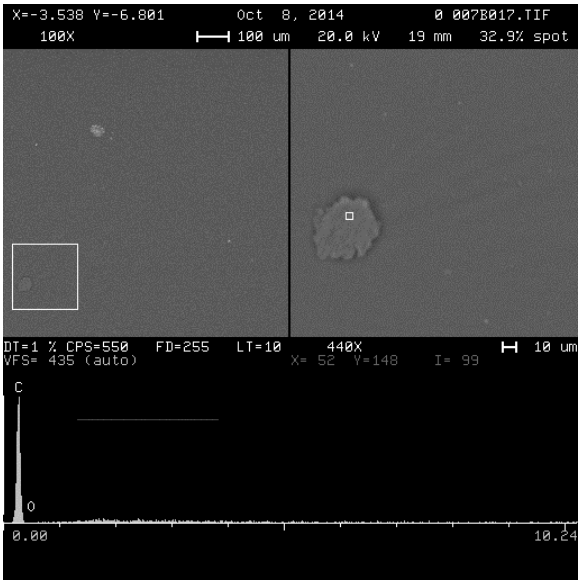


Figure 147

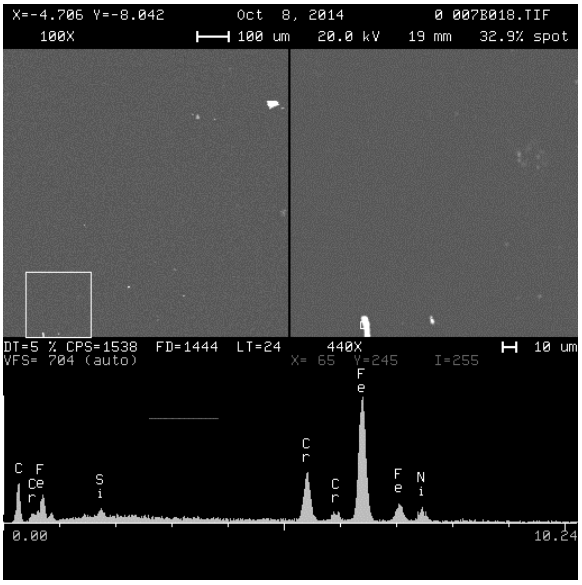


Figure 148

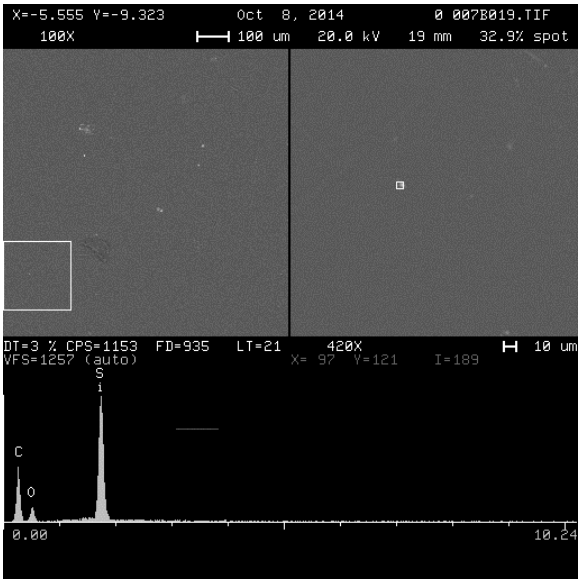


Figure 149

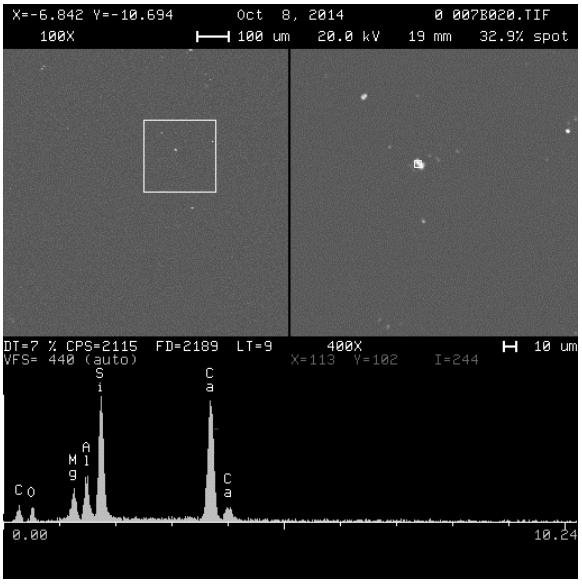


Figure 150

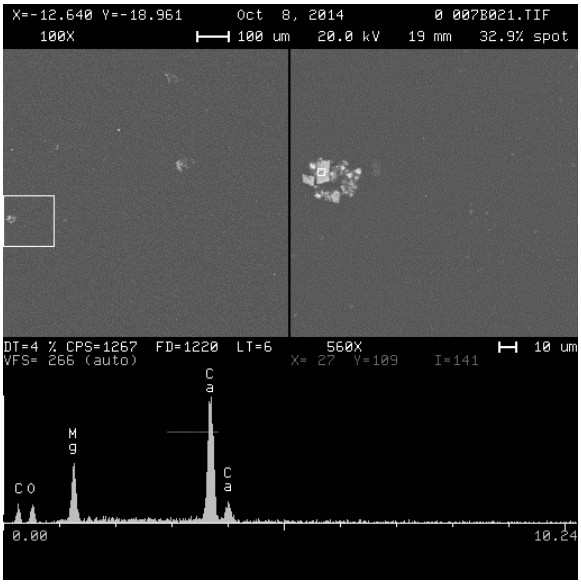


Figure 151

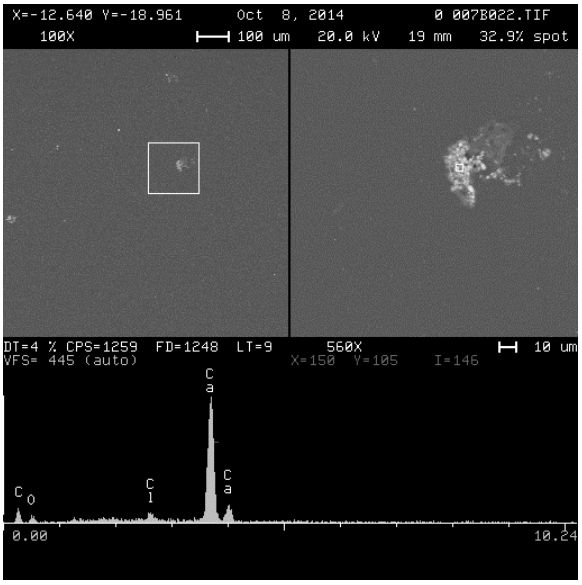


Figure 152

Sample 8B

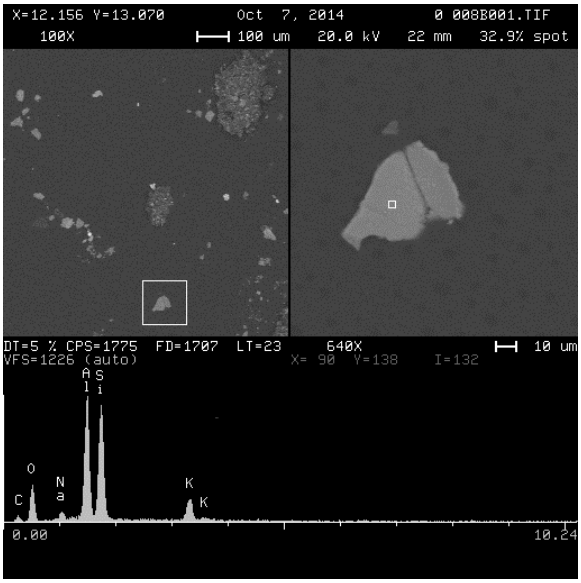


Figure 153

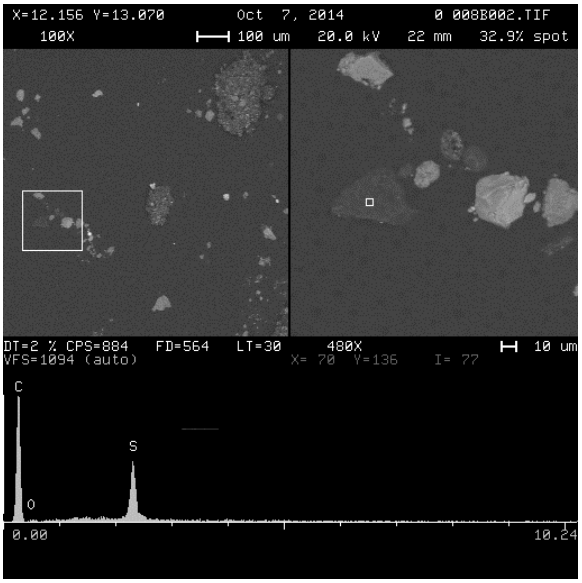


Figure 154

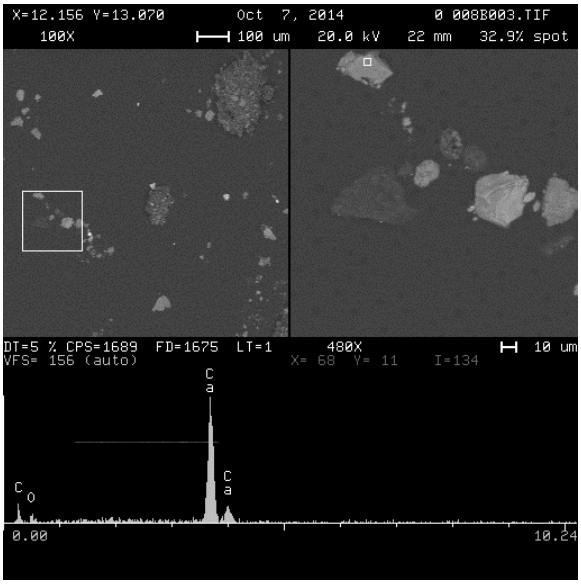


Figure 155

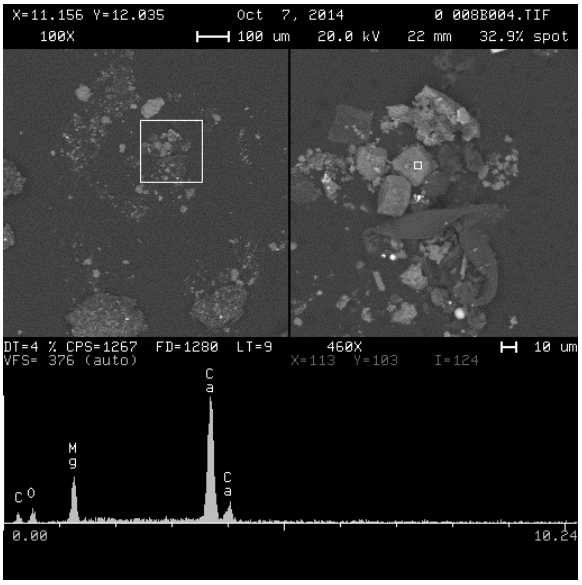


Figure 156

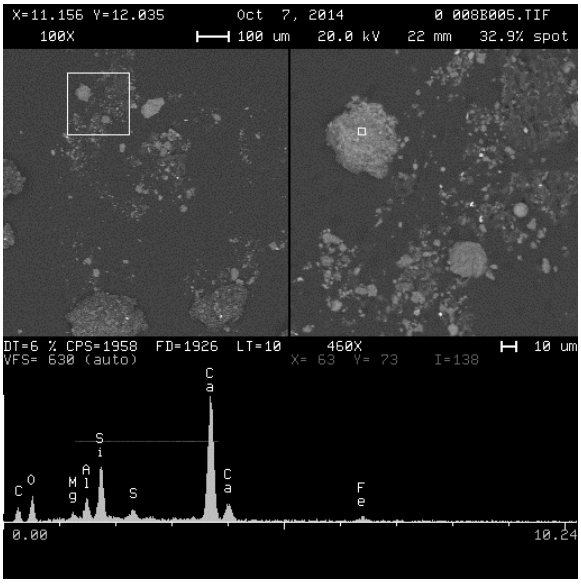


Figure 157

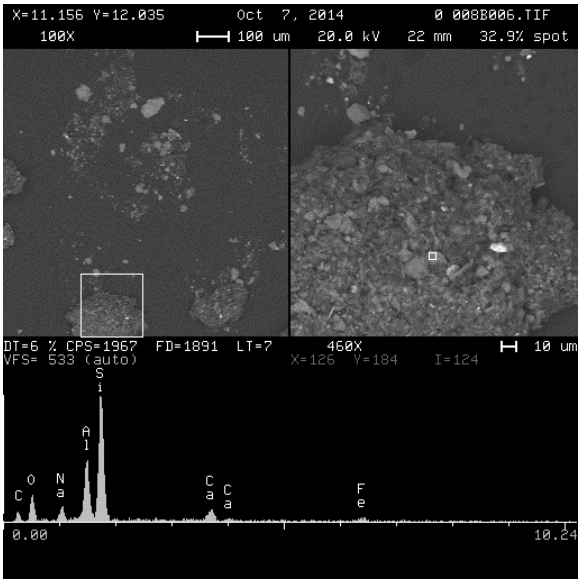


Figure 158

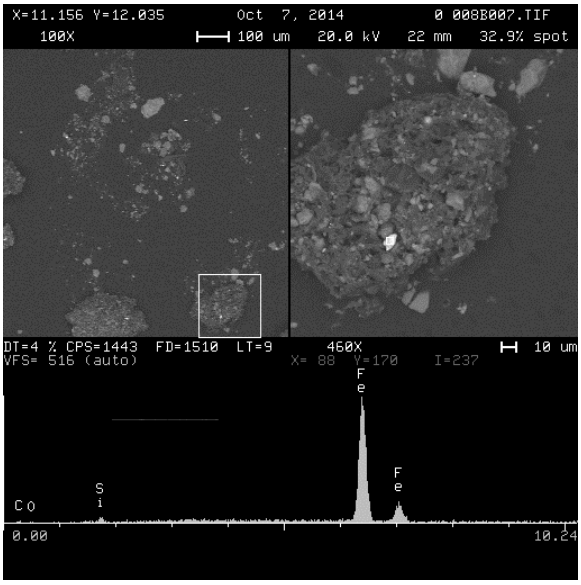


Figure 159

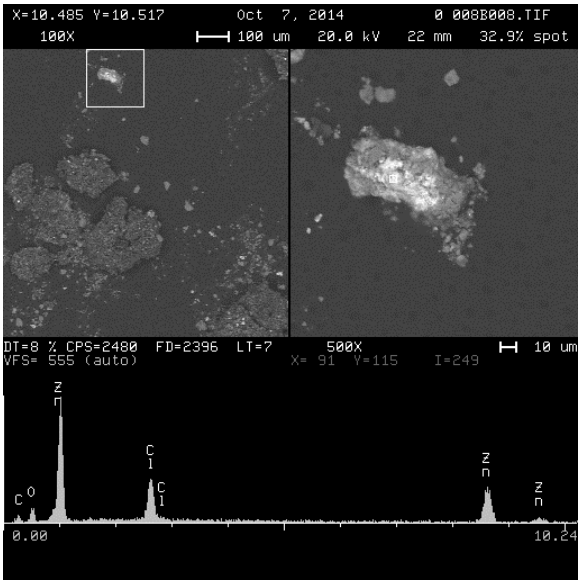


Figure 160

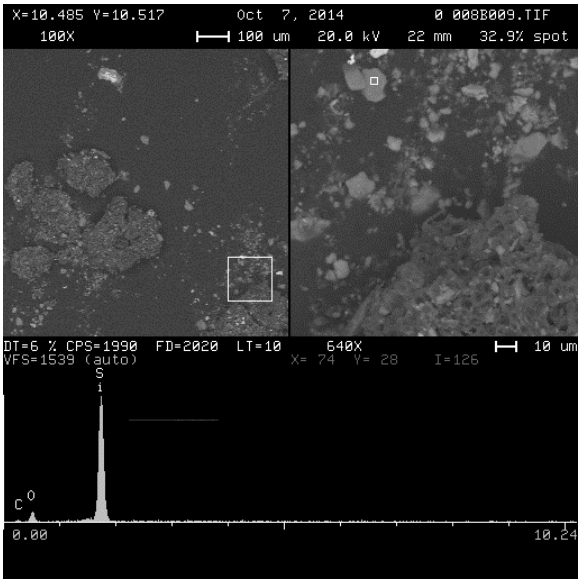


Figure 161

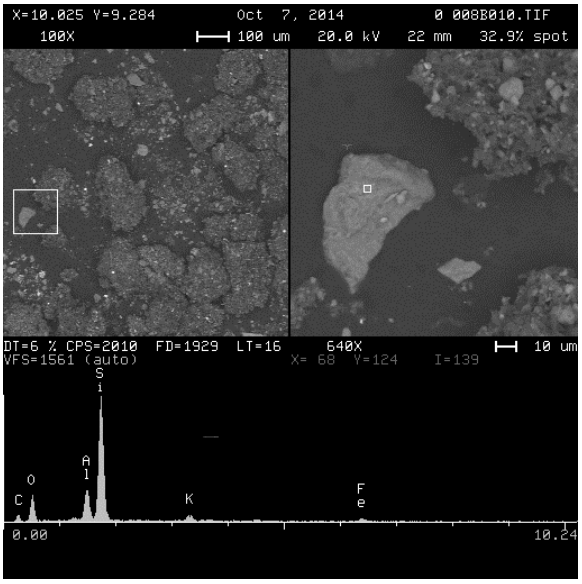


Figure 162

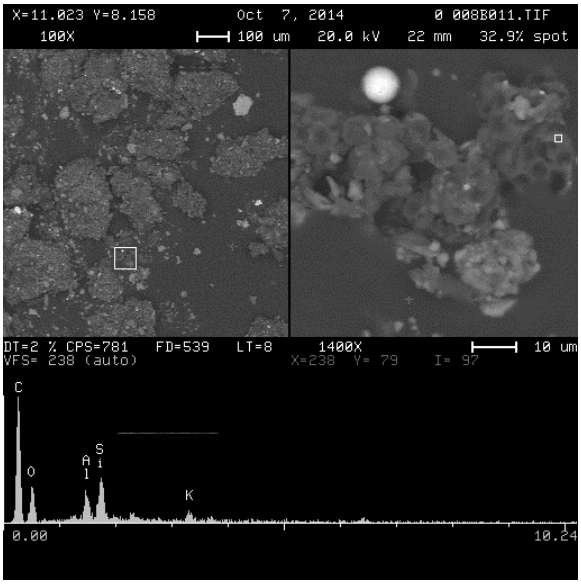


Figure 163

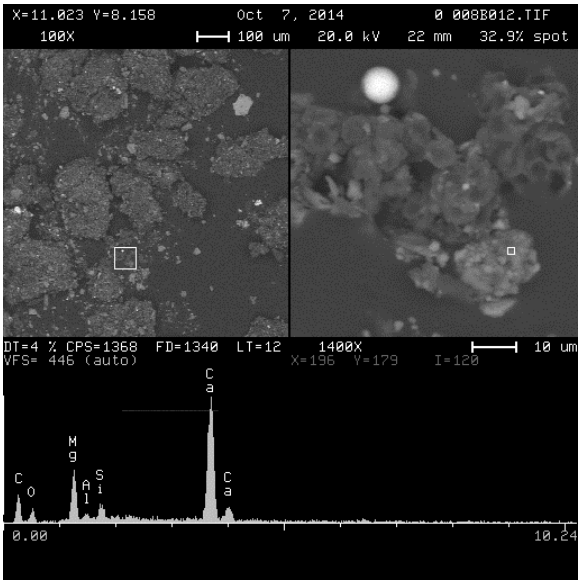


Figure 164

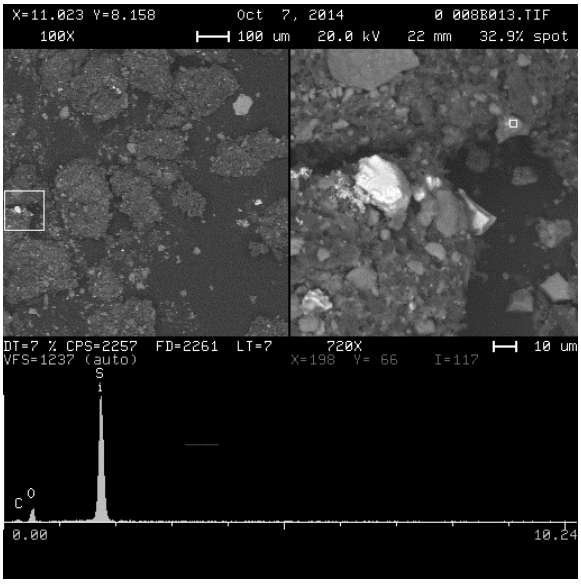


Figure 165

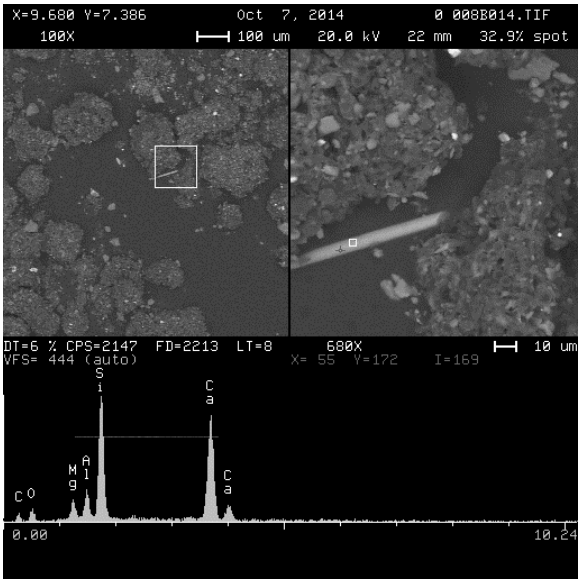


Figure 166

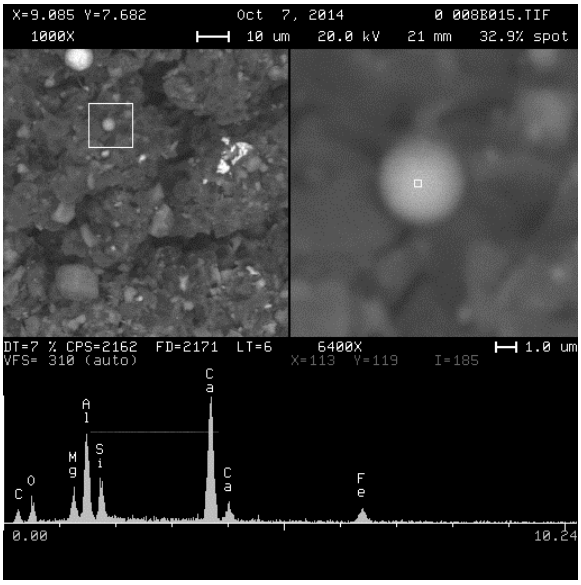


Figure 167

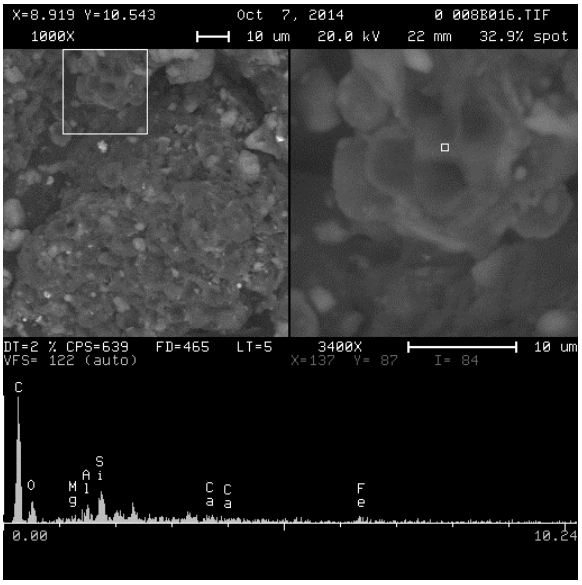


Figure 168

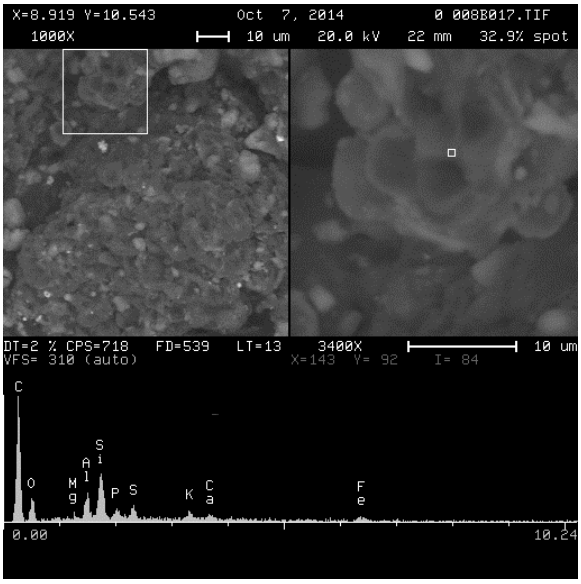


Figure 169

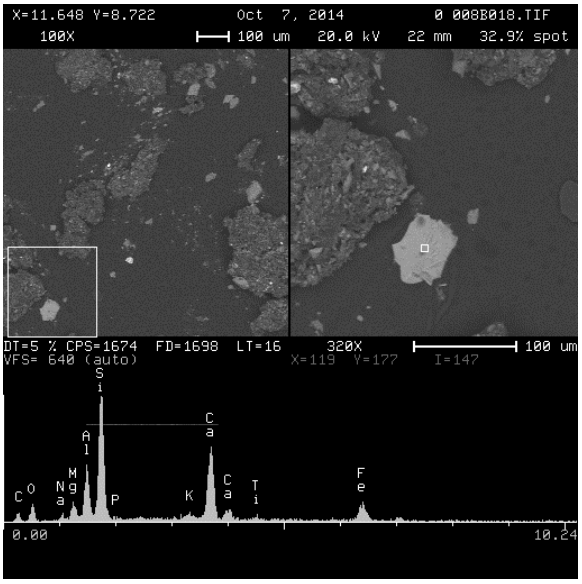


Figure 170

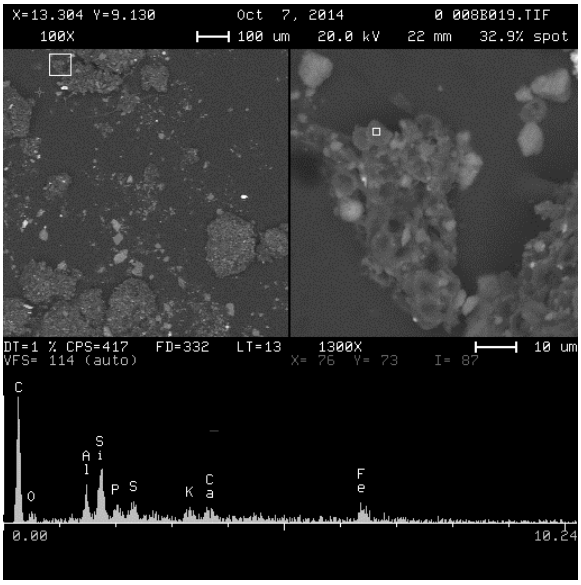


Figure 171

Sample 5C

No deposits were identified on the sample.

Sample 6C

No deposits were identified on the sample.

Sample 13C

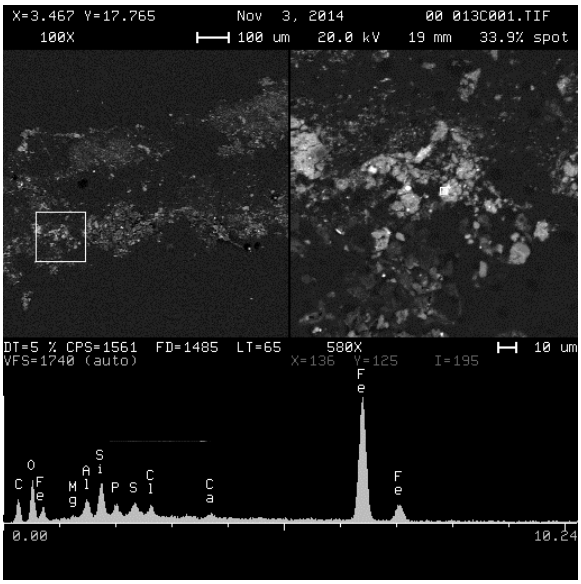


Figure 172

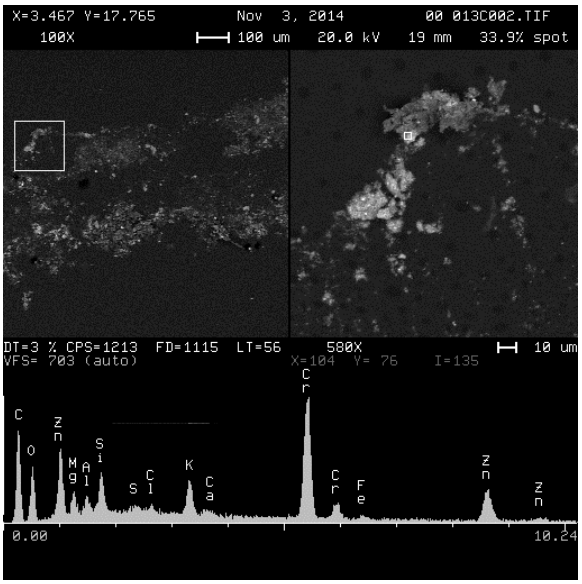


Figure 173

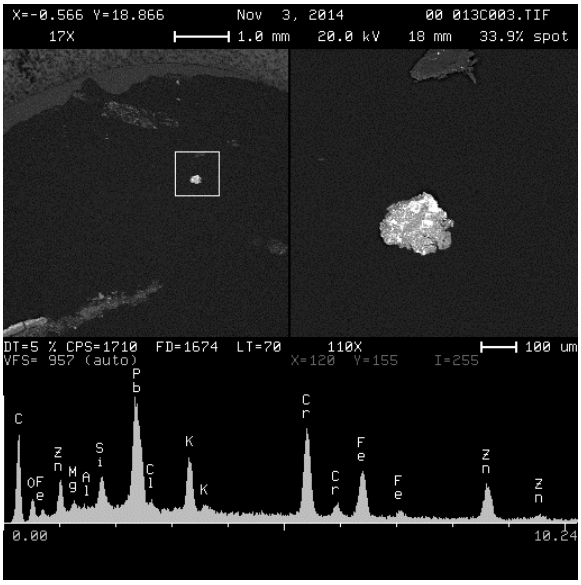


Figure 174

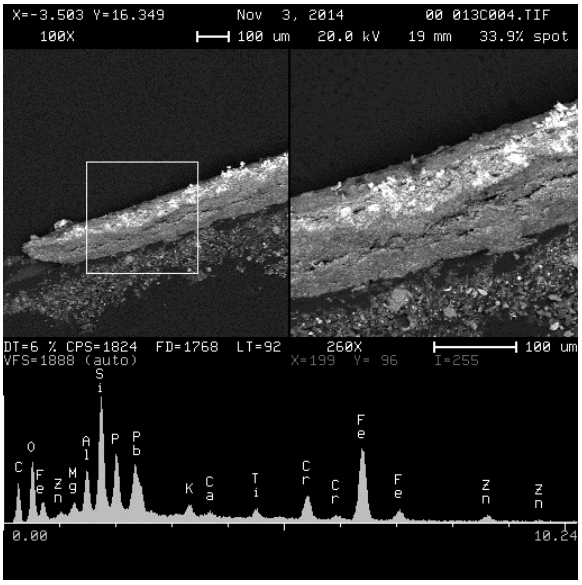


Figure 175

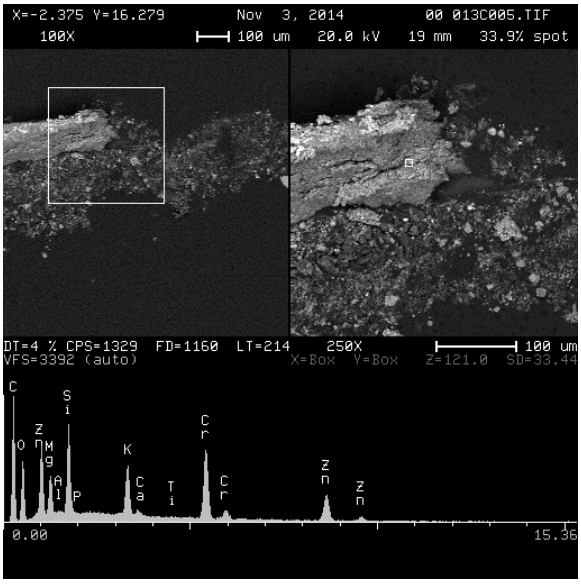


Figure 176

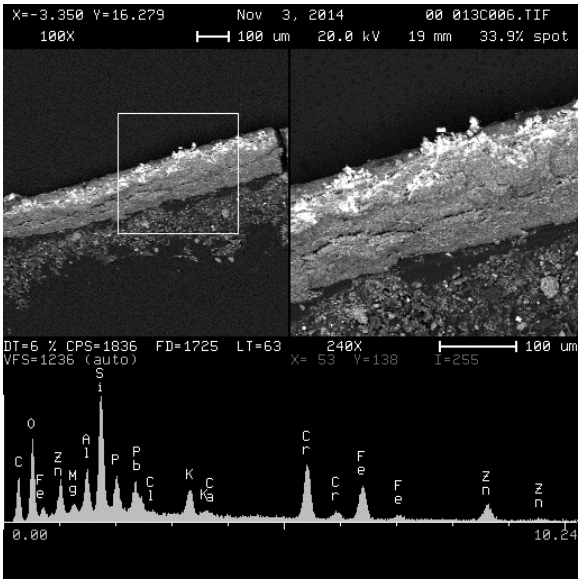


Figure 177

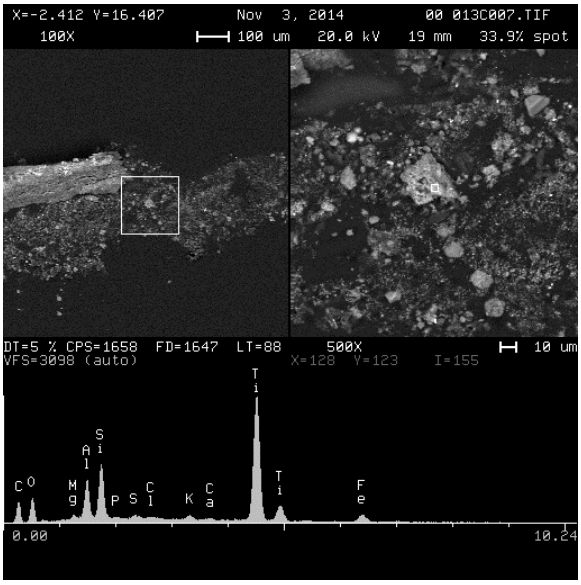


Figure 178

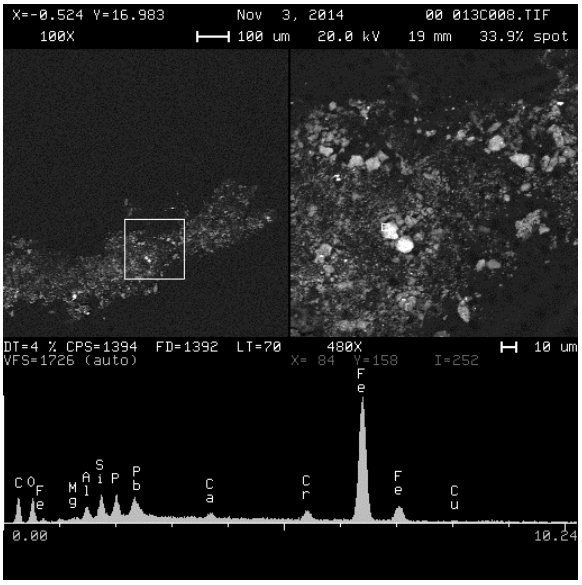


Figure 179

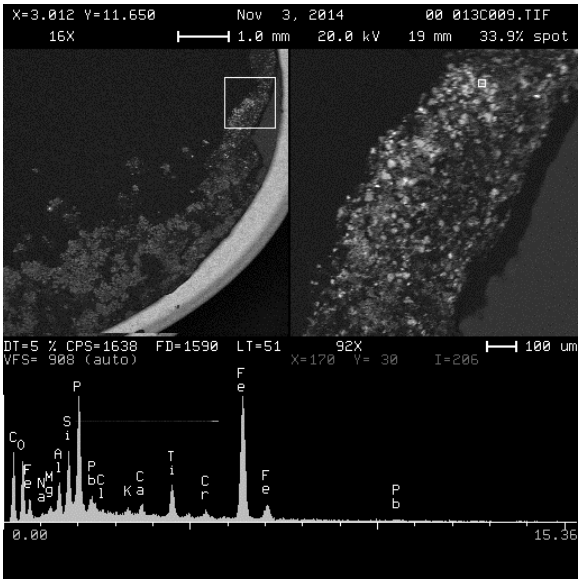


Figure 180

Sample 14C

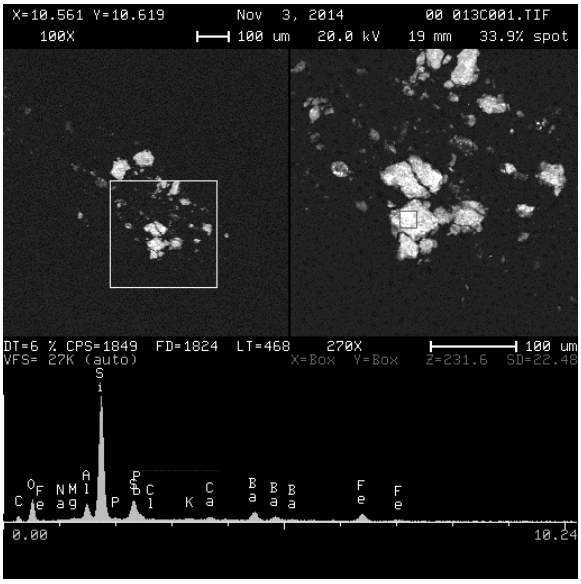


Figure 181

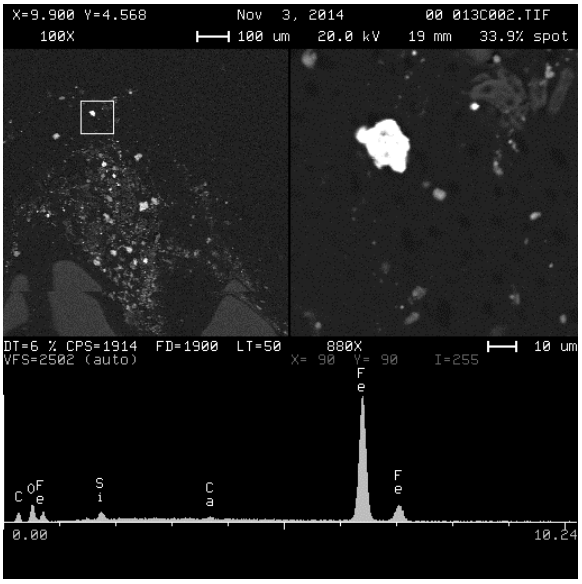


Figure 182

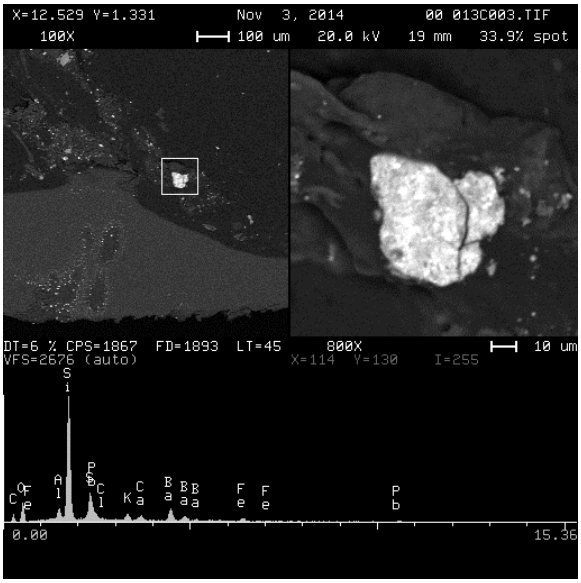


Figure 183

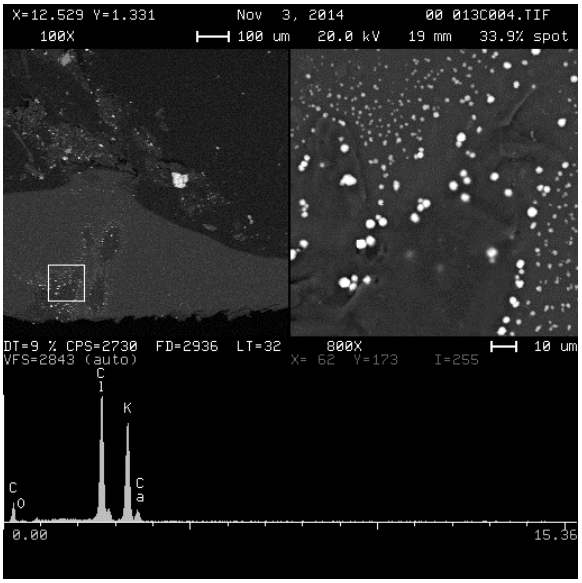


Figure 184

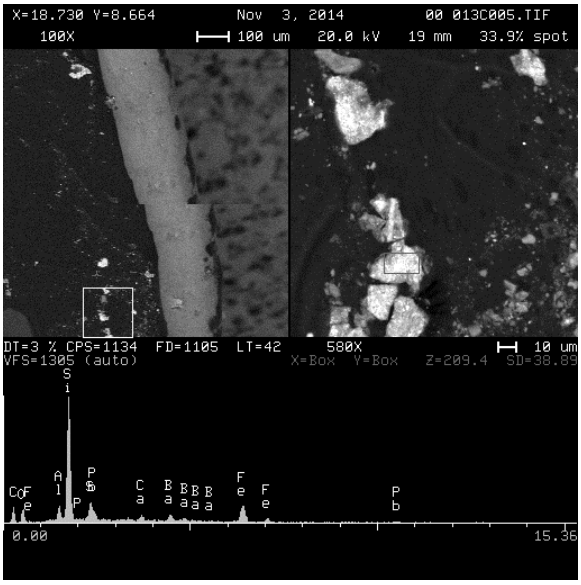


Figure 185

Sample 15C

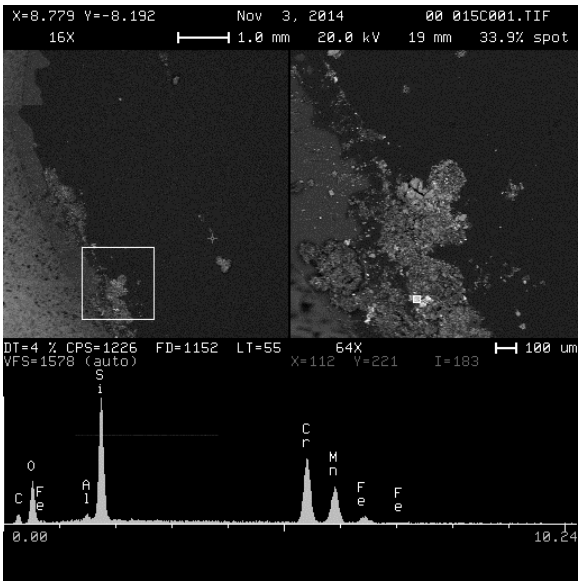


Figure 186

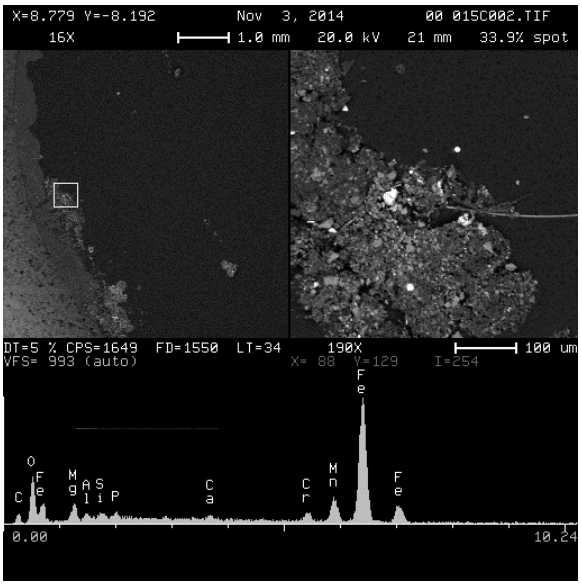


Figure 187

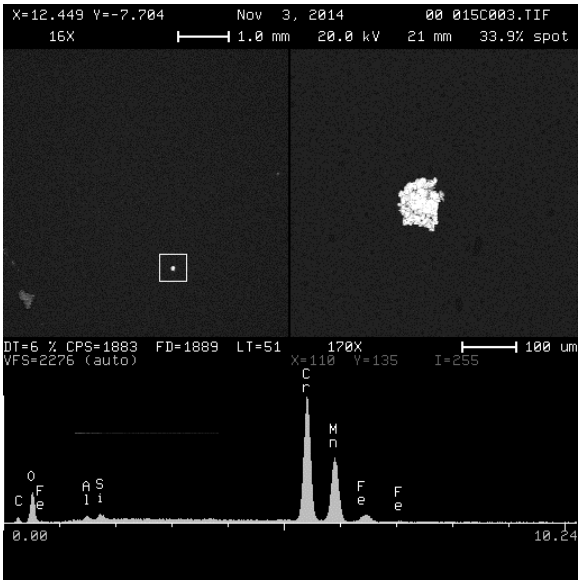


Figure 188

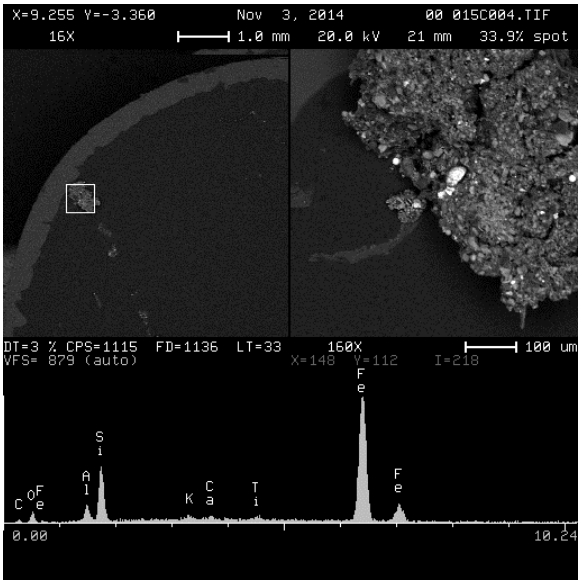


Figure 189

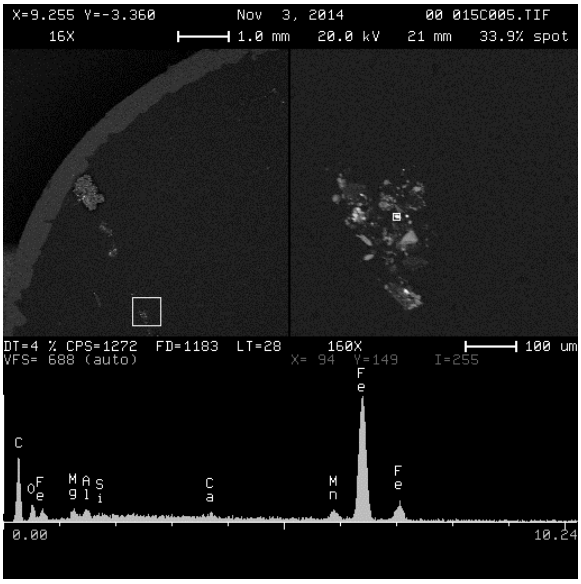


Figure 190

Sample 1C

No deposits were identified on the sample.

Sample 3C

No deposits were identified on the sample.

Sample 4C

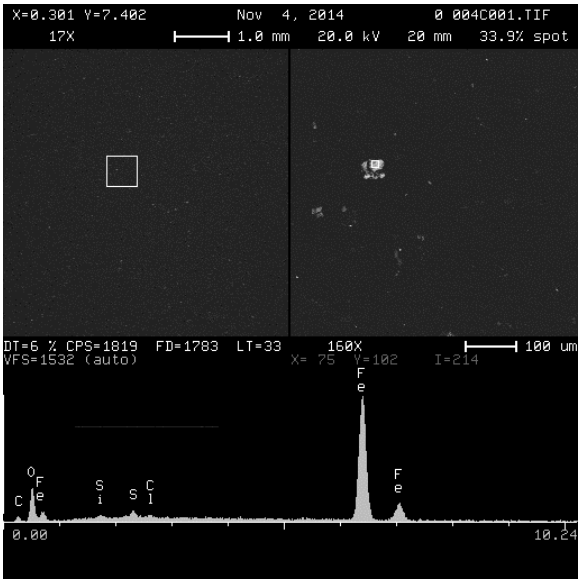


Figure 191

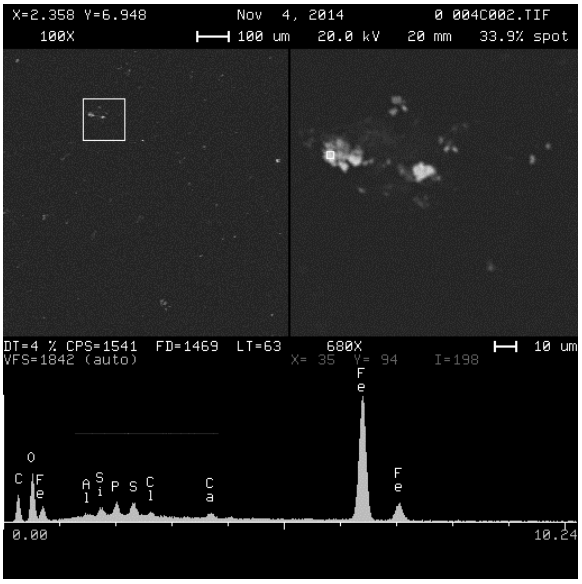


Figure 192

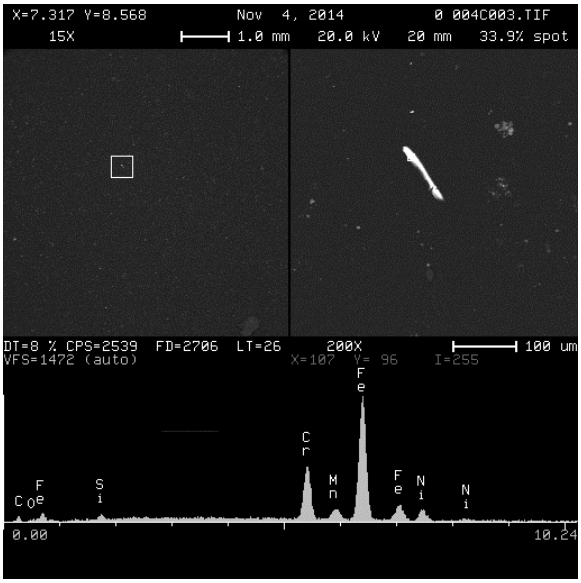


Figure 193

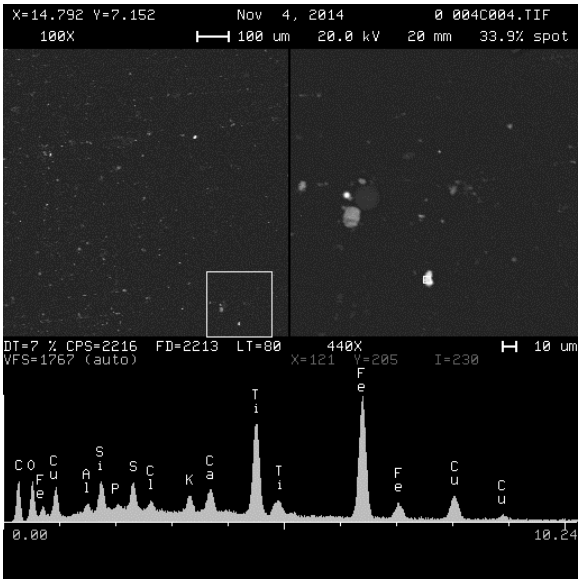


Figure 194

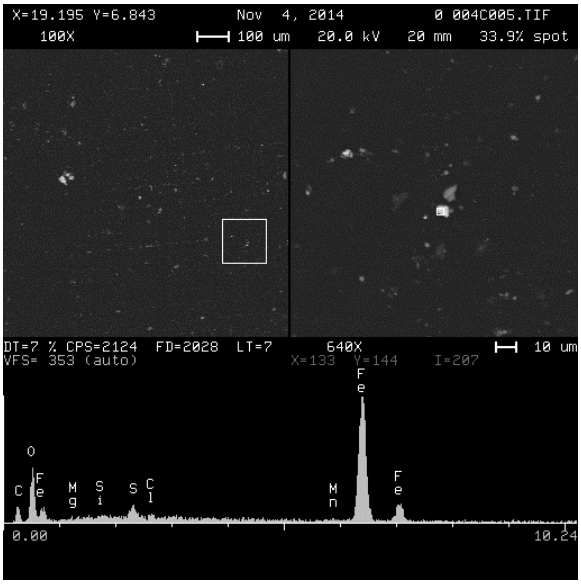


Figure 195

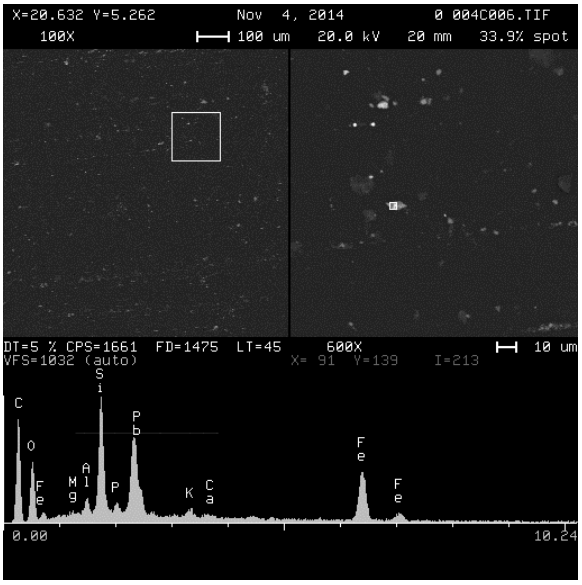


Figure 196

Sample 5C

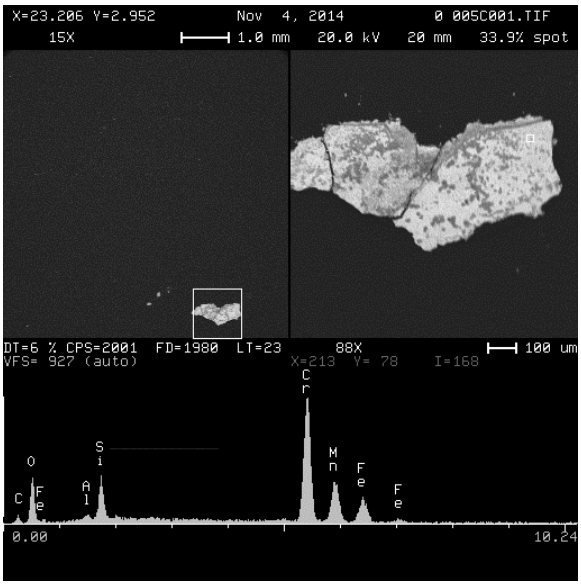


Figure 197

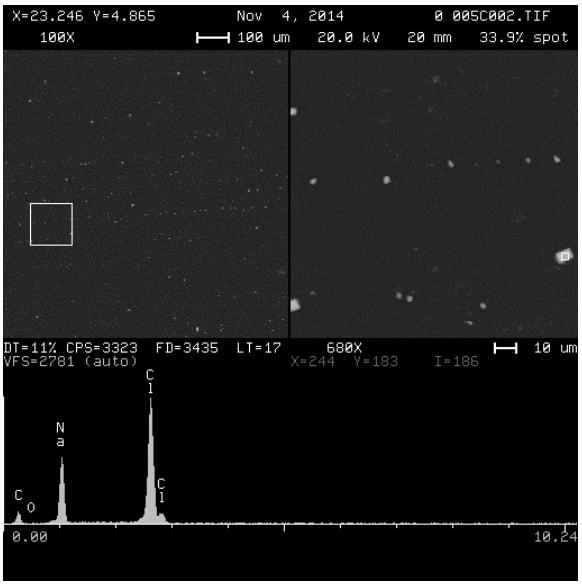


Figure 198

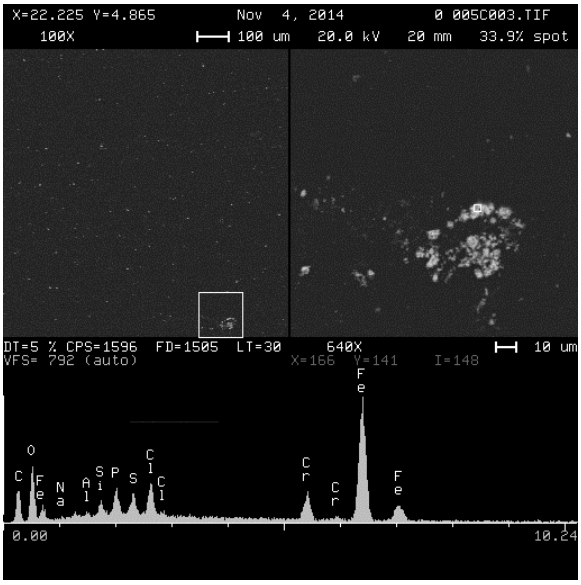


Figure 199

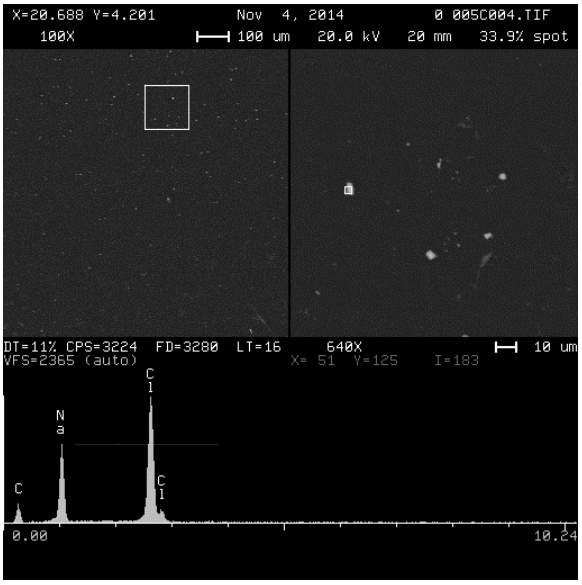


Figure 200

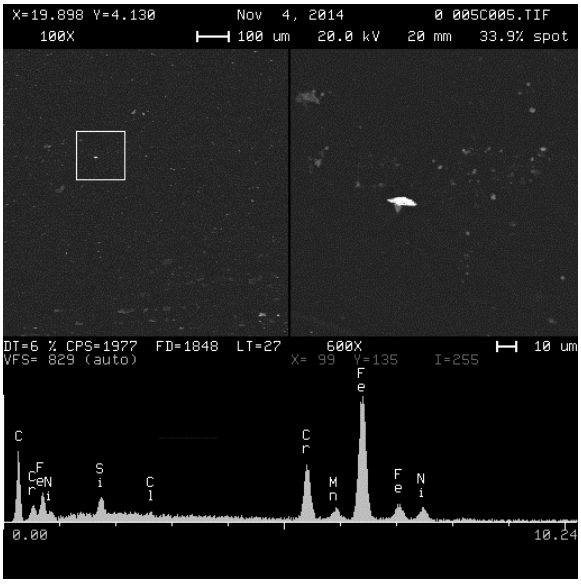


Figure 201

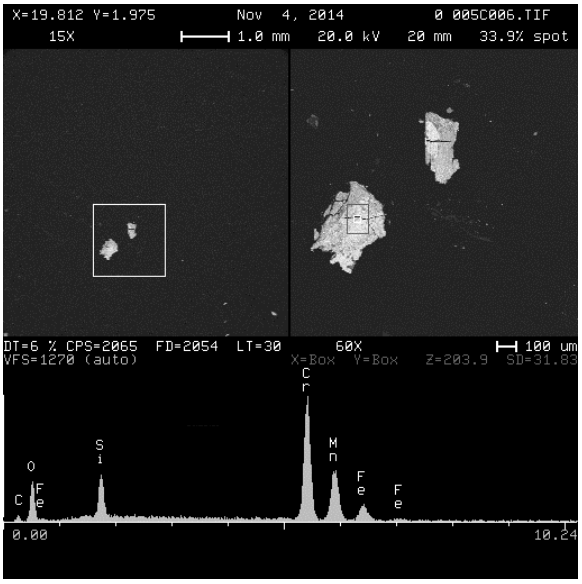


Figure 202

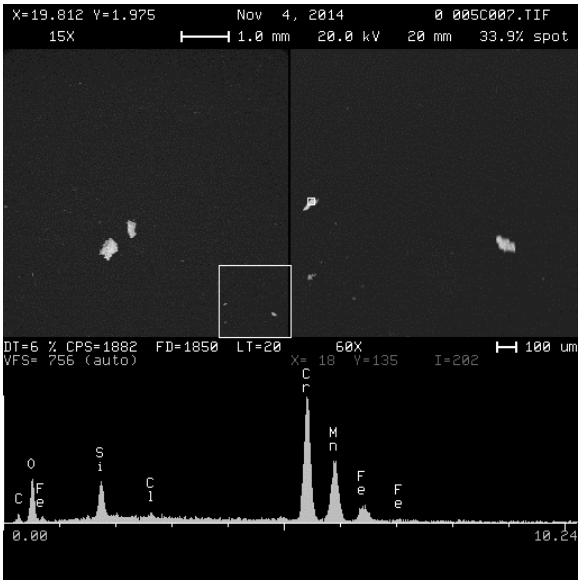


Figure 203

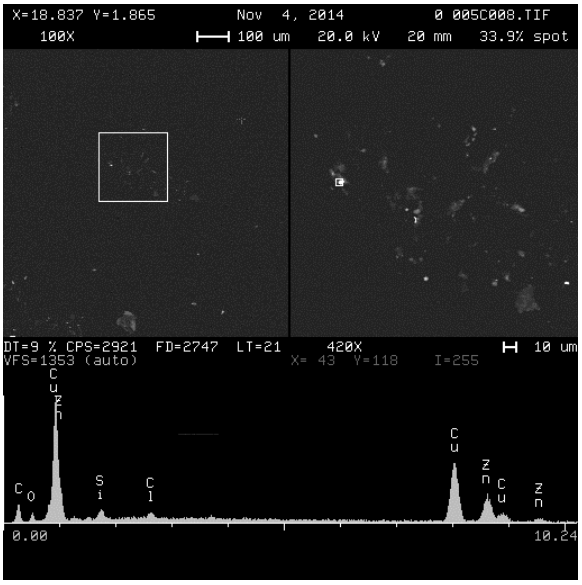


Figure 204

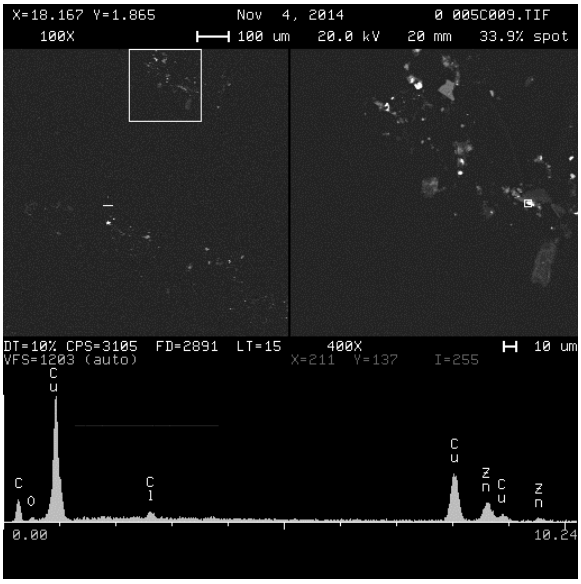


Figure 205

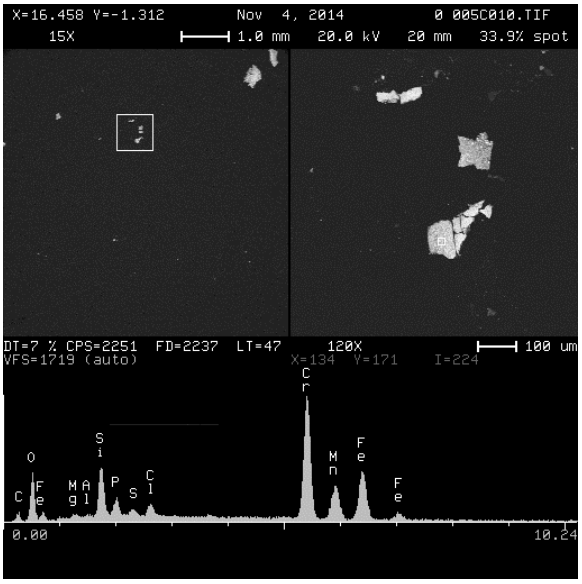


Figure 206

Sample 6C

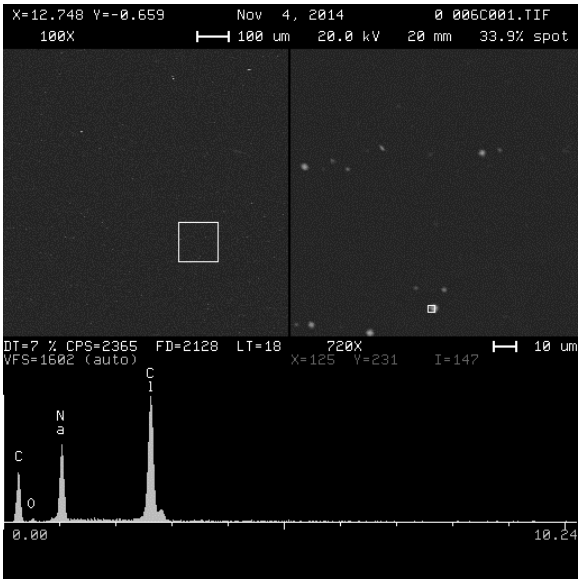


Figure 207

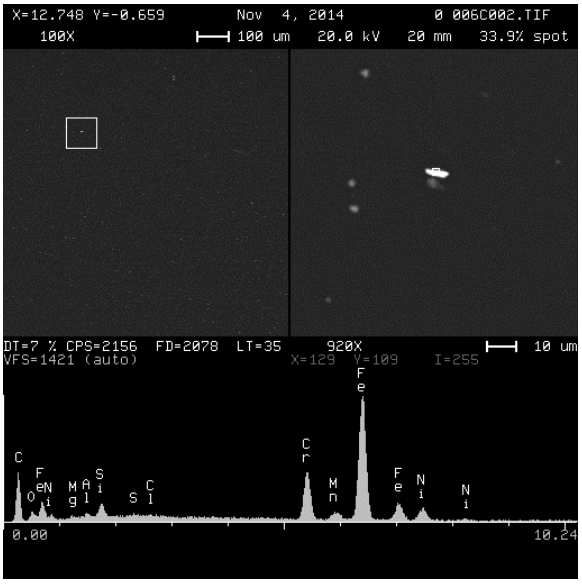


Figure 208

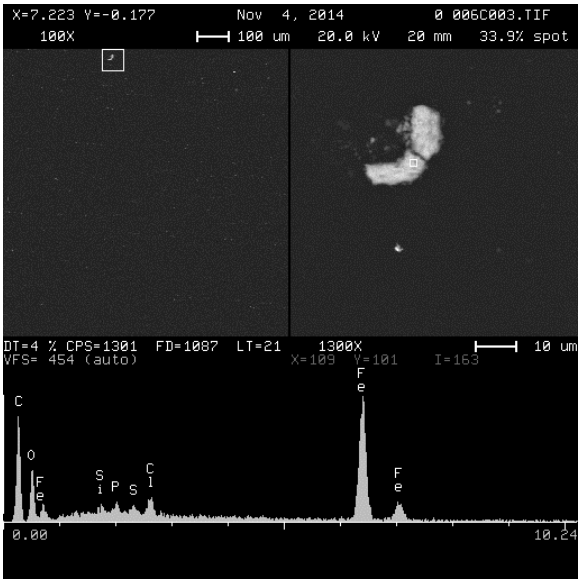


Figure 209

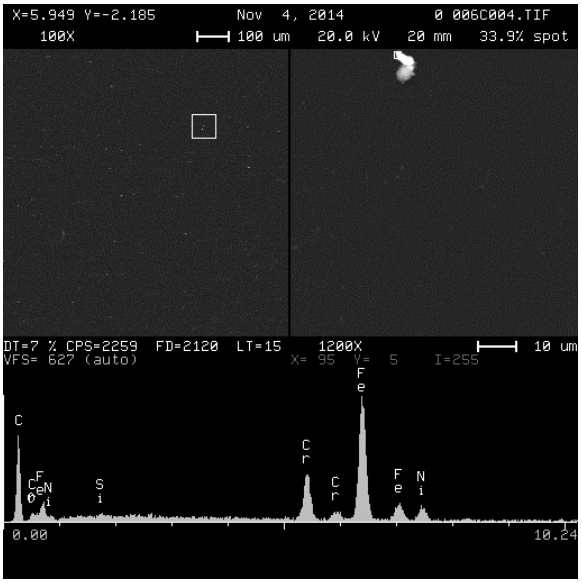
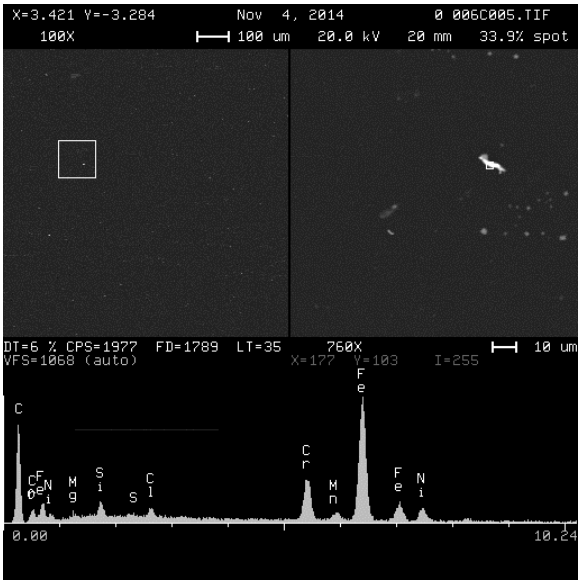


Figure 210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Nov 4, 2014
0 006C005.TIF
100X
100 um
20.0 kV
20 mm
33.9% spot
DT=6 % CPS=1977 FD=1789 LT=35
760X
10 um
VFS=1068 (auto)
X=177 Y=103 I=255
C
Cr
Mn
Fe
Fe
Ni
Mg
Si
S
Cl
0.00
10.24

Figure 211

APPENDIX I -
DOCUMENTATION PHOTOGRAPHS FOR CLEANING TRIALS

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CLEANING TRIAL DOCUMENTATION

Overall

Figure 1. Overall Cleaning trials A through K before

Figure 2. Overall Cleaning trials A through K before

Figure 3. Overall Cleaning trials A through K after

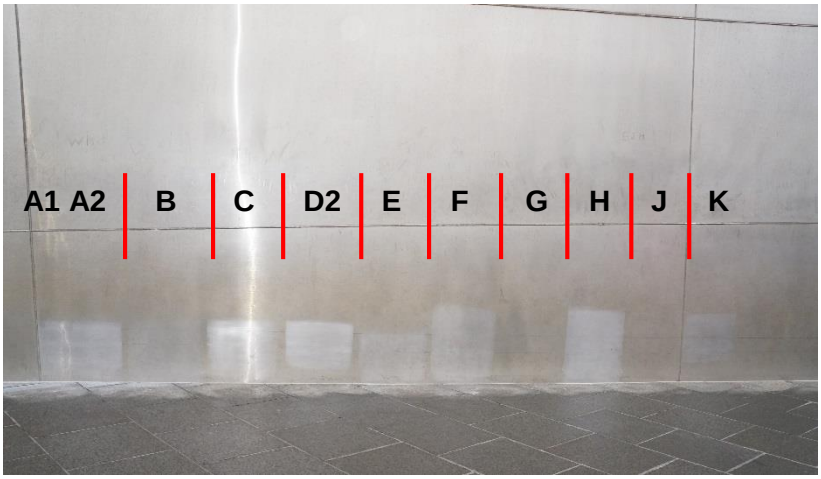

Figure 4. Overall Cleaning trials A through K after

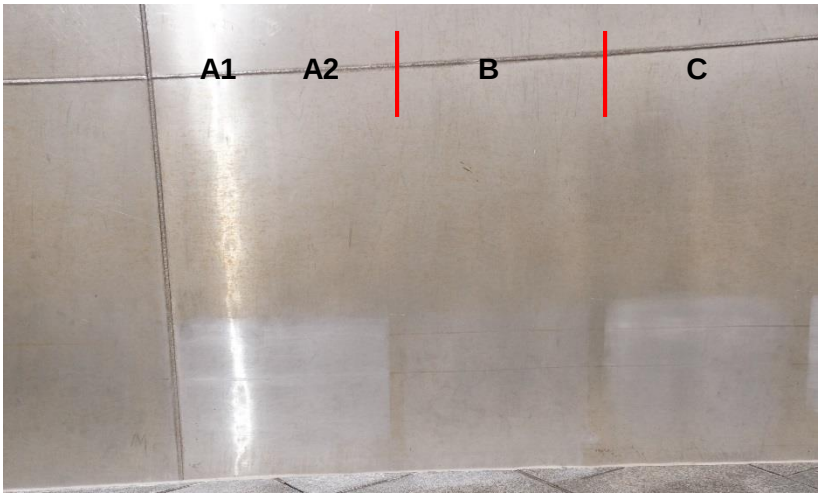

Figure 5. Overall Cleaning trials A through C after

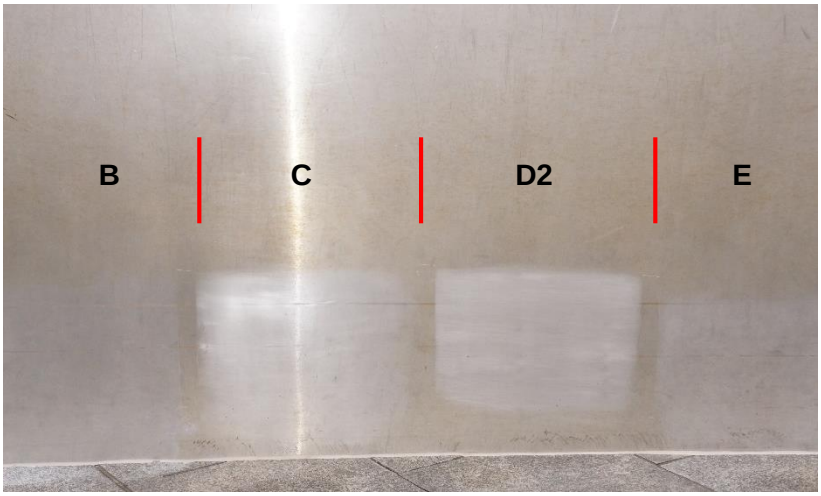

Figure 6. Overall Cleaning trials B through E after

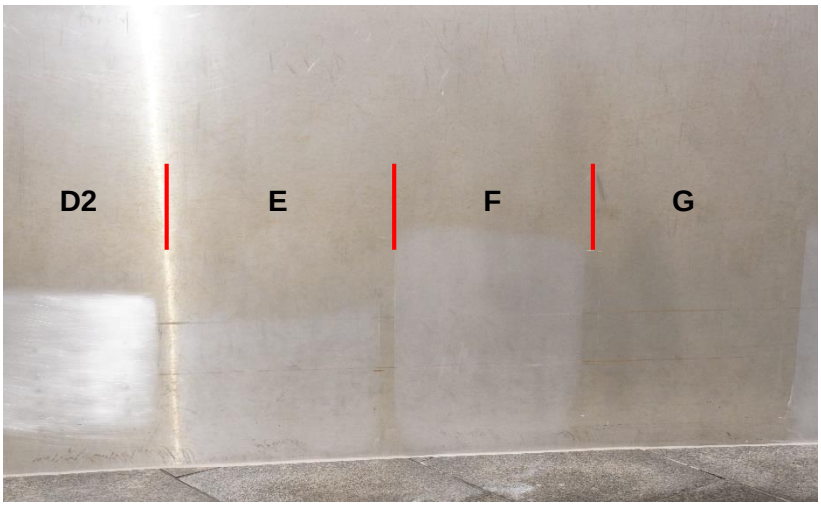

Figure 7. Overall Cleaning trials D2 through G after

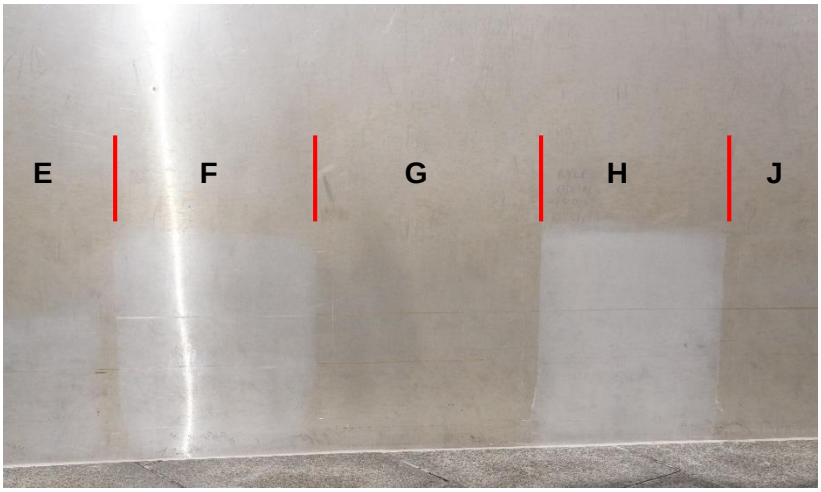

Figure 8. Overall Cleaning trials E through J after

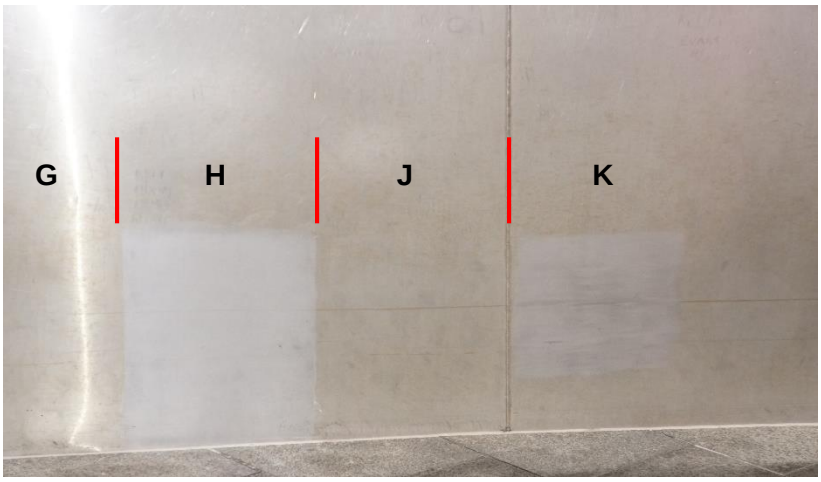

Figure 9. Overall Cleaning trials G through K after

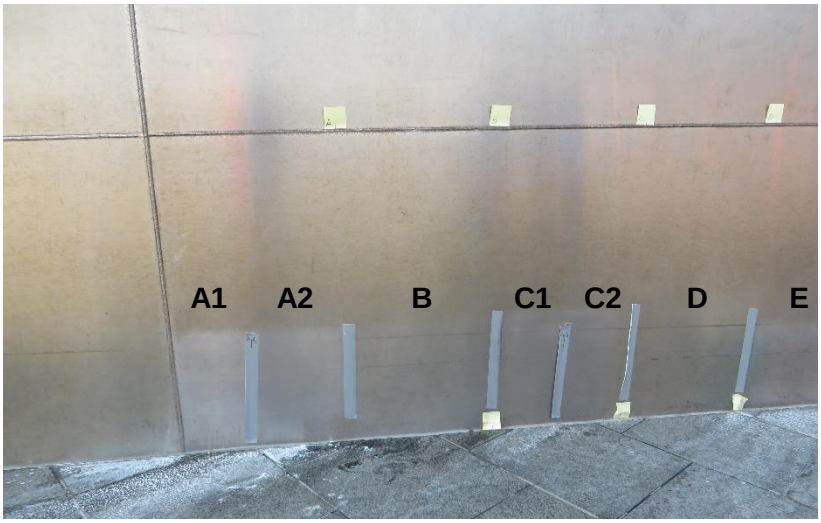

Figure 10. Overall Cleaning trials A through E after

Figure 11. Overall Cleaning trials A2 through F after

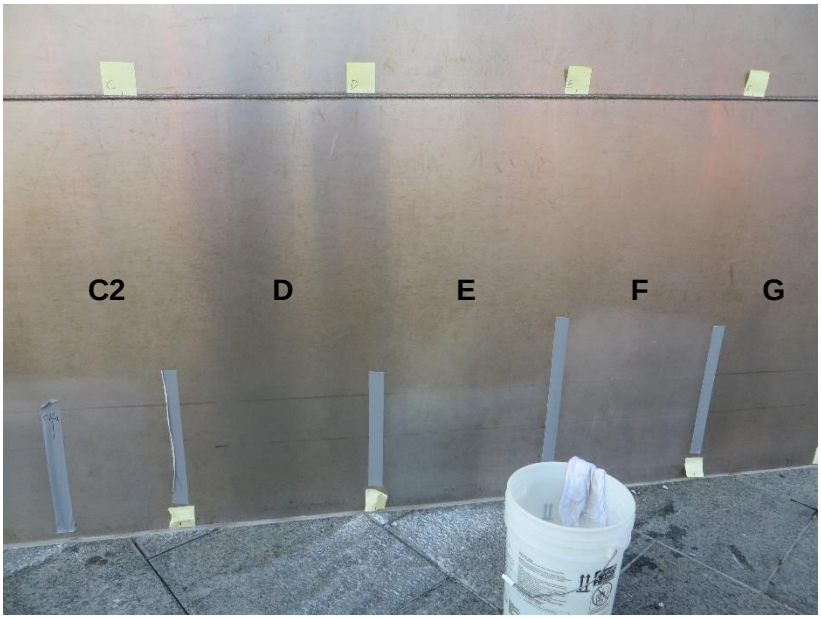

Figure 12. Overall Cleaning trials C2 through G after

Figure 13. Overall Cleaning trials E through J after

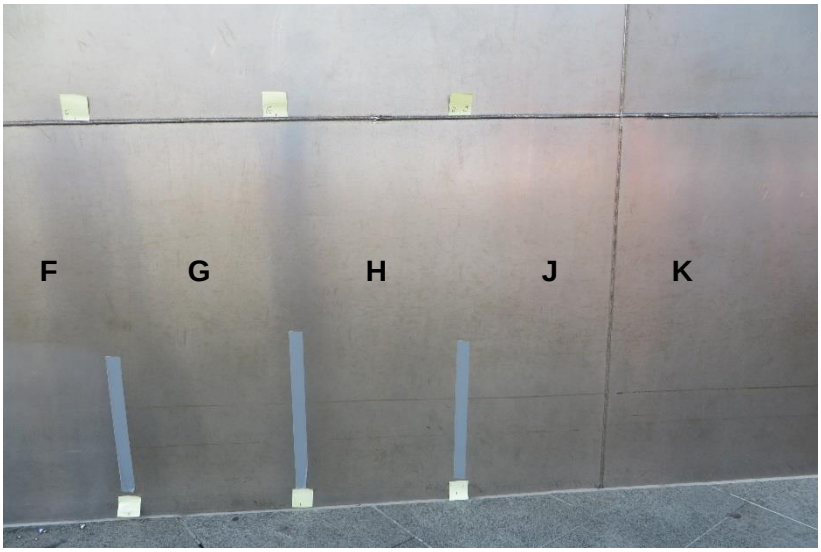

Figure 14. Overall Cleaning trials F through K after

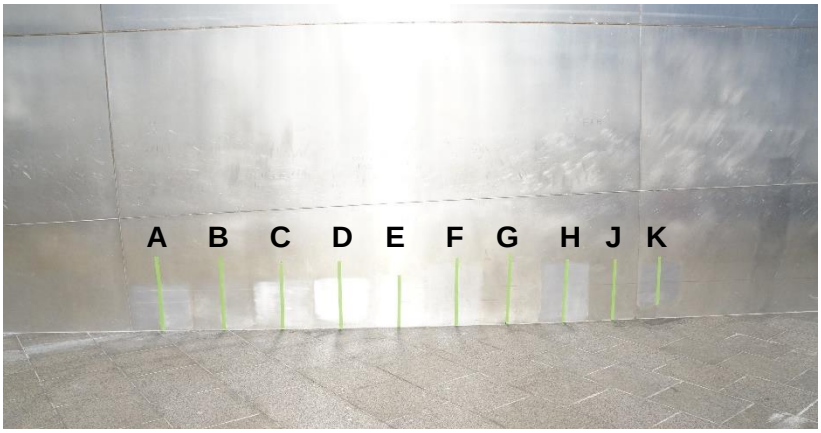

Figure 15. Overall Cleaning trials A through K after—note tape divides each sample in half

Figure 16. Overall Cleaning trials A through K after

Trial A

Figure 17. Trial A before

Figure 18. Trial A during

Figure 19. Trial A after

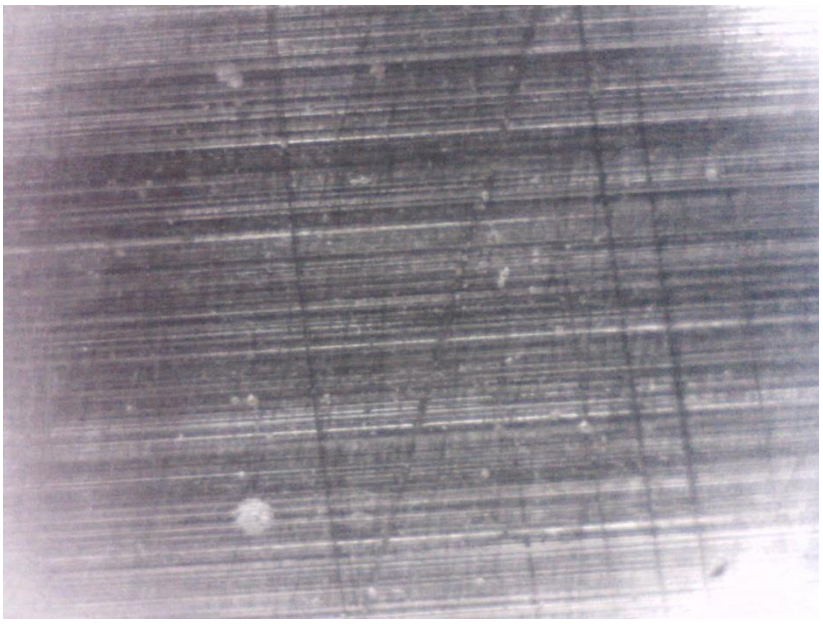

Figure 20. Photomicrograph Trial A after

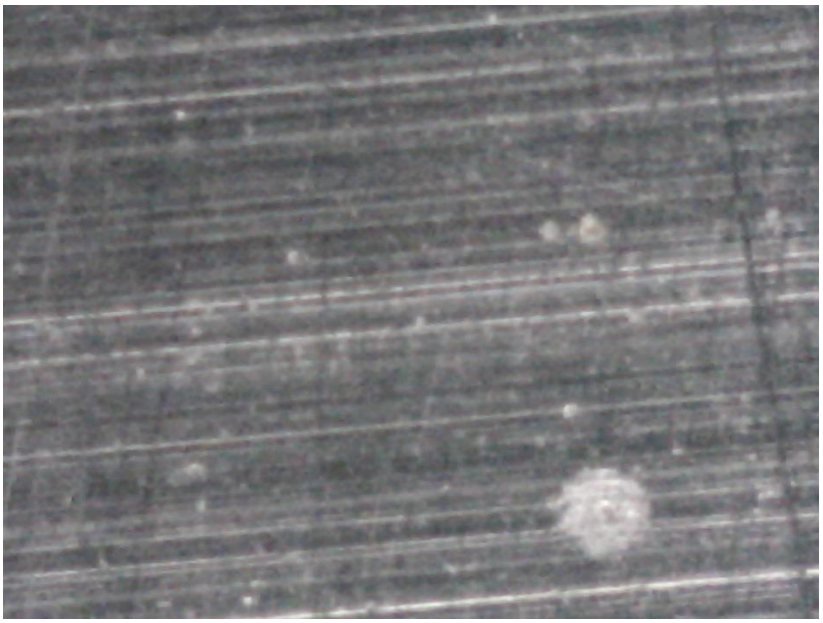

Figure 21. Photomicrograph Trial A after

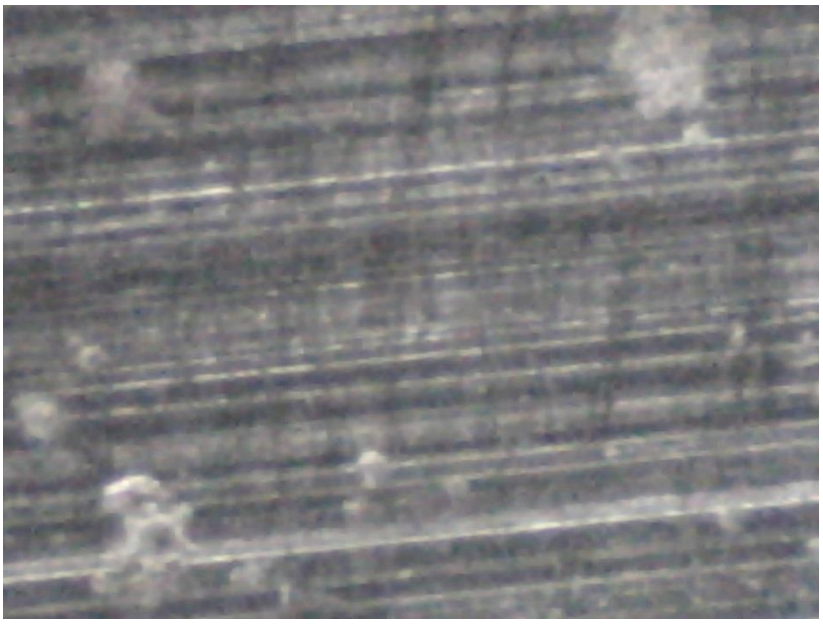

Figure 22. Photomicrograph Trial A after

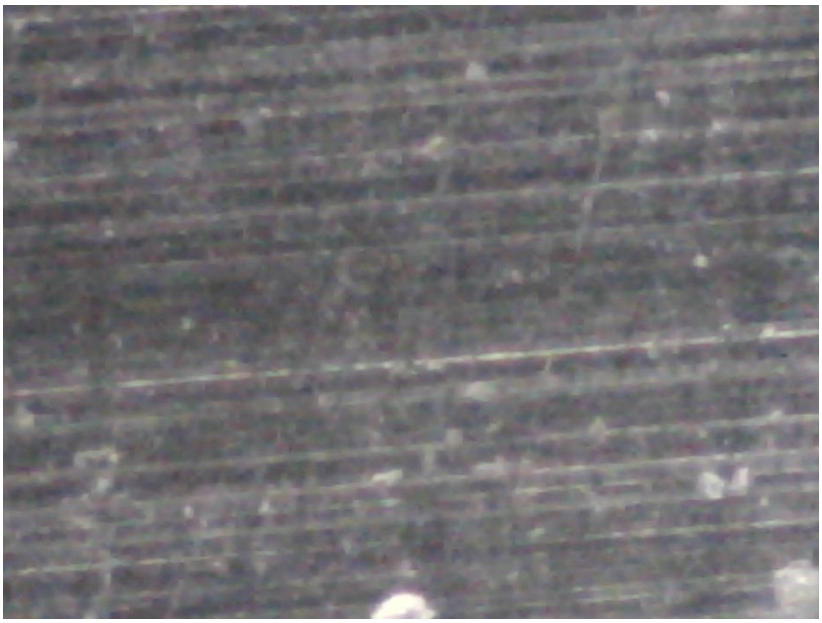

Figure 23. Photomicrograph Trial A after

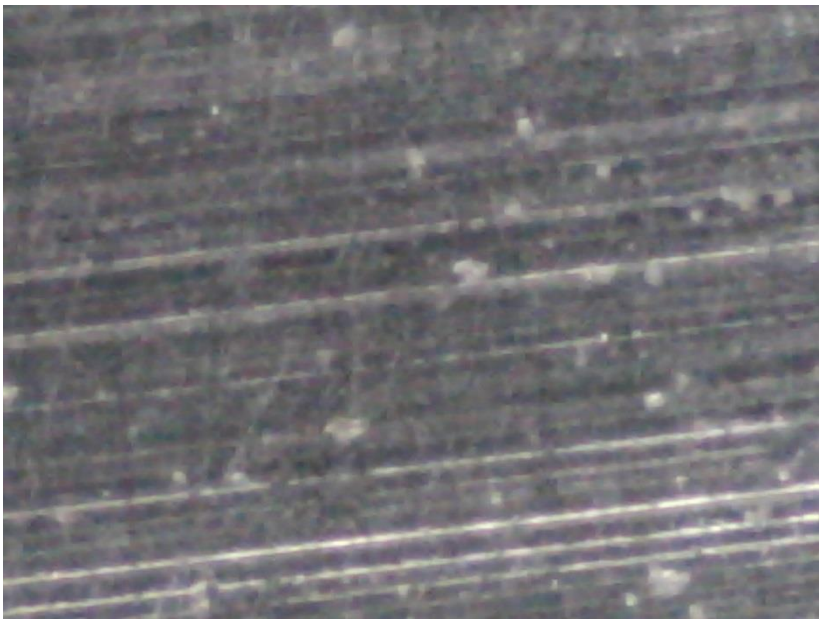

Figure 24. Photomicrograph Trial A after

TRIAL B

Figure 25. Trial B before

Figure 26. Trial B after

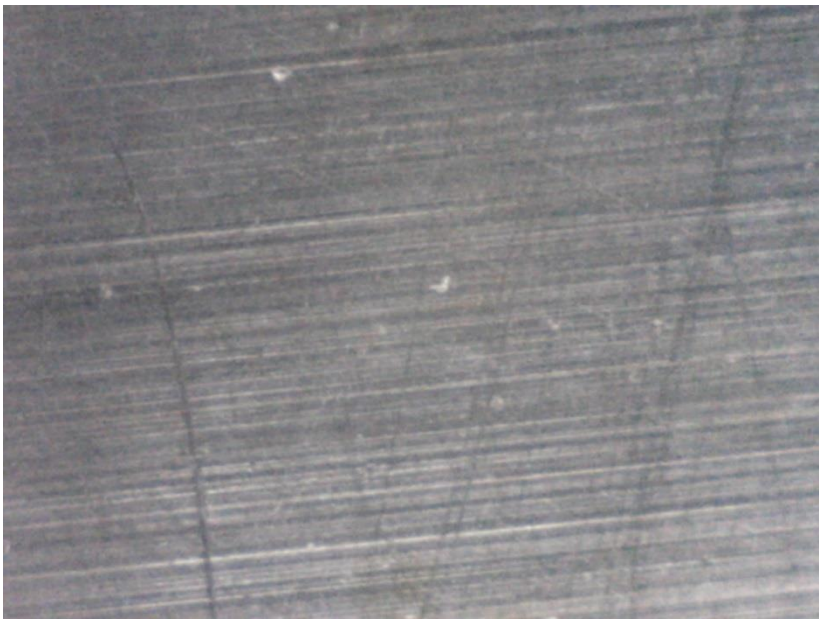

Figure 27. Photomicrograph Trial B

Trial C

Figure 28. Trial C Before

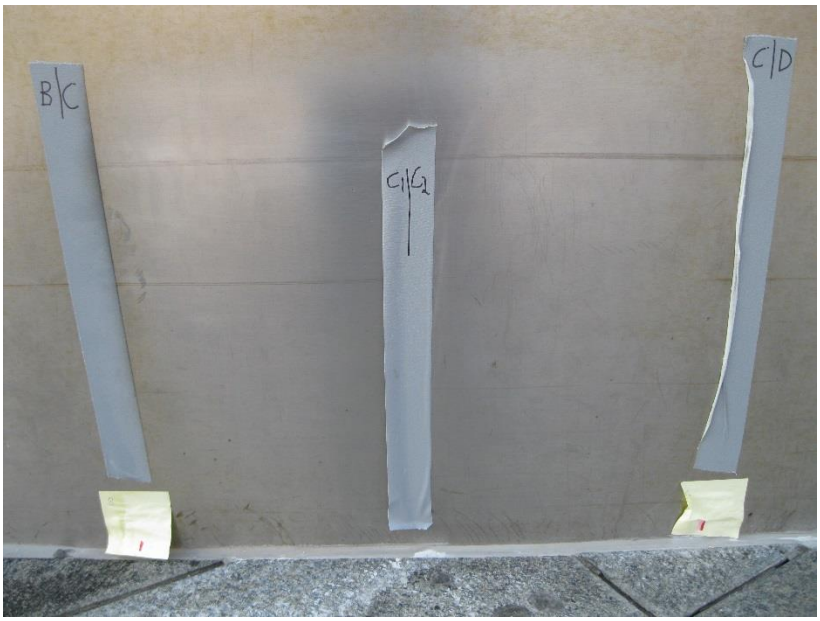

Figure 29. Trial C after

Figure 30. Trial C after

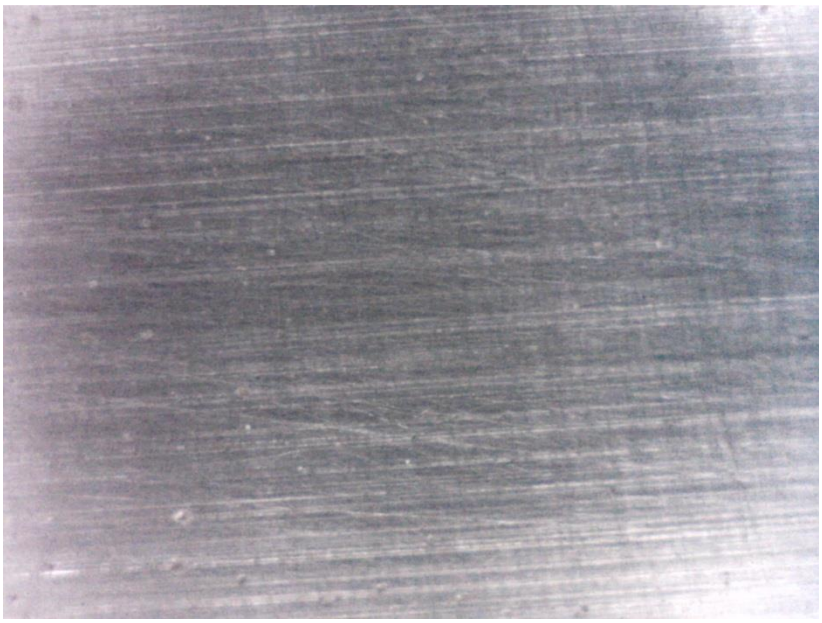

Figure 31. Photomicrograph Trial C after

Figure 32. Photomicrograph Trial C after

Figure 33. Photomicrograph Trial C after

Trial D

Figure 34. Trial D after

Trial D2

Figure 35. Trial D2 after

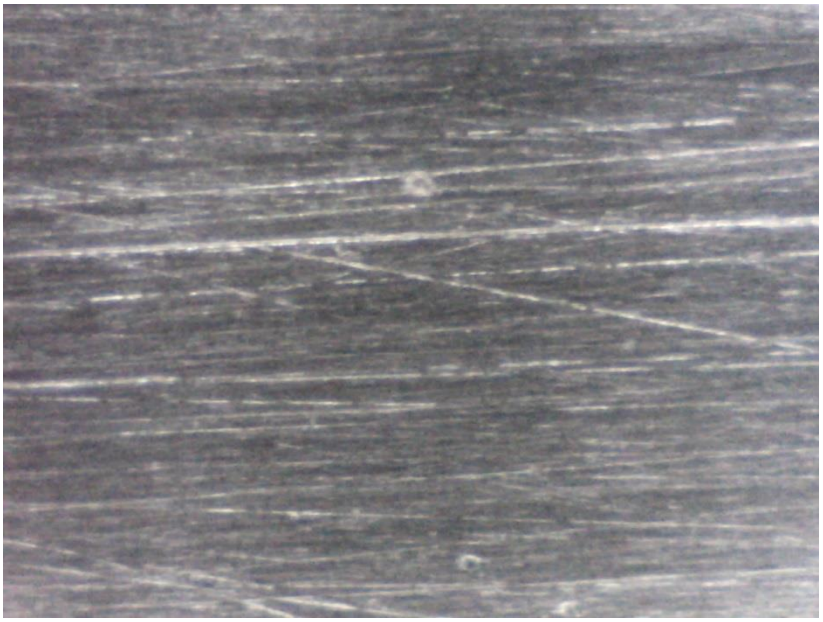

Figure 36. Photomicrograph Trial D2 after

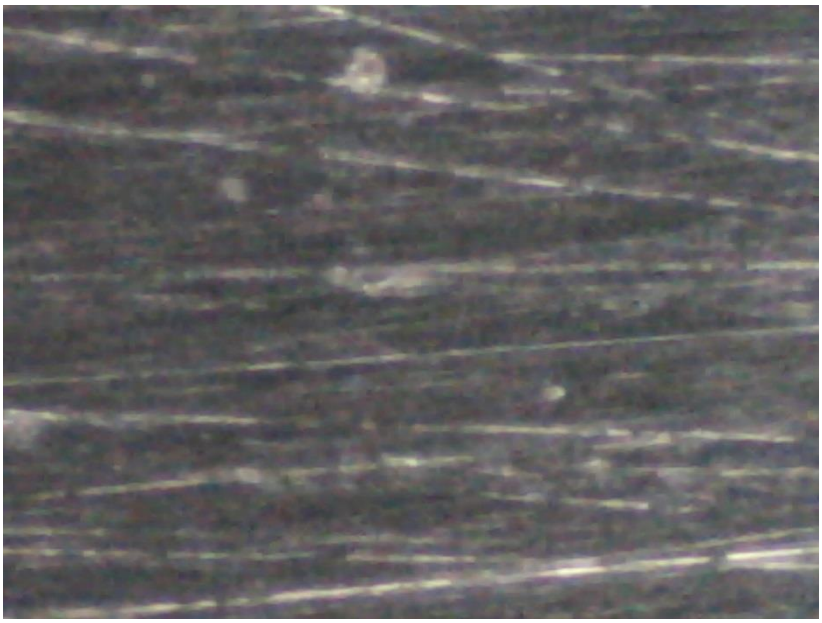

Figure 37. Photomicrograph Trial D2 after

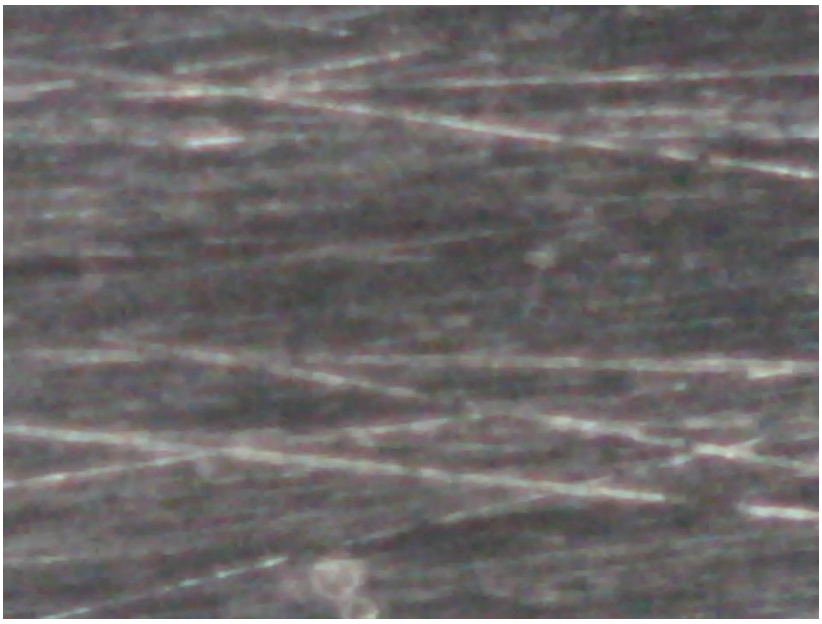

Figure 38. Photomicrograph Trial D2 after

Trial E

Figure 39. Trial E before

Figure 40. Trial E during

Figure 41. Trial E after

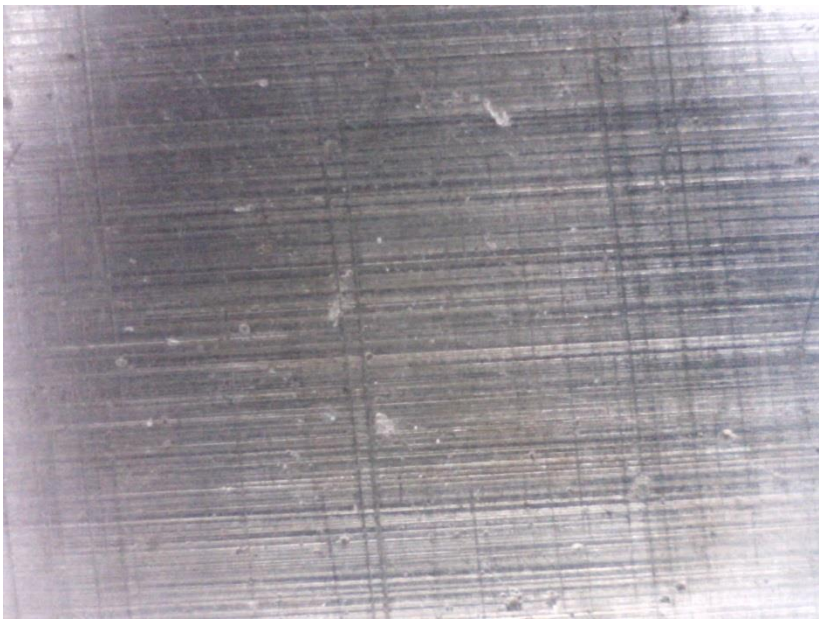

Figure 42. Photomicrograph Trial E after

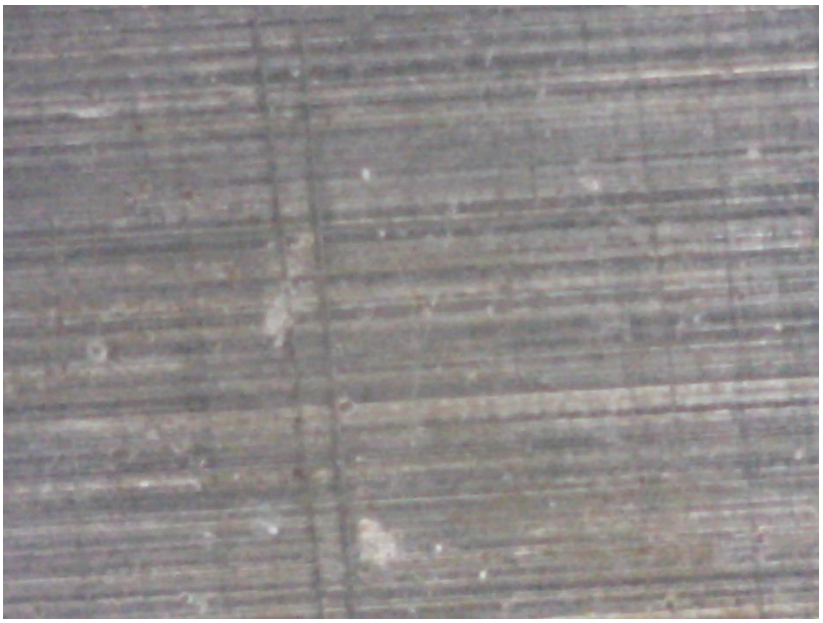

Figure 43. Photomicrograph Trial E after

Figure 44. Photomicrograph Trial E after

Trial F

Figure 45. Trial F before

Figure 46. Trial F after

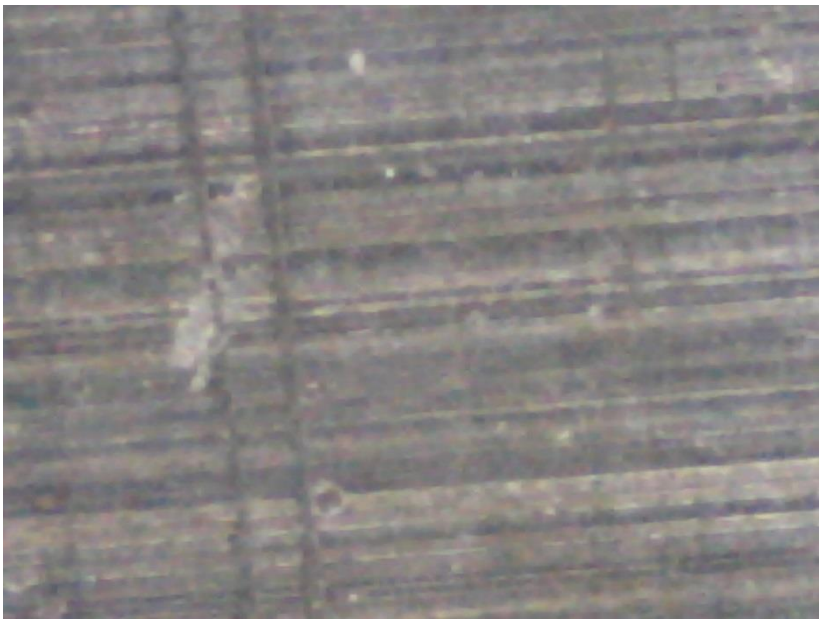

Figure 47. Photomicrograph Trial F after

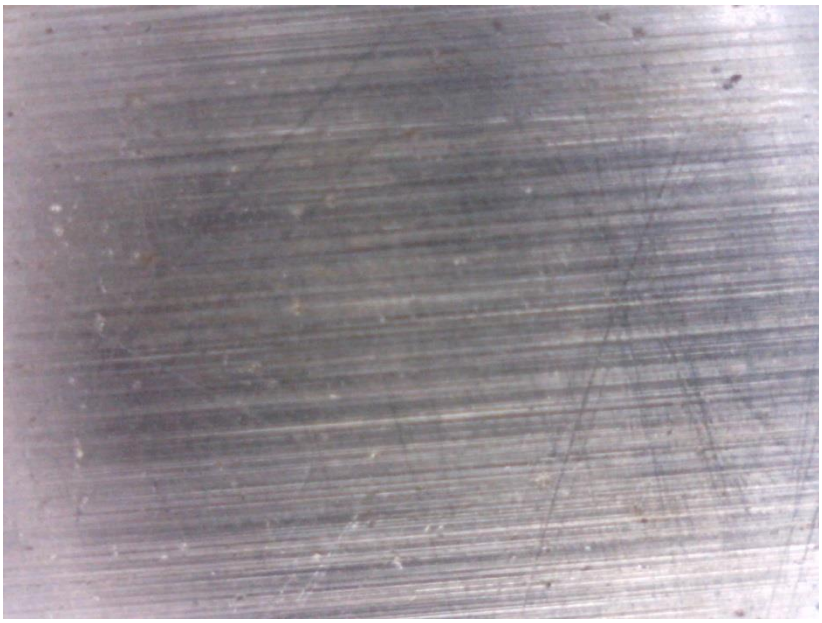

Figure 48. Photomicrograph Trial F after

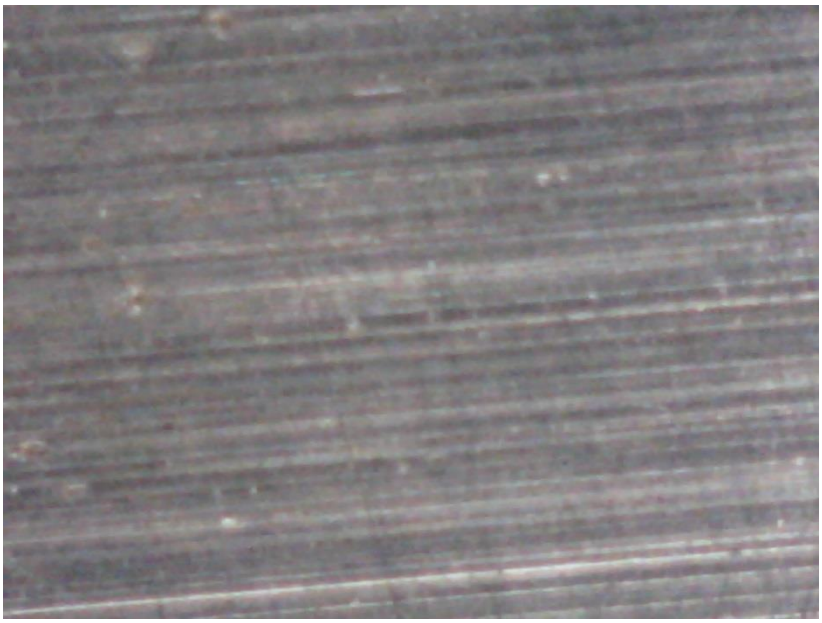

Figure 49. Photomicrograph Trial F after

Trial G

Figure 50. Trial G before

Figure 51. Trial G after

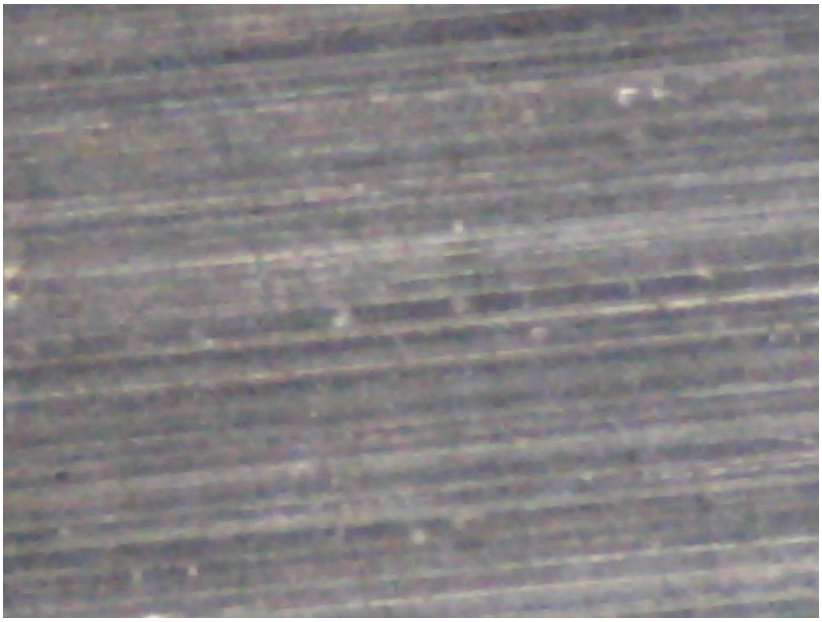

Figure 52. Photomicrograph Trial G after

Figure 53. Photomicrograph Trial G after

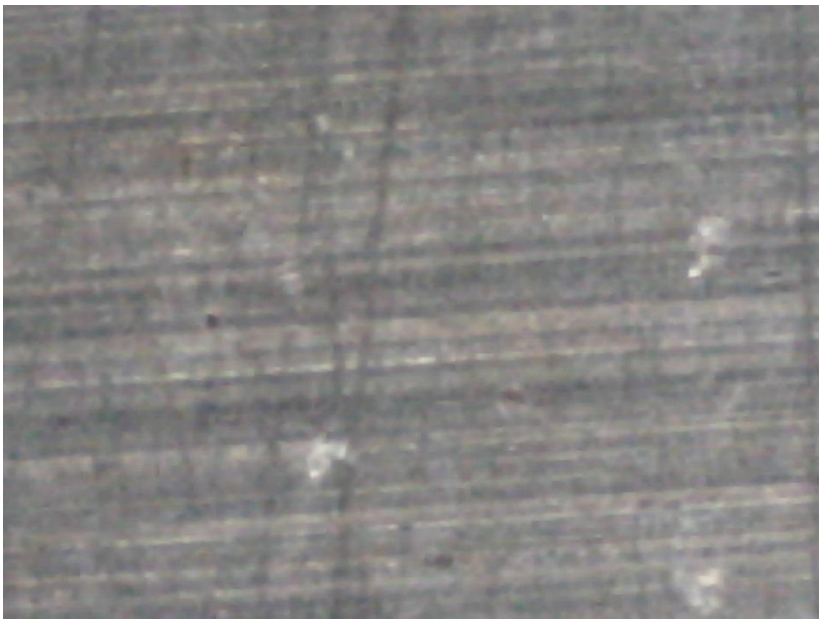

Figure 54. Photomicrograph Trial G after

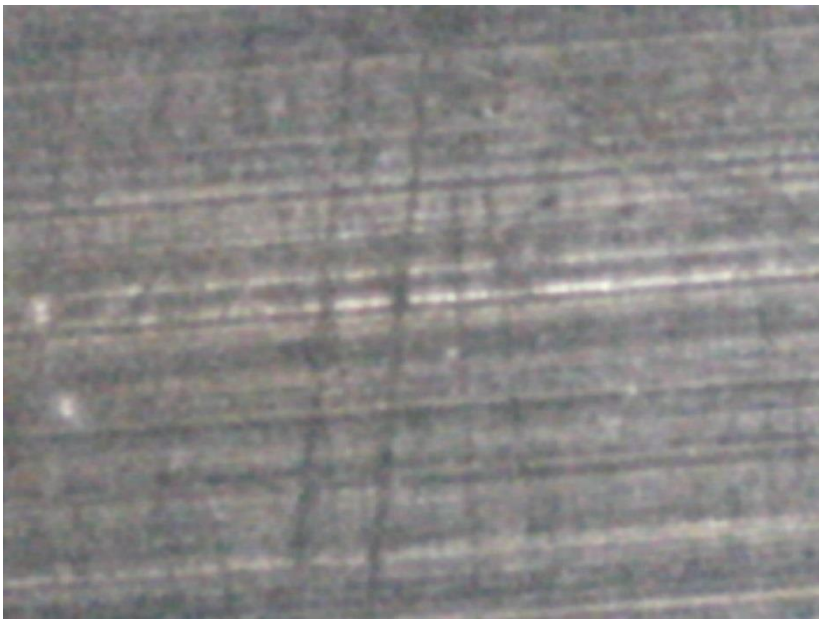

Figure 55. Photomicrograph Trial G after

Trial H

Figure 56. Trial H before

Figure 57. Trial H after

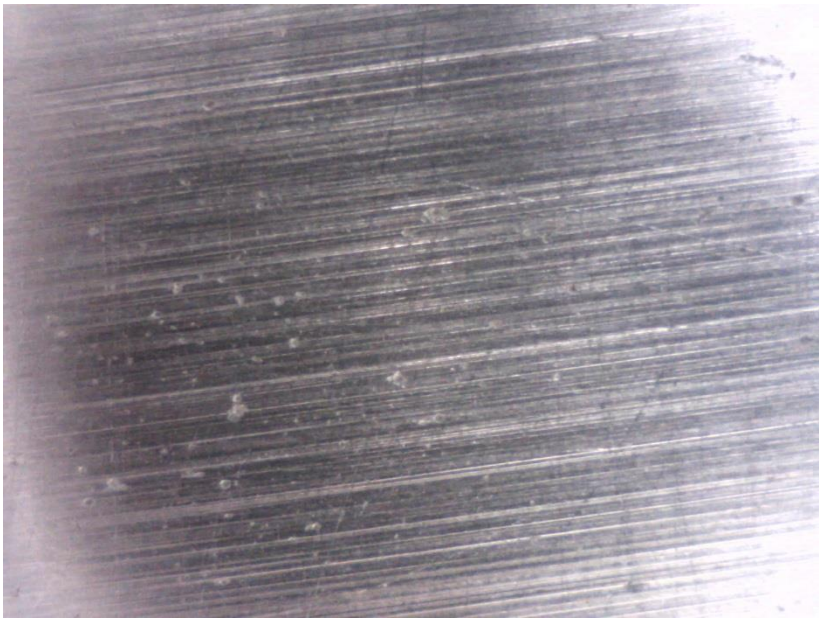

Figure 58. Photomicrograph Trial H after

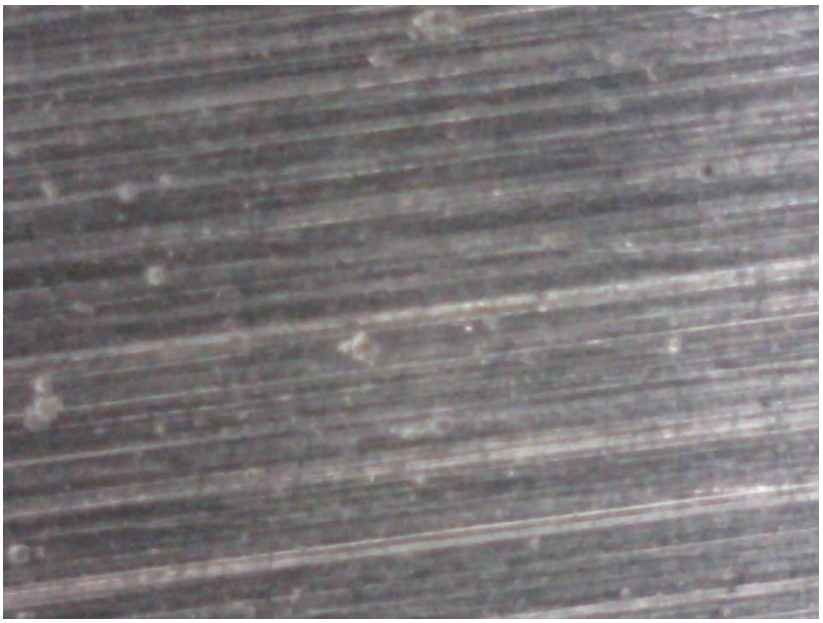

Figure 59. Photomicrograph Trial H after

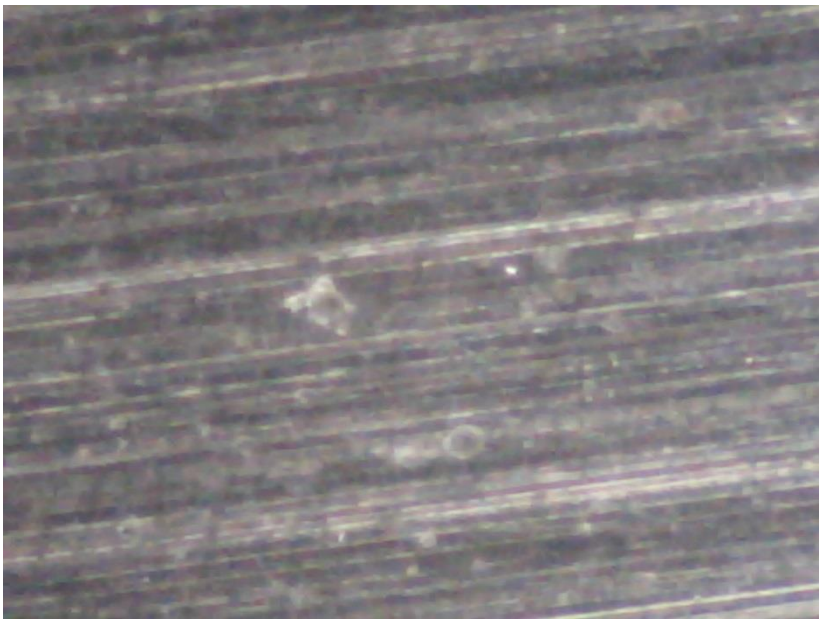

Figure 60. Photomicrograph Trial H after

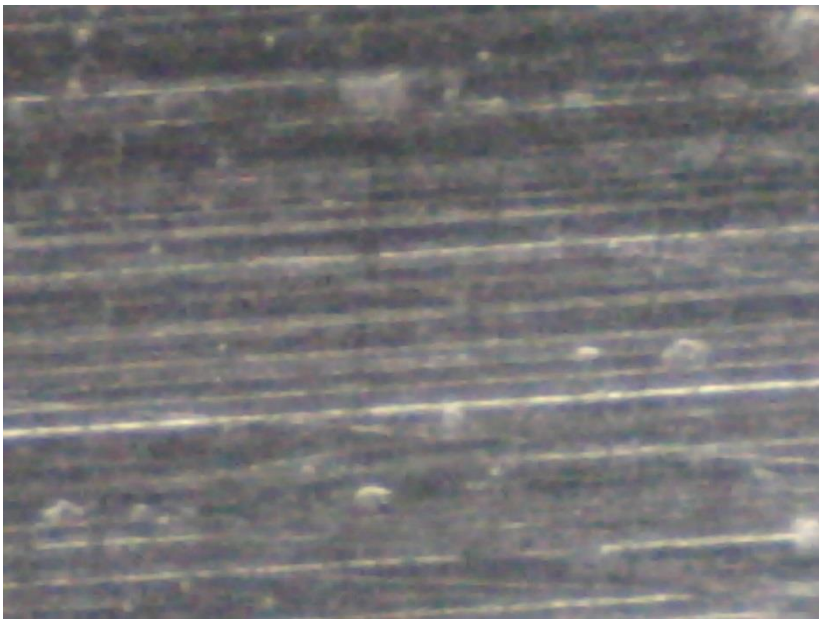

Figure 61. Photomicrograph Trial H after

Trial J

Figure 62. Trial J before

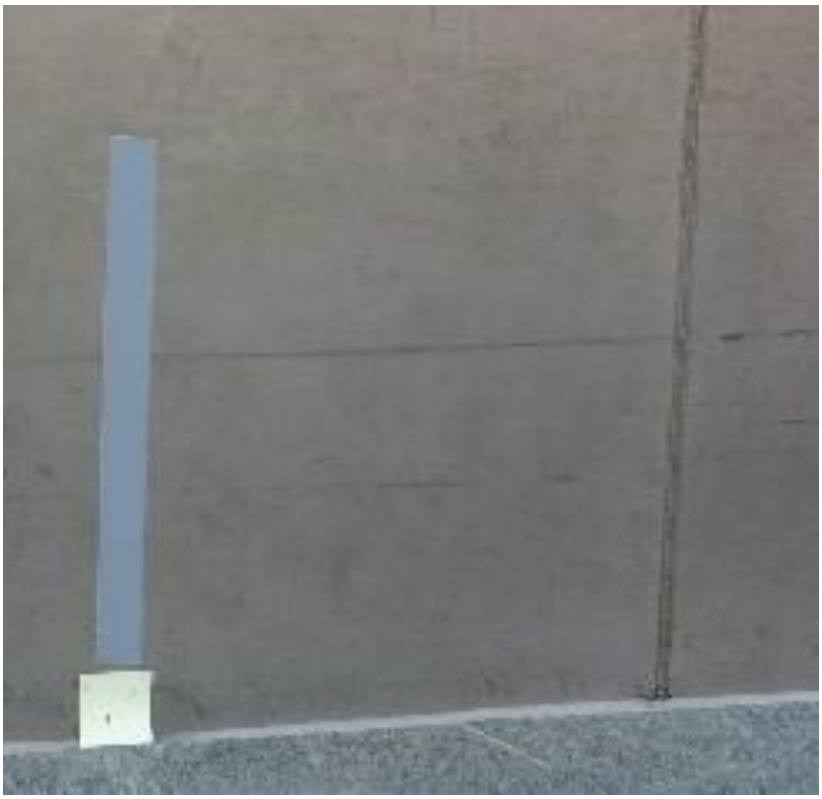

Figure 63. Trial J after

Figure 64. Photomicrograph Trial J after

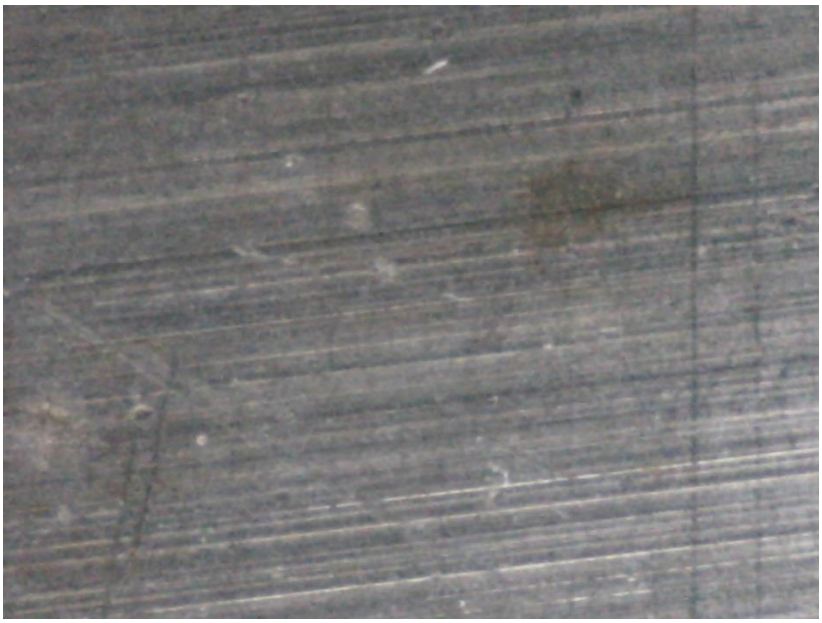

Figure 65. Photomicrograph Trial J after

Figure 66. Photomicrograph Trial J after

Trial K

Figure 67. Trials K before

Figure 68. Overall Cleaning trials F through K after

Figure 69. Trial K during

Figure 70. Trial K during

Figure 71. Trial K after

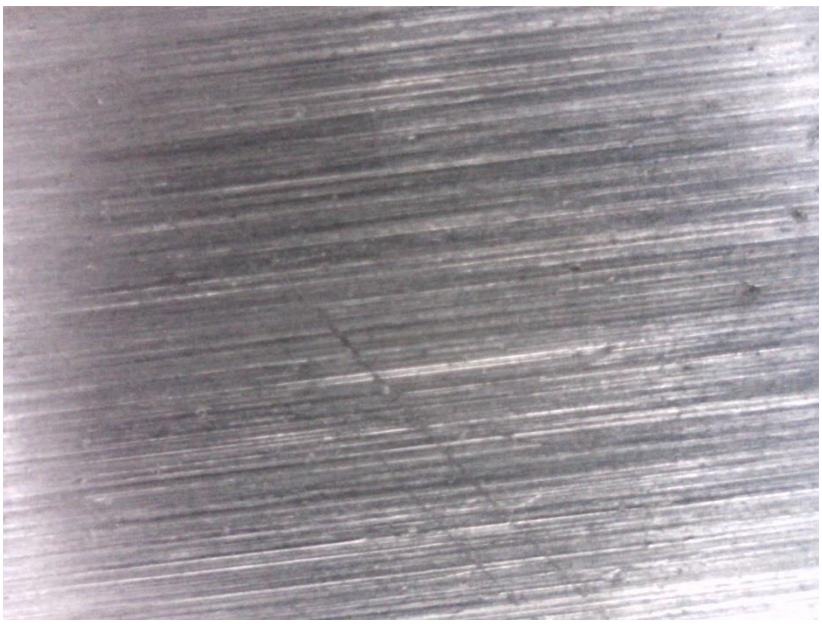

Figure 72. Photomicrograph Trial K after

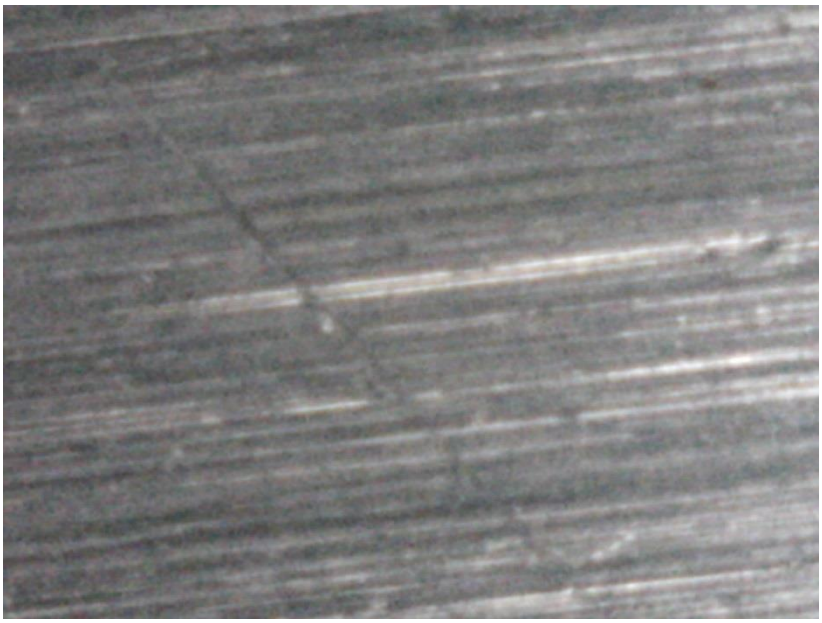

Figure 73. Photomicrograph Trial K after

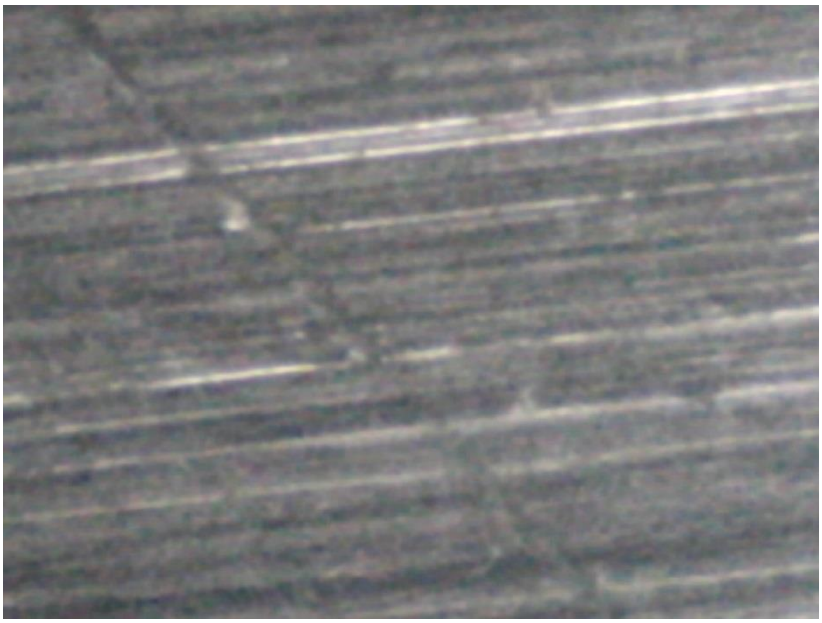

Figure 74. Photomicrograph Trial K after

Trial L

Figure 75. Trial L before

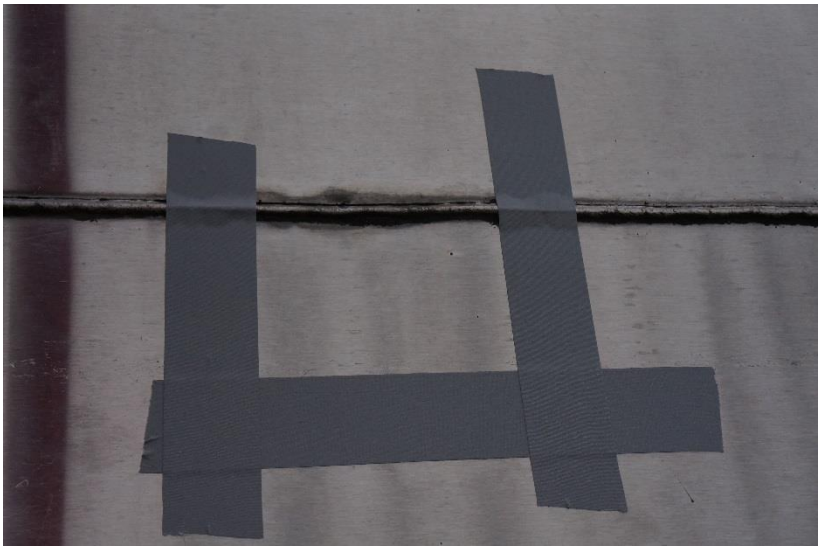

Figure 76. Trial L before

Figure 77. Trial L after

Figure 78. Trial L after

Trial M

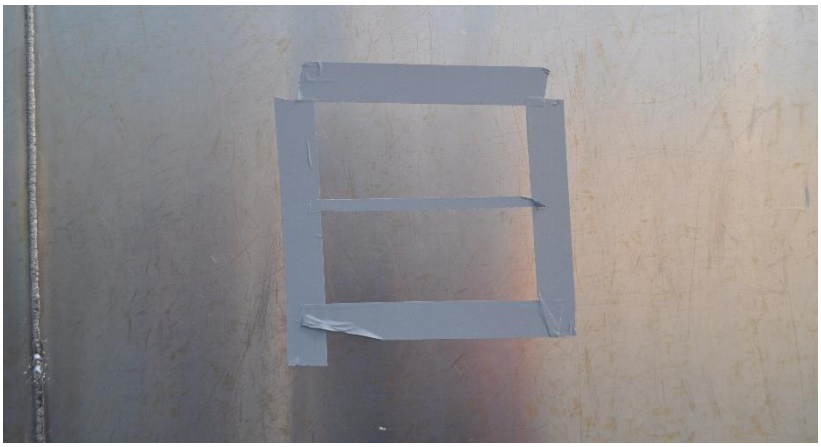

Figure 79. Trial M before

Figure 80. Trial M before

Figure 81. Trial M after

Figure 82. Trial M after

Trials N

Figure 83. Trial N before

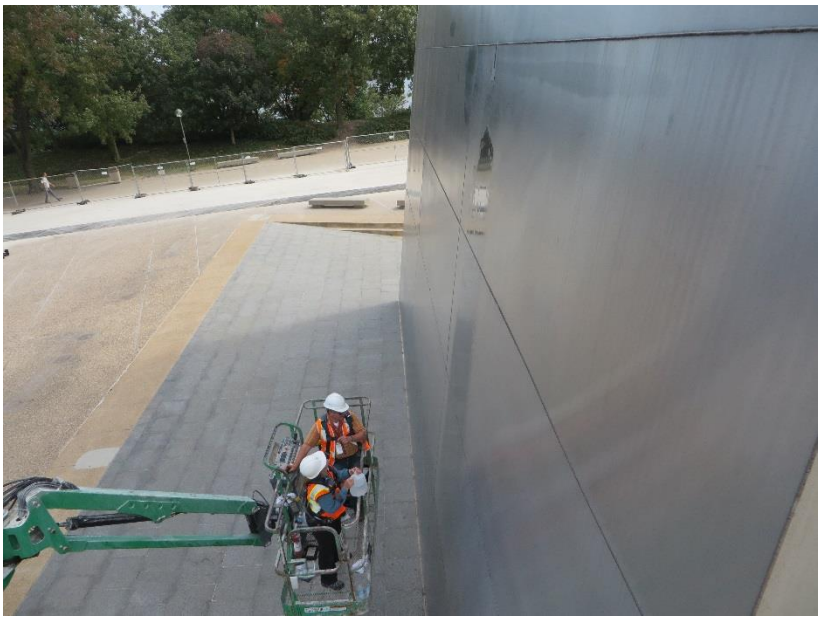

Figure 84. Overall Trial N during

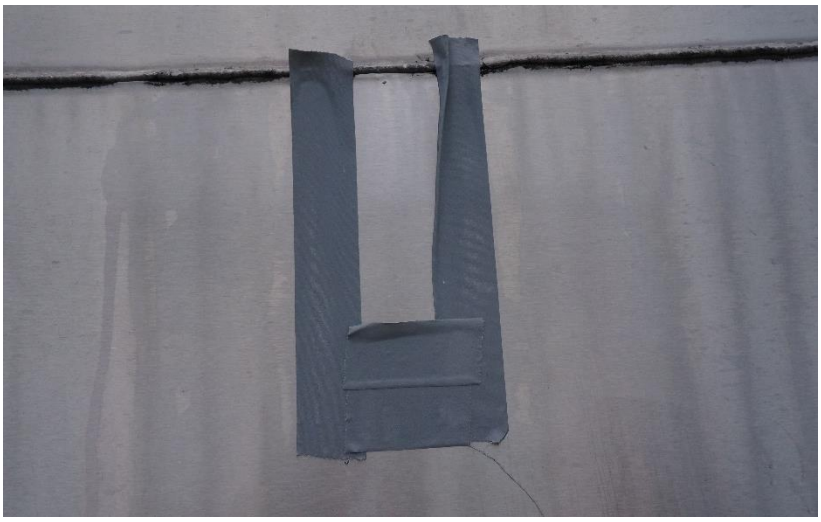

Figure 85. Trial N during

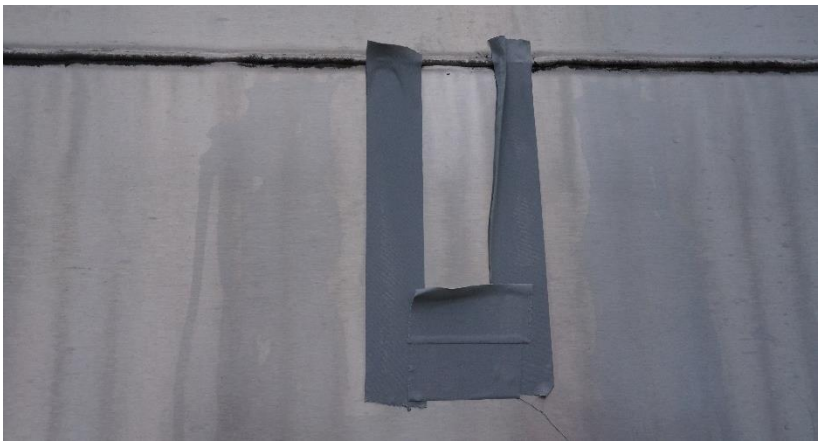

Figure 86. Trial N during

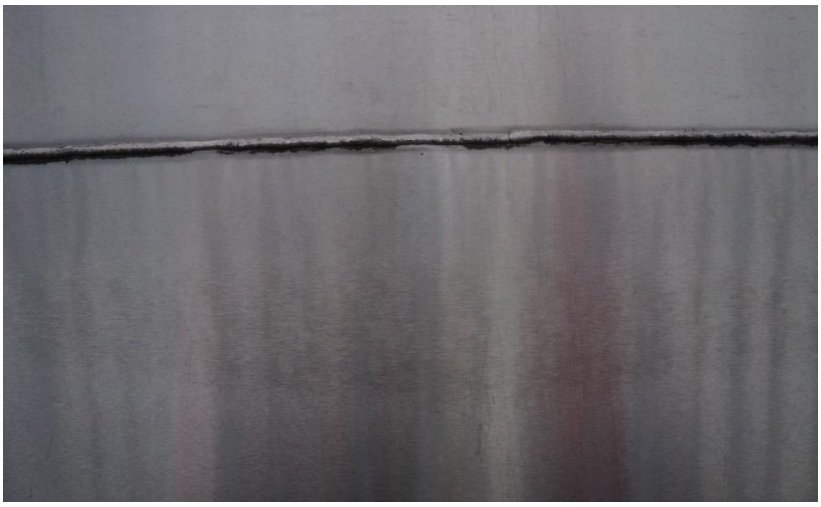

Figure 87. Trial N after

Trial O

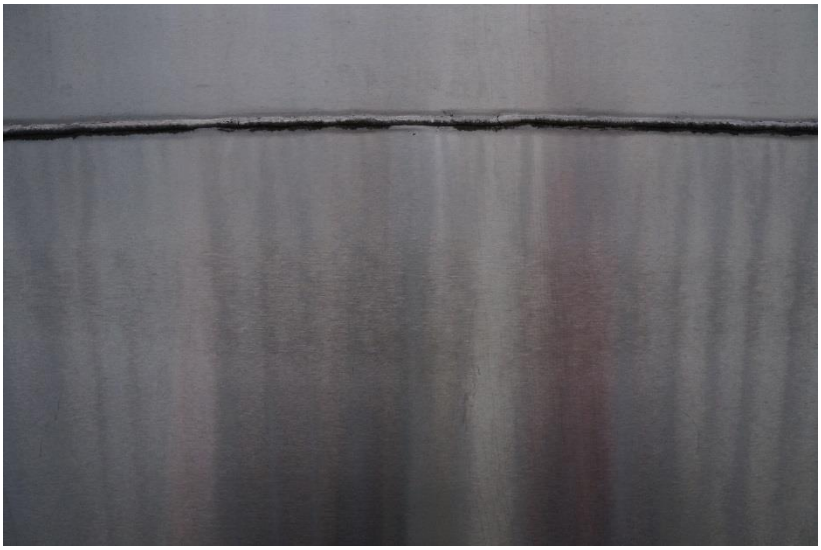

Figure 88. Trial O before

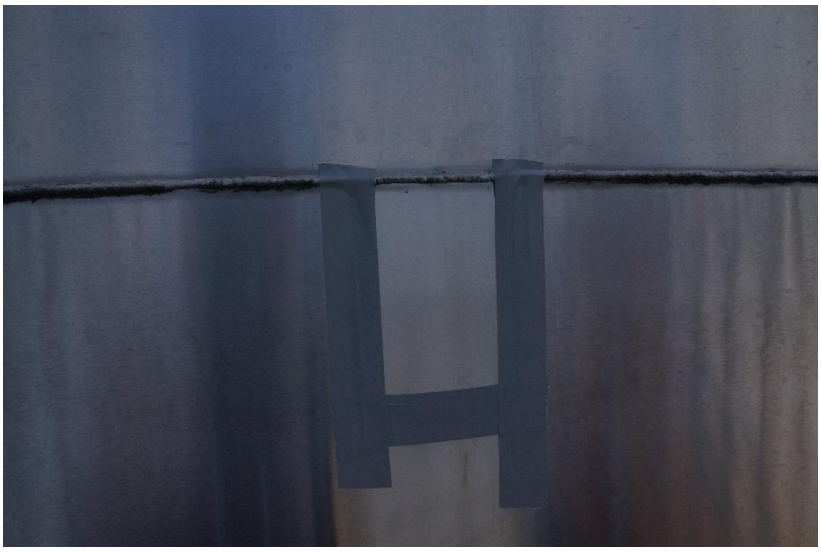

Figure 89. Trial O during

Figure 90. Trial O after

Trial P

Figure 91. Trial P before

Figure 92. Trial P after

Wax and Lanolin Trials

Figure 93. Wax and lanolin trials before

Figure 94. Wax and lanolin Trials after

Trials 1 through 6

Figure 95. Cleaning Trials 1 through 6 before

Figure 96. Overall location of cleaning samples 1 through 6.

Figure 97. Cleaning Trials 1 through 6 after

Figure 98. Cleaning Trials 1 through 6 after

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APPENDIX J -
TMR CONSULTING REPORT

Gateway Arch, St. Louis, Missouri

Metallurgical Assessment of the Stainless Steel Exterior Including: Weld Condition, Overall Performance, Site, Surface Discoloration and Deposit Evaluation

Prepared for:

Wiss, Janney, Elstner Associates, Inc.
10 South LaSalle Street, Suite 2600
Chicago, Illinois 60603

Prepared by:

TMR Consulting
3209 McKnight East Drive
Pittsburgh, Pennsylvania 15237
412.369.0377

14-944 (CMH)
February 27, 2015

Gateway Arch, St. Louis, Missouri

Metallurgical Assessment of the Stainless Steel Exterior Including: Weld Condition, Overall Performance, Site, Surface Discoloration and Deposit Evaluation

Report prepared by Catherine Houska with assistance from William Pratt

A - Investigation Goals

The goals of this investigation were to examine and evaluate the condition and structural integrity of the stainless steel plate exterior of the Gateway Arch, including the welds and surface discoloration, and suggest corrective action(s) if necessary as well as comment on expected performance based on those findings and a site assessment. Assistance was also provided during the cleaning trials and assessment of finish appearance variations, and that has been summarized by Wiss, Janney, Elstner in their report.

The investigation was based on multiple phone calls; visual assessment of the surface during two site visits; a corrosion site assessment based on current conditions and those that existed during the previous fifty years; collection of representative surface samples using gun shot residue (GSR) kits; laboratory evaluation of weld samples; review of available project, archive and technical documents; surface chloride testing; and SEM/EDS (Scanning Electron Microscopy and Energy Dispersive Spectroscopy) of both the GSR kits and weld samples.

B - Conclusions

Overall the Gateway Arch is in very good condition. Although at least some welds are sensitized due to re-welding and excessive heat input, no corrosion was found adjoining the welds on the North leg indicating that the environment has not been corrosive enough for the sensitization to cause corrosion. The service environment is less corrosive now then it has been historically due to the dramatic reduction in pollutants from heavy industry. Weld imperfections were found within the five samples collected but none were of concern. The stainless steel appears to be the specified Type 304 with matching chemistry filler metal.

The base had light surface staining due to microscopic superficial shallow deicing salt corrosion pitting but it is a purely aesthetic issue. Very low concentrations of chlorides that are consistent in chemistry with deicing products were found in most of the surface samples and were probably from nearby roadways. The samples were collected in the autumn and the monument is well rain-washed during the summer, so this should be representative of the lowest chloride concentrations during the year.

The pavement at the base is heated and deicing products are reportedly not used. If the National Park Service were to consider using a deicing product in the future, then calcium magnesium acetate (CMA) should be used. Unlike chloride containing products (e.g. sodium chloride, magnesium chloride, calcium chloride, potassium, chloride, etc.) or urea, CMA is not corrosive to stainless steel or other construction materials.

The chloride related light staining at the base maybe the result of graffiti scratching creating a rougher surface or differences in rain washing. Hot water power washing in the spring with a chloride releaser additive such as Chlor-Wash or Chlor-Rid could minimize further staining and help to remove other surface accumulations.

Several long deep scratches along the base, which contained embedded iron, are a potential long-term concern. Even if the rest of the base is not cleaned, this embedded iron should be removed because the stainless steel underneath it will continue to corrode under the corrosion deposit. This area should be monitored if no cleaning is done.

Higher on the North leg most of the discoloration was grey, black or brown in color with some scattered small areas of superficial red toned staining. The deposits found on the surface correlate with the industries that are currently present or were in the area during the past 50 years and were mainly soil, fly ash, iron and steel slag, and iron particles. In a few locations there were also copper, copper zinc, lead, and titanium particles. The very localized scattered red toned surface staining above the base is associated with oxidation of the iron particles from nearby industry. These are assumed to be old deposits since emissions of this type are no longer permitted and the industries from which many of these particles were probably emitted have shut down. Small amounts of chlorides (deicing salt) were found on most of these samples from the highways surrounding the site.

Unless there is a dramatic change in the environment, such as much higher chloride salt levels, there is no concern about the continued good performance of the Gateway Arch.

C – Executive Summary

1. **1960's Metal Production Technology** - This stainless steel was produced prior to the introduction of AOD (Argon Oxygen Decarburization) furnace technology into the US stainless steel industry. Both higher carbon and sulfur levels must be assumed because of the technology that was used at that time and they can affect corrosion resistance.

2. **Stainless Steel Plate and Weld Filler Metal Chemistry** – Neither of the stainless steel plate producers (Outokumpu and ATI) nor the Gateway Arch archive had retained the original chemistry certifications. The weld filler metal supplier(s) are unknown and no certifications had been retained in the archives. The weld sample size agreed by the NPS and WJE was quite small and it was necessary to retain the samples. This made it impossible to do a full laboratory chemistry evaluation. Alloy verification was done using Scanning Electron Microscopy and Energy Dispersive Spectroscopy (SEM/EDS). This technique is not exact and is only permissible for general alloy verification. The plate appears to be the specified Type 304 with an appropriate matching chemistry filler metal.

3. **Site Corrosiveness Assessment** – Deicing chlorides (salts) are used on highways surrounding the site and that use has increased during the past fifty years. They are far enough away to make likely deicing salt exposure low based on the IL DOT/Argonne National Lab/NADP research in the Chicago area. Only very small amounts of chlorides were found on the surface using sensitive GSR lifts during the September and October 2014 inspections.

   Although there are still some industrial plants in the area, their emissions are minimal relative to the high levels of heavy industrial pollution that were once found in the city due metal production, coal burning power, chemical and other plants. The surface deposits are

described in item 7. Environmental emission regulations and changes in local industry have significantly reduced exposure to potentially corrosive pollution. This site is less corrosive then it was over most of the monument's life.

4. **Appearance, Cleaning & Remedial Action** – The cleaning and surface restoration trials are discussed in the WJE report. Further corrosion of the base could be limited by removal of the embedded iron from scratched areas, cleaning to remove corrosion staining and surface deposits, and chemical passivation in accordance with ASTM A967 to remove surface sulfides exposed by accidental and deliberate surface abrasion. The technical reasons for this are described in this report. Chemical passivation is most commonly done with nitric acid but other acids (e.g. phosphoric, oxalic, etc.) are acceptable if applied in accordance with A967.

   If the base were power washed annually, additional staining should be minimal unless more iron is embedded in the surface. No coating or cleaning method should be used without the review and approval of a stainless steel metallurgist that specializes in atmospheric corrosion and aesthetic finishes. It is assumed that these options will be discussed in the WJE report.

5. **Weld Sensitization–** All five of the weld samples came from the lower sections of the North leg. Based on a review of the archives, these areas had been welded at least twice and some areas may have been welded three times, which explains their large size relative to the plate thickness. Even with today's low-carbon levels, the high levels of heat input associated with repeated welding of plate could cause sensitization (precipitation of carbides at grain boundaries), which decreases the corrosion resistance of the stainless steel plate adjoining the weld. Sensitization was found in the microstructures of all the samples, but neither they nor any area that was inspected exhibited the characteristic corrosion pattern associated with sensitization related corrosion. After 50 years of service, that indicates that even sensitized Type 304 is corrosion resistant enough for the current environment.

6. **Weld Imperfections** – Numerous weld imperfections were documented during visual examination and microscopic evaluation of the weld samples, including small areas of porosity, weld spatter, and weld slag. No cracking or significant corrosion was found at these imperfections after 50 years of service.

7. **Chloride and Surface Deposit Evaluation** – Minor amounts of deicing chlorides (salts) were found on the surface along with industrial particulates (i.e. fly ash, small ferrochrome oxide, iron and steel slag, iron, copper, copper zinc, lead, and titanium), carbon rich material (i.e. spores, pollens), clay materials, silica (sand), dolomite, mineral wool, paint particles, and calcite and magnesia alumina silicates.

   With the exception of the clay, sand, pollen and other characteristic constituents of normal surface "dust", the other accumulations can be explained by current and past heavy industrial activities in the area and nearby highways. The industrial pollutants could have been from plant emissions, dust generated as buildings were torn down or brown field site soil disturbed during reclamation or redevelopment. The iron particles that were not obviously from steel mills (i.e. iron without other elements) are typical of carbon steel particulate from construction sites.

The environment is not corrosive enough for these deposits to present a concern other then minor surface discoloration so their presence on the surface is a purely aesthetic issue. The iron particles found throughout these deposits could cause more red toned staining as they oxidize (i.e. corrode).

8 **Embedded Iron** - There were scratches on the surface of the base with embedded iron particles from carbon or alloy steel. The largest of these extend along the base, are relatively deep and may have been from a snowplow. This surface contamination should be removed because the deposit creates a crevice and corrosion does not stop when the iron has corroded away. The exposure of these areas to deicing salt increases the corrosion rate. Over time, linear, concentrated thickness loss due to corrosion could make weld repair necessary. Removal of the contamination should be with either a handheld electro-polishing wand or stainless steel pickling paste painted on to these localized areas with a small brush in accordance with ASTM A380 followed by chemical passivation to improve the corrosion resistance. Pickling is the most common chemical procedure used by the industry to remove oxides and heavily embedded iron contamination and consists of an acid mixture containing 8 to 20% (by volume) nitric acid (HNO_3) and 0.5 to 5% (by volume) hydrofluoric acid (HF). Pickling will dull the finish locally but careful limited application should mean that it is not noticeable.

D- Equipment List

Cameras: Panasonic DMC-FZ28 and Nikon Coolpix 4500
Sectioning: Buehler Samplmet Abrasive Cutter
Sanding: 4x36” and 1x30” belt sanders, 5” rotary disc sander
Mounting Compound: Buehler Varidur System
Abrasives: Aluminum Oxide-80, 120, 240 grit /Silicon Carbide-400, 600 grit
Polishing Abrasives: Buehler 6 micron and 1 micron diamond paste
Polishing Lubricant: Buehler Metadi Fluid
Polishing Pads: Buehler Microcloth PSA
Etchant: 10g oxalic acid dissolved in 90 mL of distilled water
Etching Mask: 3M 470 Electroplater’s Tape
DC Power Supply: BK Precision Model 1710
Microscope: Nikon Optiphot
Stereoscope: Leica MZ6
SEM/EDS Gunshot residue SEM/EDS sampling kits (small and large area)
Scanning Electron Microscope with Energy Dispersive Spectroscopy capability

E - 1960’s Stainless Steel Production and Chemistry

We were unable to locate the original mill or weld filler metal chemical certifications in the Gateway Arch archives. There has been considerable industry consolidation since the 1960’s and the mills that produced the plate are now part of the corporate history of ATI Allegheny Ludlum and Outokumpu. The Eastern Stainless mill (Outokumpu) has been closed for over 20 years. Neither firm had retained the 50-year old mill certificates but both provided information about the technology and testing capability of that time period. The archive records did not identify the source of the filler metal.

The stainless steel used for this project predates the installation of the first AOD furnace in the United States. Eastern Stainless, which supplied half of the plate for this project, became the

first US stainless steel mill to use an AOD in 1974. ATI began using AOD furnaces not long afterwards. AOD furnaces very efficiently remove impurities, including carbon and sulfur, and make overall chemistry control easier. So metal produced prior to their widespread use typically has higher levels of both elements and would not meet the requirements of the "low carbon" Type 304L austenitic stainless steels typically specified when welding sections that are 0.125 inches in thickness or greater today.[1]

Additionally, it typically took about three days to obtain heat chemistry during that time period so melt shops had higher target levels of alloying elements like chromium and nickel to ensure the desired properties. During the 1960's, the Type 304 plate specified for this project would have been ordered to ASTM A167. Type 304 and other common stainless steels were moved to ASTM A240 many years ago and A167 was recently withdrawn.

F – Weld Procedures

Welding procedure qualification records were found for the vertical and horizontal stainless steel butt joints in the archives dated January 7, 1964 (vertical) and May 18, 1963 (inclined horizontal).[2] It was not clear whether either was a final procedure and it appears that there were procedures for other joint configurations based on the correspondence in the file.

Both indicated that MIG welding was to be used, but there were different argon-CO_2 helium cover mixtures for each joint orientation. Both indicated that weld clean up was to be with a wire brush, there were to be two weld passes and a grooved back up root treatment. A Pittsburgh-Des Moines Steel Company letter dated December 5, 1963 mentioned removal of "weld haloes" (heat tint) using electrolytic methods.[3] Electrolytic cleaning wands are commonly used to remove heat tint today and it is an old technology, which probably has not changed much during the past 50 years. Presumably it was used in combination with brushing to restore corrosion resistance. Oakite 33, which is still sold today, was used to clean and degrease the surface prior to welding.[4] Both AWS Code and ASME code Section IX were referenced in the weld procedures.

G - Weld Sample Collection and Analysis

Five sample areas were selected on the North leg of the Arch after examination of the welds using a lift. Initially samples were only to be collected from the West face of the intrados but much higher levels of weld spatter and larger dark colored deposits were observed on the extrados welds making it desirable to see if there were other differences. Permission was obtained to obtain one sample from the extrados. The samples, which were approximately 0.75 inches in diameter, were removed by A. Zahner Company using a hole-saw with guides to prevent movement and the holes were filled with plugs welded in place followed by hand held electro polishing to remove heat tint and restore corrosion resistance.

The samples were centered on the welds and included small areas of both plates. We deliberately selected sample areas with larger weld beads, obvious weld repair or the other visual cues that might indicate a possible imperfection, since assessment of any problems would be the best indicator of any performance concerns. All of the samples came from the

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[1] Telephone and email conversations during 2014 with multiple current and retired employees of
[2] JEFF Archives, McDonald, Box 11, Folder 4 and Box 17, Folder 26
[3] JEFF Archives, McDonald, Box 10, Folder 5
[4] JEFF Archives, Same letter as 3, McDonald, Box 10, Folder 5

lower sections of the North leg. A mixture of "field" and "shop" welds were selected under the assumption that they had been exposed to the two different welding conditions.

However, during the second site visit, the daily reports were found and reviewed in the archives' Eero Saarinen files. The report dated September 4, 1963 indicated that the carbon and stainless steel shop welds had not been X-rayed properly prior to shipment. Extensive lack of penetration was found during a field X-ray. Problems with the field welding equipment were also identified around that time period. Subsequent reports included approvals for 100% X-ray inspection of all of the welds below N63 and S63. (See WJE report for architects weld designations.) Only spot X-ray checks had been done previously. All of the welds above this level were subsequently 100% inspected as they were installed.[5]

These records implied that most if not all of the carbon and stainless steel below these levels was re-welded due to incomplete penetration and some areas needed further repair after re-inspection. Therefore, all of the sample welds were probably welded at least twice with the second of those welds being a field weld. This explains the large weld beads observed relative to the thickness of the plate. Initially, weld beads that were larger in overall size (wide, a greater protrusion from the surface and uneven in appearance) were selected for samples W1 and W2, since they represented a probable worse case scenario. Unfortunately, it was not possible to keep the hole-saw guide in position to remove them and alternative welds were selected. Only relatively flat weld beads could be removed using the fixturing.

Each sample was documented and sectioned using a water-cooled abrasive cutting wheel. The metallographic sections were mounted and polished using progressively finer abrasives. A portion of the polished surface was then masked to expose a limited area for electrolytic etching. Etching was performed using an oxalic acid solution and a current density of approximately 1 amp per square centimeter for a period of 90 seconds. Using optical light microscopy each section was examined in the etched condition. Sections 1, 3, and 5 were also examined in the as-polished condition. Prior to etching, sections 1 and 5 were examined using SEM/EDS.

Appendix A includes Figures A1 through A39. These are images of each weld prior to removal, the as-received sample appearance, photo macro and micrographs of etched and un-etched weld cross-sections, and representative SEM /EDS evaluations of samples W1 and W5. Optical light microscopy of the sections revealed the following:

1. Varying degrees of sensitized were found in the grain boundaries in the heat affected zone (HAZ) of all five samples when they were examined in the etched condition. The band of sensitized grains on sample W2 was located approximately 0.045" from the edge of the weld. There was no surface corrosion associated with this sensitization on any sample examined. None of the inspectors found the classic pattern of sensitization related corrosion at any location on the Arch. This indicates that the environment has not been severe enough to present a corrosion problem to sensitized welds.

2. Varying amounts of weld porosity were noted in all of the sectioned welds. The largest weld metal void was noted in sample W4 with a diameter of approximately 0.04". Sample W5 contained a void with an approximate diameter of 0.024".

[5] JEFF Archives, Saarinen files, daily reports

3. Subsurface contamination was noted in the weld metal near the weld crown of sample W5. The composition of the contaminant was analyzed using SEM/EDS and it was identified as weld slag. Some surface slag was found on both samples W1 and W5. No corrosion was observed.

4. All of the welds in these samples appeared to be full penetration.

5. SEM/EDS confirmed the presence of manganese sulfides in the base metal of sample W1. Sulfides were seen in other samples that were not sent to the SEM for confirmation.

6. A shallow weld undercut was noted at the inside surface of the plate in sample W3. No cracking had occurred after 50 years and there was no corrosion associated with it.

Even with today's low carbon levels, the high levels of heat input associated with repeated re-welding of plate could cause sensitization (precipitation of carbides at grain boundaries), which decreases the corrosion resistance of the plate in bands adjoining the weld. Given the high carbon levels typical of stainless steel produced prior to the introduction of the AOD, the sensitization observed during weld cross sectioning is not surprising. Since the welds that were sampled were in an area known to have had weld repair, we cannot be certain that welds higher on the structure were also sensitized. None of the inspectors saw any location with the classic banded corrosion pattern that is typically associated with sensitization related corrosion. If it has not occurred after 50 years, the environment does not appear to be corrosive enough for this to be a concern.

Table 1 summarizes the weld sample locations, weld appearance, and the imperfections that were documented. The specific Appendix A figures, which document each imperfection, are noted using the letter "A" and image number. Appendix B explains these common weld imperfections.

Table 1: Weld core sample locations, observations and imperfections

Sample No.	Face	Row	Panel	Location	Observations during sample selection	Imperfections
W1	West	9	North	12 ft. from north edge of panel	Very wide rounded weld bead with possible weld slag on the surface. Identified as a field weld.	Plate: Sensitized (A4, A5), small inclusions (A6), manganese sulfide stringers (A7, A8) Weld: Surface weld slag confirmed (A9)
W2	West	10	Center	4 ft. from south edge of panel	Somewhat larger section of an otherwise smaller shop weld	Plate: Sensitized (A14, A15), a small surface void that may either be pitting corrosion or an inclusion pulled from the surface during polishing (A16) Weld: Weld porosity (A13)
W3	West	6	North	2 ft. from north edge of panel	Weld repair area, shop weld	Plate: sensitized (A20, A21, plate inclusion (A24) Weld: Outside notch on weld surface (A22), undercut (A23), weld void (A25)
W4	West	6	North	6 ft. from north edge of panel	Somewhat recessed area shop weld with possible weld slag	Plate: sensitized (A29) Weld: Numerous small voids (A28)
W5	North - extrados	8	West	1 ft. from east edge of panel	Somewhat larger weld with possible weld slag	Plate: sensitized (A34) Weld: small void (A32, A33), surface and subsurface weld slag (A35 – A39)

H - Plate and Weld Chemistry

The removal of weld samples provided the ability to determine the approximate chemistry using SEM/EDS, which provides chemical analysis of the field of view or spot analyses of minute particles. SEM/EDS analyses were done at WJE (all 5 samples) and RJ Lee (samples 1 and 5). Neither of the stainless steel plate producers (Outokumpu and ATI) nor the Gateway Arch archive had retained the original chemistry certifications. The weld filler metal supplier(s) are unknown and no certifications had been retained in the archives. The small size of the plate in the weld samples and need to retain them made it impossible to do a full laboratory chemistry evaluation, which would also have destroyed the samples. Additionally, the weld area was not large enough for a full chemical analysis.

SEM/EDS chemistry is not exact and is only permissible for general alloy verification. It simply provides guidance about the relative concentration of each alloying element in a specific area. Neither carbon nor sulfur levels can be accurately measured so neither element was included in Table 2. The SEM/EDS values were rounded to one digit. Carbon levels measurements reported are typically much higher than what is physically possible in a stainless steel alloy due to surface contamination, and this can change the relative percentages of deliberate alloying elements making them look artificially lower. Unless carbon is specifically excluded from the analysis calculations, which was not done by either lab, the concentrations of deliberate alloying element additions will appear lower then they actually are. The plate appears to be the specified Type 304 with an appropriate matching chemistry filler metal.

Table 2: SEM/EDS chemistry evaluation

Sample	Description	SEM/EDS Data for Primary Elements (Mass %)				
		Si	Cr	Mn	Fe	Ni
ASTM A167-1963	Type 304	1	18.00-20.00	2	Rem	8.0-12
A240/A240M- 2015	Type 304	0.8	17.5-19.5	2.0	Rem	8.0-10.5
W1	Stainless plate	0.4	17.2	1.8	65.7	8.8
W1	Weld	0.4	17.6	1.8	61.9	8.4
W2	Stainless plate	0.4	17.8	2.0	65.3	8.4
W2	Weld	0.5	17.8	2.0	62.9	8.3
W3	Stainless plate	0.6	18.1	2.3	64.5	8.5
W3	Weld	0.4	17.2	2.1	59.8	8.0
W4	Stainless plate	0.4	17.8	1.7	65.1	8.7
W4	Weld #1	0.4	16.8	1.5	56.5	7.6
W4	Weld #2	0.4	16.6	1.5	55.7	7.6
W4	Weld #3	0.4	17.4	1.5	60.7	8.0
W5	Stainless plate	0.4	17.5	1.6	65.8	8.5
W5	Weld	0.4	17.8	1.7	61.3	8.3

Note: ASTM values are maximums unless a range is listed.

ASTM specifically permits chemistry variation outside the allowed range when single location higher accuracy full chemistry analyses are done (See ASTM A480/A480M-13b, Table A1.1). In a high accuracy single or limited sample analysis post-production, the following chemistry variations are allowed above or below the published ASTM A240 limits without being considered out of tolerance: chromium levels of up to 0.20%, nickel up to 0.10%, and manganese of up to

0.04%. As was noted, SEM/EDS is less accurate and the carbon levels can make alloying element additions appear lower then they actually are.

Most of the samples are within the current chemistry range for Type 304. If the carbon had been eliminated from the analysis, they should meet 1963 requirements. A few scans were below ASTM requirements but a full chemistry of larger samples, as required to confirm chemistry, and they may have been within compliance. It is likely that the plate and filler metal used on the Arch meet the specification requirements. Even if some plates or filler metal was outside of the required chemistry range, there has been no corrosion problem after 50 years of service and remedial action, such as plate identification and replacement, is not reasonable.

I - Gun Shot Residue SEM Lifts

TMR Consulting has been using the gunshot residue kits, which were developed for law enforcement use, from a highly rated forensic lab (R. J. Lee, Pittsburgh) in our metallurgical surface evaluations for many years. These specialized SEM/EDS sample collection tapes can pull finer particles from the surface for analysis then any other non-destructive means of surface assessment. Per agreement with R. J. Lee, they run the scans for TMR Consulting. The full analysis of that data, identification of the specific compounds like mill slag and their source based on a review of current and local industry using multiple sources was done by TMR Consulting. Figure 3 in the main WJE report contains a diagram showing the location of each station.

The samples are broken into two groups based on the inspection visit on which they were collected. The first group of samples include a number followed by the letter “B” and were collected between September 29 and October 1, 2014 from the lower areas of the North leg which were reachable by foot or lift. The areas that had more weld spatter or a coarser polished appearance, which increases surface roughness and tension making rain cleaning less effective, generally had larger surface deposit accumulations.

The samples identified with a number followed by the letter “C” were collected by the inspectors which climbed down the North leg between October 14 and 21, 2014. The samples had to be pre-numbered since that could not be done during sample collection. Due to the limitations associated with this type of inspection, the numbers are not continuous or in a specific order. The inspectors verbally reported the sample number as they worked. A mixture of small and large sample area kits were used, but the collection surface material is identical so size was not relevant. Smaller surface area kits make collection in narrower areas possible and are sometimes more convenient to handle. The findings and sample locations are summarized in Table 4 and documentation can be found in Appendix C. Images C1 through C52 in this Appendix document some of the typical particles on each sample. Fly ash and soil were found on most samples and, in most cases, not specifically documented due to their constant presence unless combined with other elements.

The particles found on surfaces varied. Most were iron rich, often in combination with oxygen (FeO) indicating corrosion of the iron. These iron-rich particles were found in combination with fly ash and soil components (e.g. carbon rich material (spores and pollens), clay materials, silica (sand), dolomite, calcite and magnesia alumina silicates). Chlorides (probably deicing salts) in very small concentrations were found on many of the samples at all heights on the Arch. Stainless steel (iron (Fe), chromium (Cr) and nickel (Ni)), mineral wool, paint particles, copper zinc alloy, and lead particles were also found in one or a few samples but were unusual.

With the exception of the clay, sand, pollen and other characteristic constituents of normal soil, the other accumulations can be explained by current and past industrial activities in the area, particularly the steel production (iron and ferrochrome (FeCr)), a coke plant, coal fired power plants and nearby highways. Isolated iron particles are probably carbon steel from nearby carbon steel fabrication (buildings, roadways) and are common on surfaces near construction sites.[6] The environment is not corrosive enough for these deposits to have caused more then superficial dark discoloration and some light scattered small areas of red toned superficial corrosion staining, so their presence on the surface is a purely aesthetic issue. With the exception of the base, the red toned staining was mainly from iron rich particles from nearby industry. The emissions of fly ash and other industrial particulate have been dramatically reduced in recent decades, but, if the surface was cleaned, some soil that contains these elements might still continue to deposit on the exterior surface.

Soil is composed or organic matter in combination with clay, sand, and silt. Sand and silt are just small particles of rock (i.e. silica (SiO_2), dolomite ($CaMg(CO_3)_2$), magnesia alumina silicates). Most clays are phyllosilicates, which have a visibly sheet-like structure like mica when examined under an SEM. Chemically clay is aluminum silicate, which may have significant amounts of iron, alkali metals, or alkaline earths.

Ferrochrome (FeCr) is an alloy of chromium and iron containing between 50% and 70% chromium. Individual particle chemistry can vary and may have higher iron levels. The production of steel is the largest consumer of ferrochrome, especially the production of stainless steel. All particles that contained iron and chromium but no nickel, so they have been categorized as ferrochrome indicating that they do not appear to be Type 304 stainless steel from the Gateway Arch.

The typical composition of iron and steel slag is shown in Table 3. Blast furnace slag is similar to fly ash in composition but other stages in the process contain iron and other elements. The iron particles found on the surface could also have been from manufacturing operations that generate fine particulates prior to the environmental regulations that limited plant emissions or nearby construction.

Table 3: Iron and steel slag composition[7]

Type	Blast furnace slag	Converter slag	Electric arc furnace slag	
Component			Oxidizing slag	Reducing slag
CaO	41.7	45.8	22.8	55.1
SiO_2	33.8	11.0	12.1	18.8
T-Fe	0.4	17.4	29.5	0.3
MgO	7.4	6.5	4.8	7.3
Al_2O_3	13.4	1.9	6.8	16.5
S	0.8	0.06	0.2	0.4
P_2O_5	<0.1	1.7	0.3	0.1
MnO	0.3	5.3	7.9	1.0

Fly ash (SiO_2, and CaO) is also known as flue-ash, and is one of the residues generated in combustion and consists of the fine particles that rise with the flue gases. In an industrial

[6] See current and historic EPA records, https://www.stlouis-mo.gov/visit-play/stlouis-history.cfm, http://builtstlouis.net/, St. Louis' city website and other internet based information on current and historic industry.

[7] Available from the US Geological Survey and numerous steel industry resources

context, fly ash most commonly refers to ash produced during combustion of coal (coal fired power plants, coke plants, steel mills and other coal burning industry). The chemistry of fly ash varies with the coal source(s), but all fly ash includes substantial amounts of silicon dioxide (SiO_2) and calcium oxide (CaO). Other constituents will be dependent on the coal source and can include trace quantities of arsenic, beryllium, boron, cadmium, chromium, hexavalent chromium, cobalt, lead, manganese, mercury, molybdenum, selenium, strontium, thallium, and vanadium, along with dioxins and PAH compounds. Fly ash used to be released into the environment and would have been in the environment for much of the Gateway Arch's service life since there were multiple coal burning power plants in the area, a coke plant and steel mills. In recent decades, scrubber systems have been mandated and fly ash is captured prior to release into the environment. It typically either goes to land fills or is used in concrete.

Table 4: SEM/EDS sample locations, descriptions and deposit chemistry

Sample	Description	Location	Chemistry
Group 1, base of North leg, arranged from lowest to highest elevation from the ground			
8B	Small dark surface area, possible adhesive	Above 2nd weld from base, extrados	Soil, fly ash, ferrochrome, chlorides, carbon rich materials (i.e. pollens), mineral wool, and other particles including iron (C23 – C27)
1B	Grey and black particles concentrated on weld spatter	3rd weld from bottom, 1st section from right, extrados	Steel or iron slag, carbon rich material (i.e. spores, pollens etc.) and iron particles entrapped or near fly ash and soil (C1-C12)
2B	Grey, brown and black particles concentrated on weld spatter	5th weld from bottom, extrados, west side central panel	Steel or iron slag, carbon rich material (i.e. spores, pollens etc.) entrapped or near fly ash, soil and a possible paint particle (C1-C12)
3B	Dark and white surface discoloration areas and a rainbow effect in areas.	8th row from base, extrados, across weld with dark area above and streaking below, west panel	Soil, fly ash, chlorides and trace amounts iron (Fe) rich and a possible stainless steel particle (C13 – 18)
4B	Dark and white surface discoloration areas and a rainbow effect in area	Same area as 3B but below weld	Predominantly soils, chlorides, iron rich and silica particles (C13 – 18)
5B	Red toned drip area coming down from weld area	8th weld from base, river side of intrados, north panel	Predominantly ferrochrome oxide with other particles in trace amounts like chlorides, fly ash, and organics (C19 – C22)
6B	Red toned area	Unknown, taken while on lift	Ferrochrome oxides with sulfur, chlorides and phosphorous combined with mixed clay, calcite, silica, pollens and spores (C19 – C22)
7B	Dark parallel vertical drip channeling marks	Station 69, extrados	Soil, fly ash, ferrochrome, chlorides, carbon rich materials (i.e. pollens), mineral wool, and other particles including iron (C23 – C27)
Group 2, Elevated Levels North Leg, arranged from lowest to highest elevation from the ground			
15C	Black deposit	Weld 97/station 49 extrados	Ferrochrome, iron and iron or steel slag particles and soil (C51 – C52)
5C	Dark residue	Station 35, Intrados	Iron with oxygen (corrosion product), steel or iron slag, ferrochrome, chlorides, copper zinc alloy particles, and soil (C36 – C40)
6C	No visible deposits	Station 35, intrados	Ferrochrome, carbon rich organics, chlorides (some were obviously sodium chloride), iron particles, soil (C41 – C43)
1C	Dark residue	Station 34, intrados	Tape surface stuck to collection box and could not be analyzed
3C	Black residue	Same area as 1 but to right	Tape surface stuck to collection box and could not be analyzed
4C	Dark residue	Weld 52/Station 31, extrados, central panel	Iron with oxygen (corroding iron), ferrochrome, lead, titanium, copper, chlorides, iron or steel slag, and a stainless particle with no oxygen (no corrosion) (C28 - C35)
13C	Red toned deposit	Exhaust grating, between slates, station 12/weld 6,	Copper zinc (Cu Zn), ferrochrome, iron or steel slag combined with oxygen, silica (sand),

		extrados	magnesium chlorides (deicing salt), and some titanium (C44 – C48)
14C	Black deposit	Exhaust grating, Station 12/weld 6, extrados	Silica (probably sand) and iron (probably from the steel mill) (C49 – C50)

Note: At least trace amounts of fly ash and soil components were found on all the samples and were not documented unless it was the primary constituent. See Figure 3 in the WJE report for a diagram showing the station locations.

J – Embedded Iron Contamination

There are scratches on the surface of the base with embedded iron particles from carbon or alloy steel. The deepest and largest of these extend along the base, are relatively deep and may have been from a snowplow. There are additional areas with small amounts of embedded iron in graffiti but these are less concerning because they are localized small areas and there is far less iron contamination.

This iron surface contamination should be removed, particularly from the long deep scratches, because the corrosion product from this deposit creates a crevice and does not allow oxygen to reach the surface. Corrosion of the stainless steel under the carbon steel corrosion product deposit will continue. Crevice corrosion can occur when the surrounding exposed stainless does not corrode and the rate of corrosion is higher. The exposure of these areas to deicing salt will increase the corrosion rate.

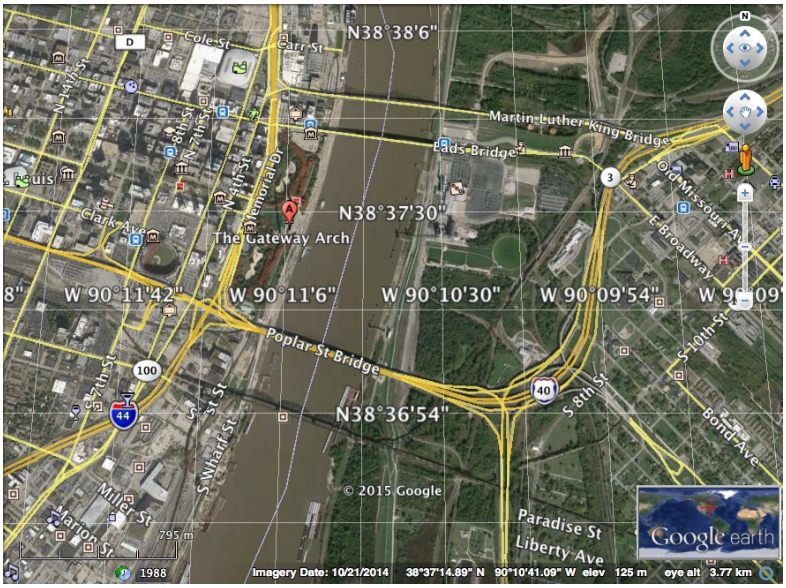
Over time, this linear, concentrated increased thickness loss due to corrosion could lead to thickness loss that presents a concern and weld repair might then become necessary. That is easily avoided. Removal of the contamination should be with stainless steel pickling paste painted on to these localized areas with a small artists brush in accordance with ASTM A380 followed by chemical passivation to improve the corrosion resistance within the scratch. Pickling will dull the finish locally but careful limited application should not make it noticeable since it is so close to the ground. These strong acids should only be used in compliance with manufacturers recommendations to ensure operator safety and to prevent damage to surrounding materials.

Figure 1: Embedded carbon steel, probably from a snow plow blade (Photo taken by authors in 2014)

K - Site Corrosion Assessment

Chlorides from deicing salt were found on the surfaces. Highways surround the site and they are within the documented distance that deicing salt can travel. Only very small amounts of chlorides were found on the surface during the September and October 2014 inspections. The high winds documented at the top and elevated sides indicate that most of the structure is probably well rain washed during storms.

Other then very small, localized areas, such as the elevated areas where iron and ferrochrome particles were found, the only corrosion observed on the surface was at the base. This area would not be as effectively washed by rain as elevated areas with higher wind levels. Light staining caused by microscopic deicing salt related pitting was observed at the base. Very little residue was found on the surface when a Chlor-Test was done, but that would not be unusual in the fall. This corrosion is superficial and could easily be removed.



Figures 2 and 3: Google Earth image (Left) showing the highways and bridges immediately around the site which are adding deicing salts (chlorides) to the environment and the superficial corrosion staining at the base caused by deicing salt exposure. (Right photo taken by authors in 2014)

Various sources were reviewed to determine the industrial pollution sources that have been in the area since the construction of the Gateway Arch. Many possible industrial plant sources have shut down or changed what they are producing during the past 50 years. The industries in the area, which could have contributed to the residue found in the surface deposits included several steel mills including Granite City Steel; companies that may have had steel foundries or manufacturing steps could put metallic particles in the air; St. Louis Army Ammunition Plant; Carondelet Coke Plant; three coal fired power plants Cahokia, Union Electric, and Venice; Sauget Industrial and Big River Zinc (zinc refinery); Cerro Copper (copper alloys); and chemical plants such as Monsanto and Pfizer.

L - Surface Cleaning, Restoration and Maintenance

The cleaning and refinishing trials at the base of the monument are discussed in the Wiss Janney Elstner report. In addition to the aesthetic considerations, there are technical reasons to

consider some cleaning of the base of the monument. The primary concern is deeply embedded iron particles in scratches because corrosion of the stainless steel could continue under the crevice created by the iron corrosion product. This could be removed selectively with an electro polishing wand or with appropriate chemicals in accordance with ASTM A967. Some of the deeper scratches with heavily embedded iron may require careful removal of the iron with pickling paste, as described in A380, or an electro polishing wand.

The scratches in the surface of the base, including those not associated with iron contamination, increase the likelihood of corrosion in two ways. They roughen the surface, which increases corrosive deposit accumulation and corrosion, and open up the sulfide inclusions documented in the plate. Corrosion can initiate at sulfide inclusions when it would not occur otherwise. Surface sulfides can be removed by chemical passivation in accordance with ASTM A967 and manufacturers' recommendations about dwell time after the surface is cleaned to remove staining, dirt, oils and other deposits. Passivation that is done correctly by a firm that specializes in chemical cleaning of stainless steel will not change the appearance of the surface. No cleaning should be done unless a stainless steel metallurgist that specializes in finishes and atmospheric corrosion approves the procedures. Removing the shallower scratches is ideal from the standpoint of limiting corrosive deposit build up, but cleaning and passivation can be done without their removal.

Since the paving around the monument is heated, no deicing products are reportedly used. If the NPS should decide to use deicers at some future time, non-corrosive deicers that only work at somewhat higher temperatures (above 15 F) should be considered, such as calcium magnesium acetate (CMA). Hot water power washing of surfaces in early Spring, preferably with Chlor-Wash or Chlor-Rid which more effectively release chloride salts from surfaces, would also minimize staining.

Based on a review of the archive materials, the Arch was cleaned as the crane and supporting structure was removed. This included removal of carbon steel contamination, refinishing and cleaning. Use of pickling paste or chemical passivation products would be common today but we do not know what was used in this operation. Either would have removed surface sulfides and could be a factor in the essentially corrosion free performance of elevated areas.

Archive documentation makes it clear that the surface was not uniform in appearance upon completion. It is difficult to achieve finish consistency with polished bare metals in the field. Handling and installation damage was documented in the architect's daily reports and field refinishing was done. Field refinishing to eliminate damage never produces a completely uniform surface and it is always far less consistent then finishes applied under controlled factory conditions. Improving overall finish consistency in the field would be a highly labor intense process and perfection is not possible.

It is assumed that any work on elevated areas would be to remove the areas of dark discoloration from surface deposits. If abrasives that are capable of changing the finish morphology are used, they will change the appearance of those areas and that could result in visible areas of inconsistency. Either chemicals capable of removing the deposits without affecting the stainless steel or very fine abrasives that are not capable of changing the stainless steel surface would be needed.

Appendix A: Weld Sample Evaluation

Figure A1: W1, prior to removal (Photo taken by authors in 2014)

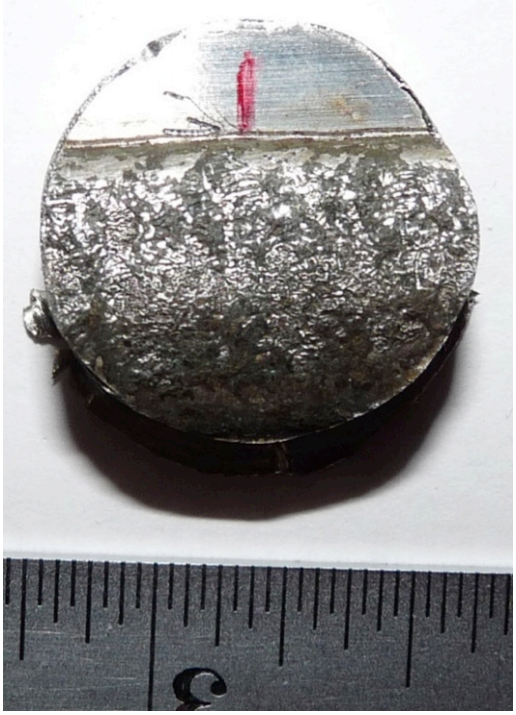


Figure A2: W 1 as-received condition. (Scale=1/32") (Photo taken by authors in 2014)

Figure A3: Macrograph cross of section W1 in the etched condition (Photo taken by authors in 2014)

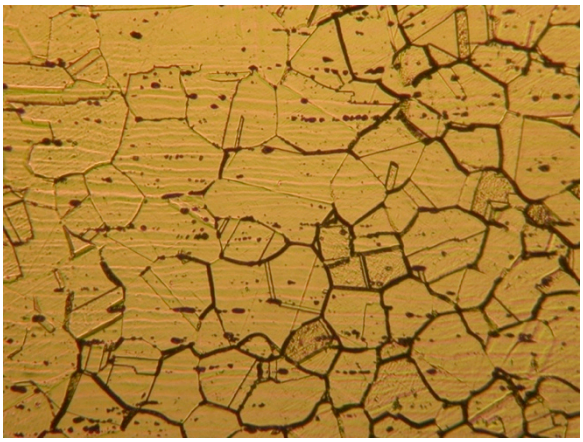


Figure A4: Micrograph of W1 in the etched condition showing sensitized grains (right) and grains that are not sensitized (left). (256x) (Photo taken by authors in 2014)

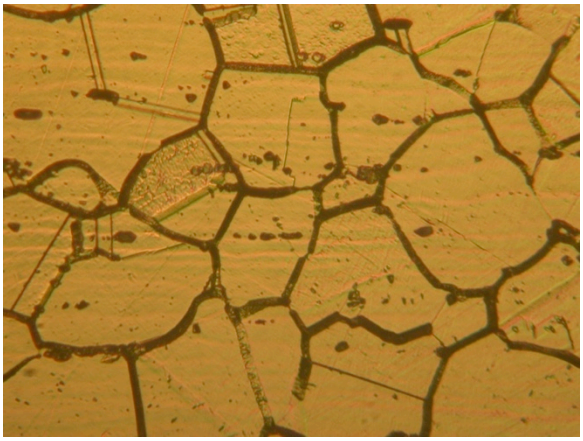


Figure A5: Micrograph of W1 in the etched condition showing sensitized grains in the plate. (517x)(Photo taken by authors in 2014)

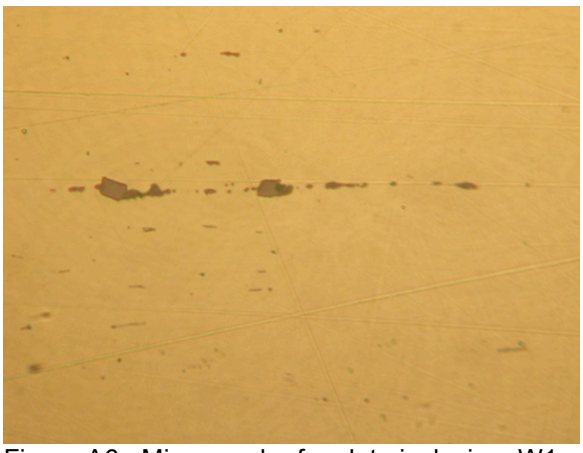


Figure A6: Micrograph of a plate inclusion, W1, as-polished condition. (517x) (Photo taken by authors in 2014)

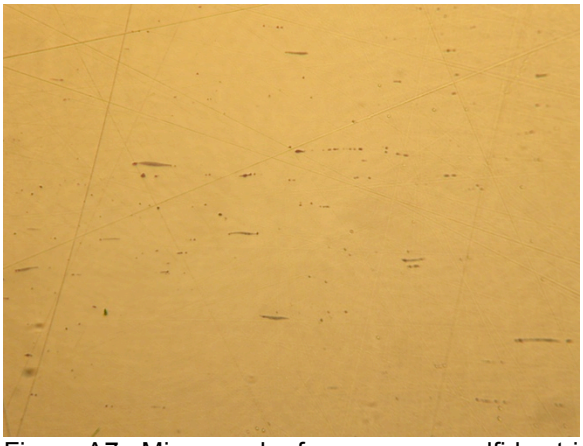


Figure A7: Micrograph of manganese sulfide stringers in the plate, W1, as-polished condition. (256x) (Photo taken by authors in 2014)

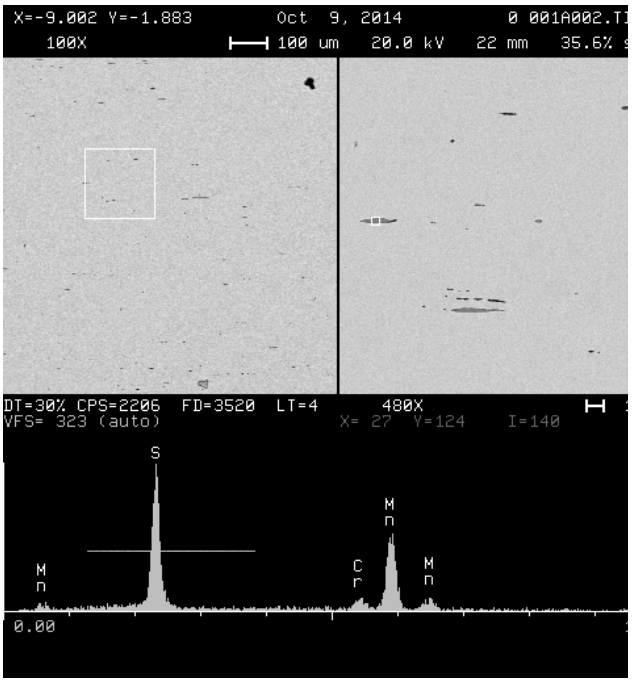


Figure A8: SEM/EDS confirming the presence of manganese sulfide stringers (RJ Lee SEM sample scan 2014)

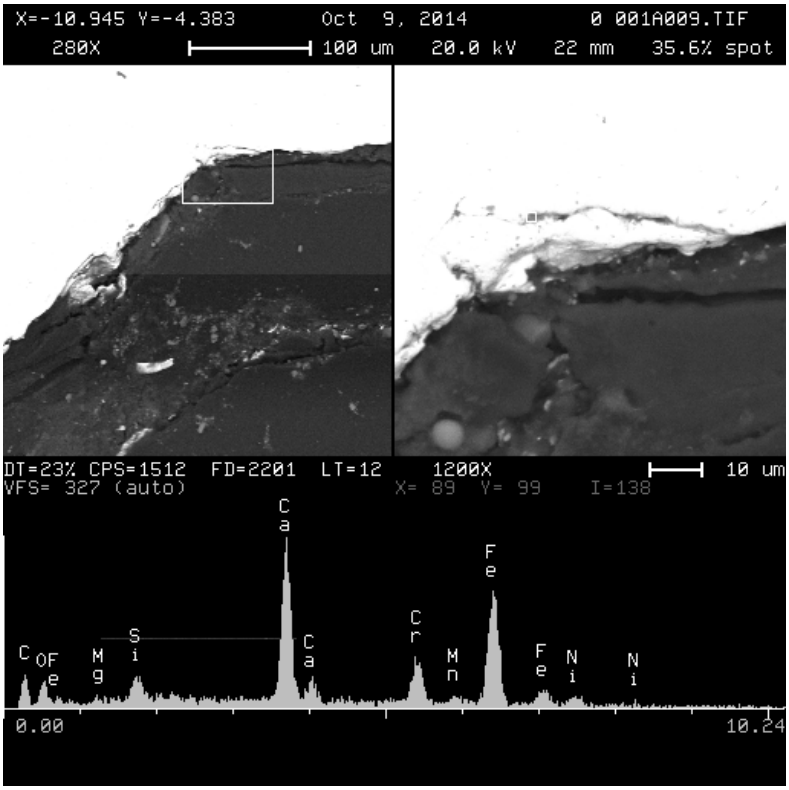


Figure A9: SEM/EDS showing some W1 surface weld slag (Ca and Si) (RJ Lee SEM sample scan 2014)

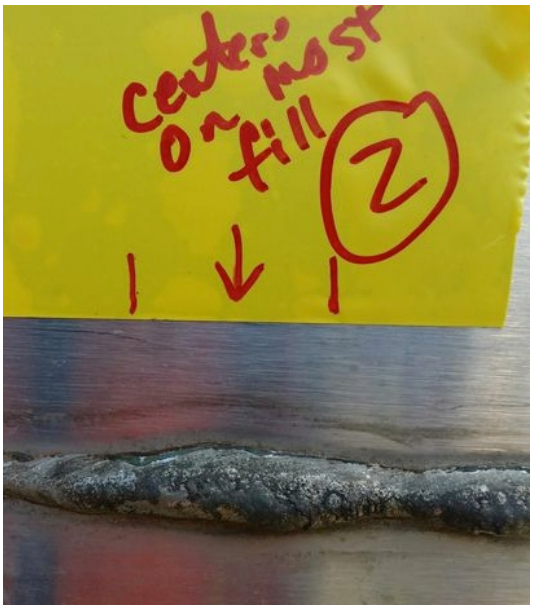


Figure A10: W2 prior to removal (Photo taken by authors in 2014)

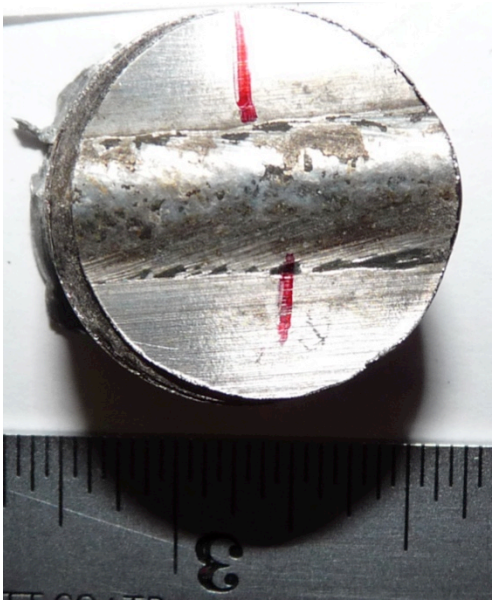


Figure A11: W2 as-received condition. (Scale=1/32") (Photo taken by authors in 2014)

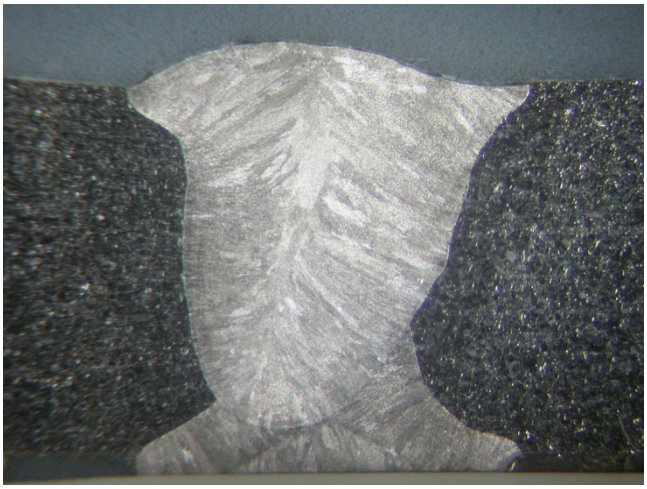


Figure A12: Macrograph of W2, etched condition (Photo taken by authors in 2014)

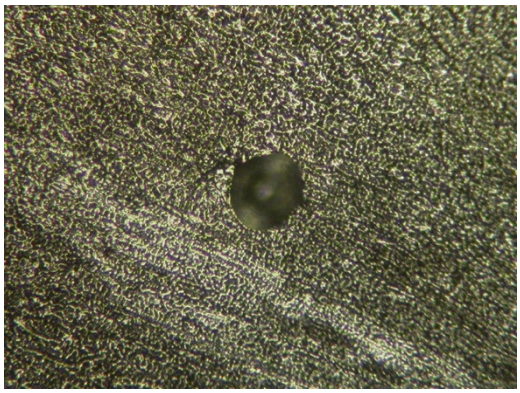


Figure A13: Micrograph of W2, etched condition, weld porosity, approximate diameter 0.004" (Photo taken by authors in 2014)

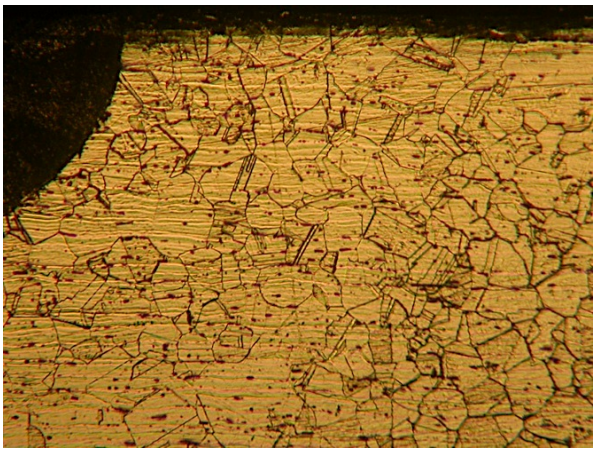


Figure A14: Micrograph W2 etched condition showing weld metal (top left corner), a band of grains that are not sensitized (center) and a band of sensitized grains (right). (122x) (Photo taken by authors in 2014)

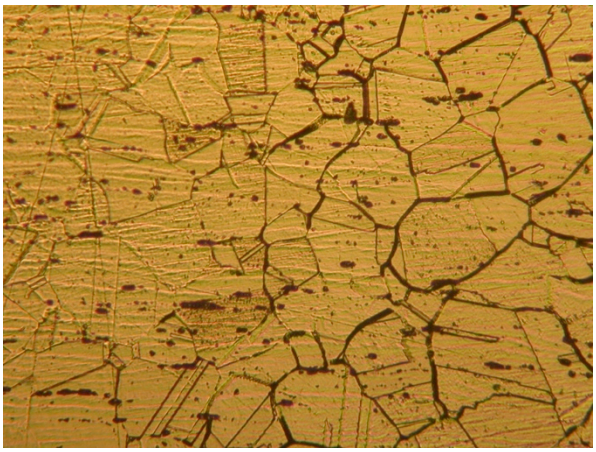


Figure A15: Micrograph W2, etched condition showing sensitized grains (right) and grains that are not sensitized (left). (256x) (Photo taken by authors in 2014)

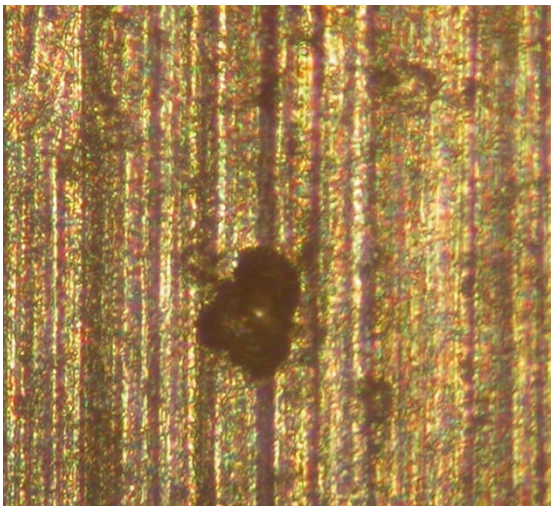


Figure A16: Cut, un-mounted section of the surface of the W2 sample with a small void of approximately 0.002” diameter located approximately 0.045” from the edge of the weld. This may have been very minor corrosion pitting of the surface since there are similar very small pit like shapes on the surface around it, but there was no visible staining when we examined it. Alternatively, an inclusion could have been pulled out of the surface during polishing. (Photo taken by authors in 2014)

Figure A17: W3 prior to removal (Photo taken by authors in 2014)

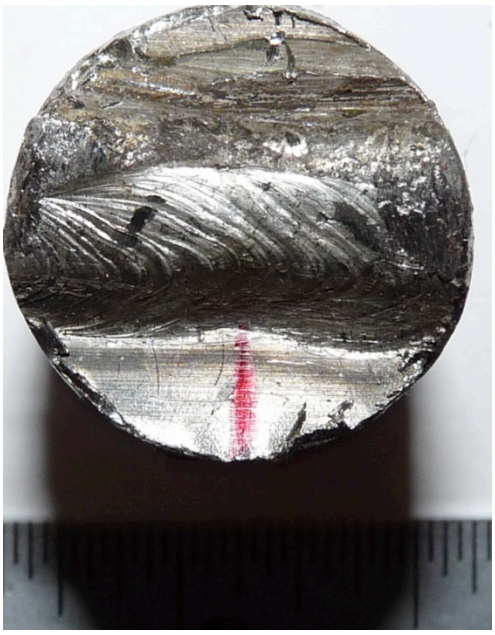


Figure A18: W3 as-received condition. (Scale=1/32")(Photo taken by authors in 2014)


Figure A19: Macrograph of W3, etched condition. (Photo taken by authors in 2014)

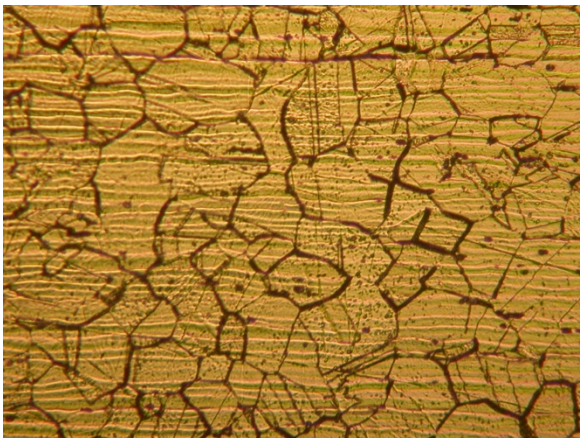


Figure A20: Micrograph W3, etched condition showing sensitized grains in the plate. (256x) (Photo taken by authors in 2014)

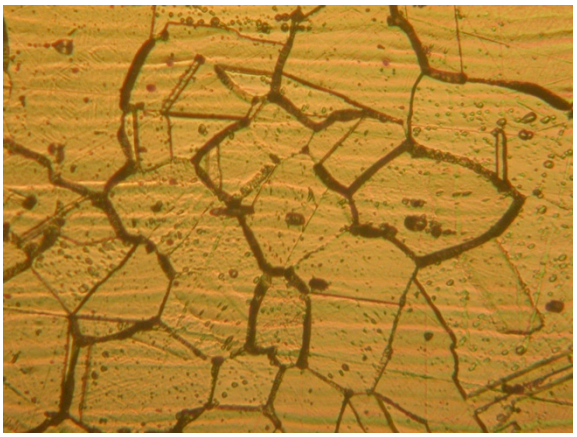


Figure A21: Micrograph W3, etched condition close up of sensitized grains in the plate. (517x) (Photo taken by authors in 2014)

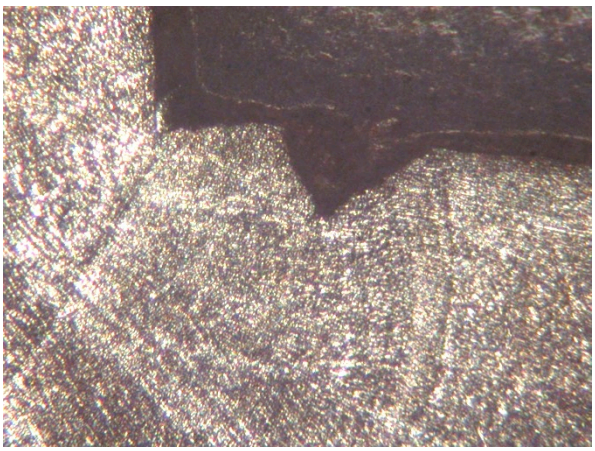


Figure A22: Micrograph W3, etched condition showing a notch in the outside weld surface. (122x) (Photo taken by authors in 2014)

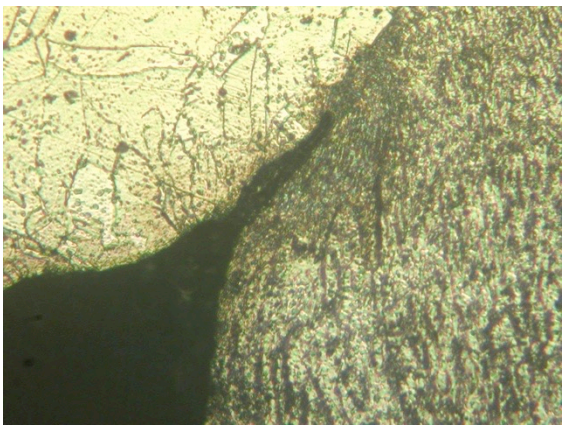


Figure A23: Micrograph W3, etched condition showing shallow undercut where the weld metal and base metal meet, inside surface of the plate. (517x) (Photo taken by authors in 2014)

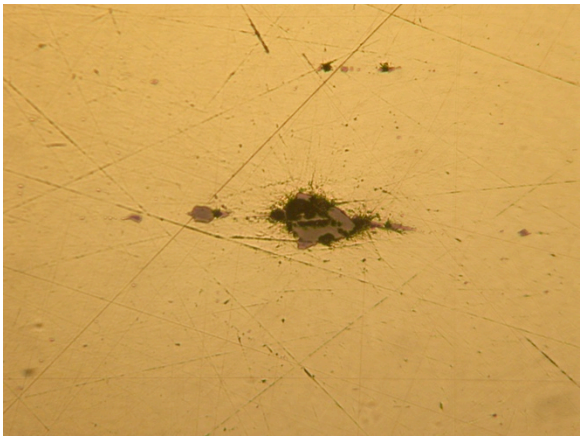


Figure A24: Micrograph, W3, plate inclusion, as-polished condition. (256x) (Photo taken by authors in 2014)

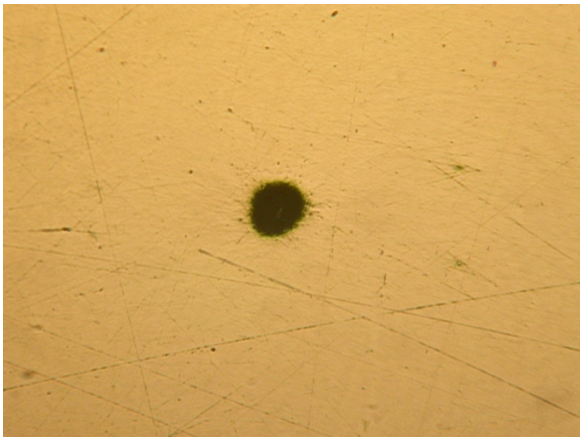


Figure A25: Micrograph, W3, weld void, approximate diameter 0.004”, shown as-

polished condition. (Photo taken by authors in 2014)

Figure A26: W4 prior to removal (Photo taken by authors in 2014)

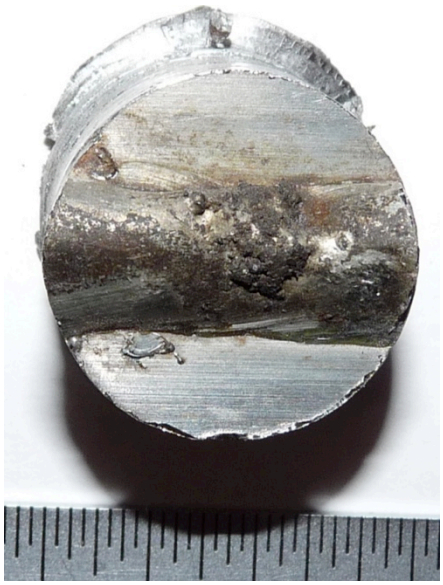


Figure A27: W4 as-received condition. (Scale=1/32") (Photo taken by authors in 2014)

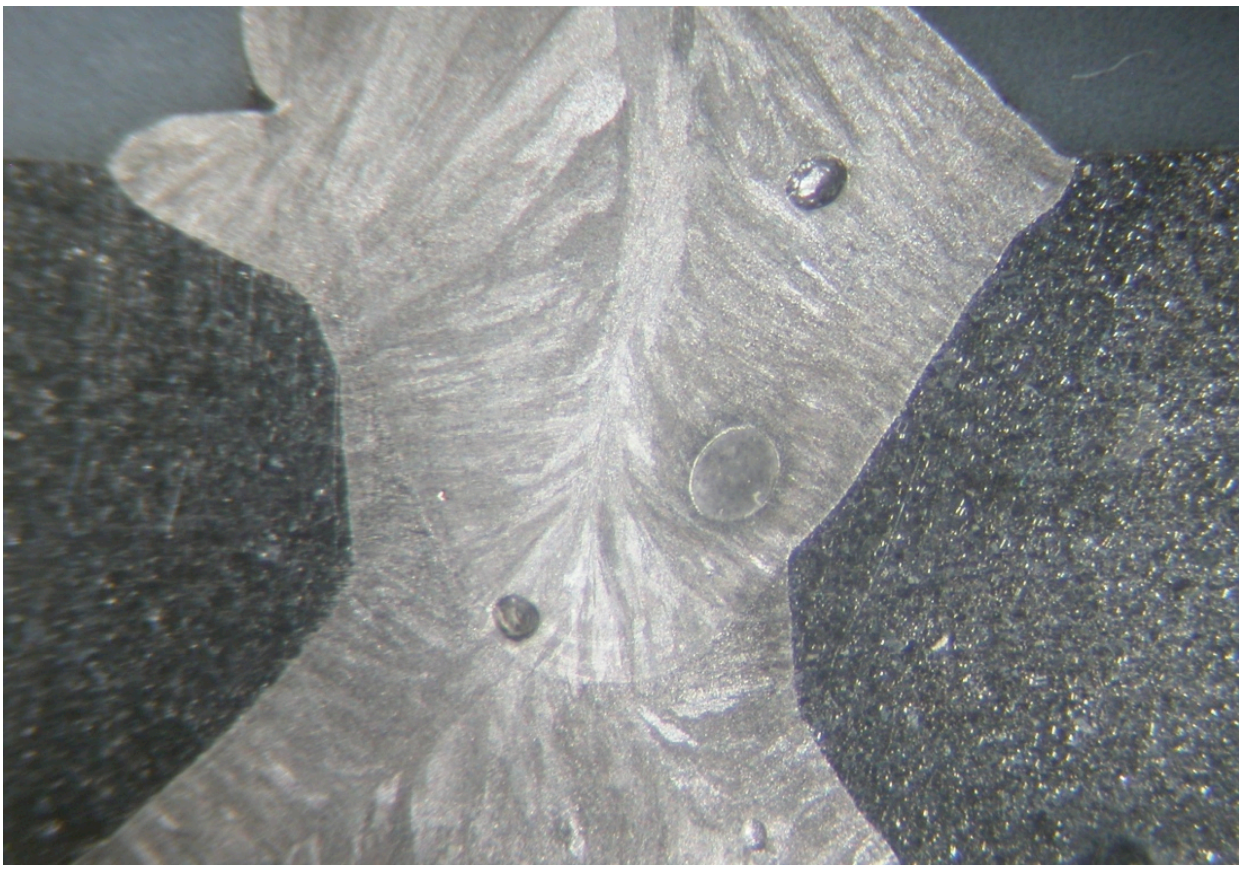


Figure A28: Macrograph, W4, etched condition, showing weld porosity. The largest void, which is located near mid thickness, has an approximate diameter of 0.04". (Photo taken by authors in 2014)

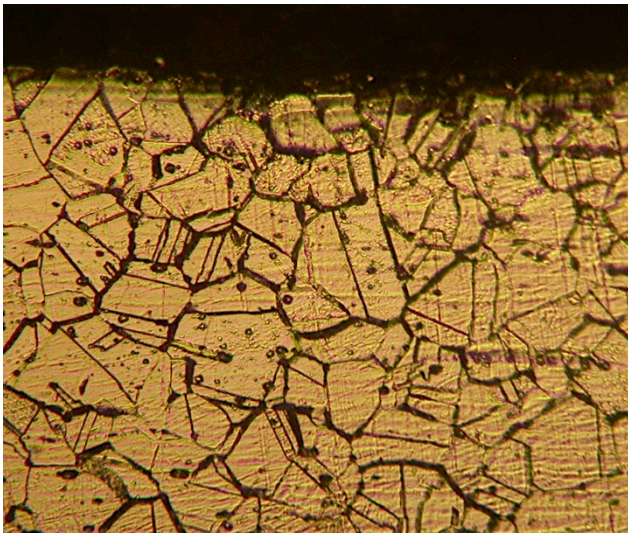


Figure A29: Micrograph, W4, etched condition showing sensitized grains near the outside surface of the plate. (256x)
(Photo taken by authors in 2014)

Figure A30: W5 prior to removal (Photo taken by authors in 2014)

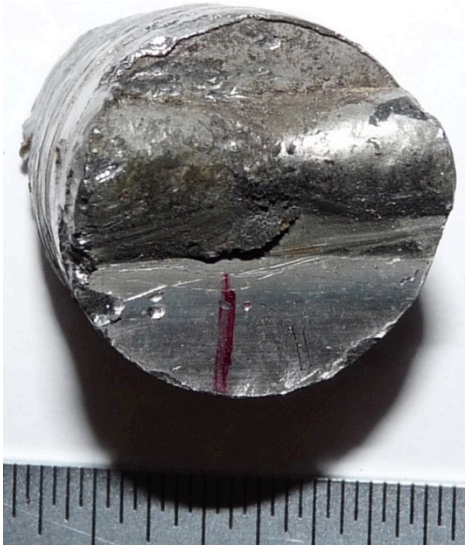


Figure A31: W5 as-received condition. (Scale=1/32") (Photo taken by authors in 2014)

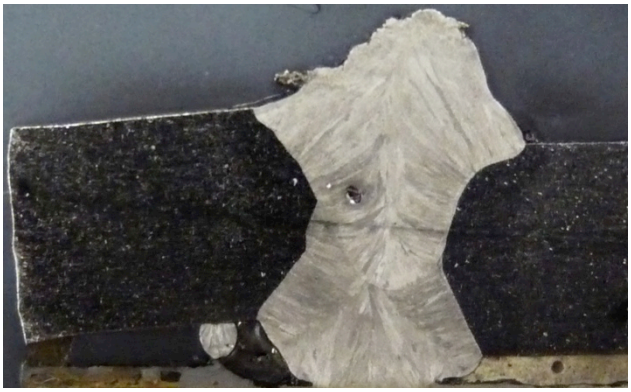


Figure A32: Macrograph W5 etched condition with a visible void. The minor plate misalignment is not a structural concern. (Photo taken by authors in 2014)

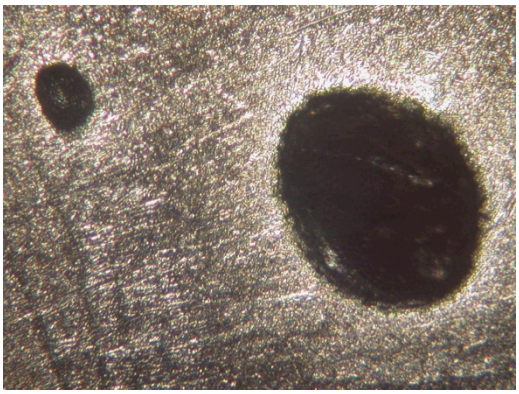


Figure A33: Micrograph W5 etched condition showing porosity in the weld metal with approximate diameter of 0.024”. (Photo taken by authors in 2014)

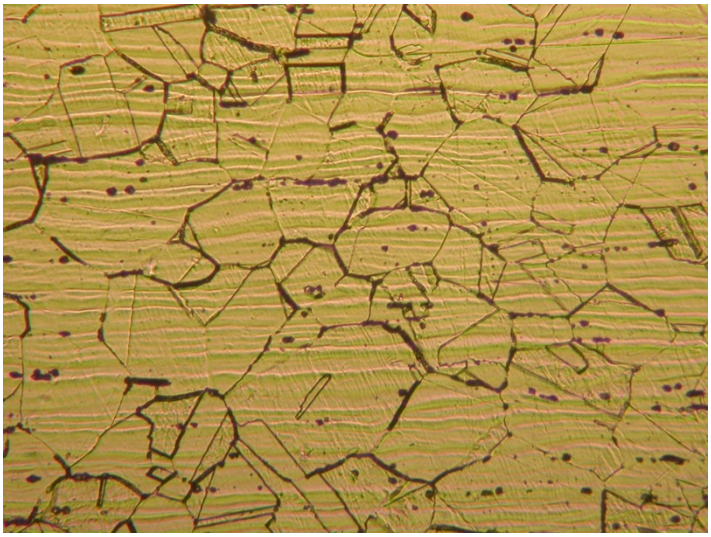


Figure A34: Micrograph sample 5, etched condition showing sensitized grains in the plate. (256x) (Photo taken by authors in 2014)

Figure A35: W5 after sectioning through weld slag contamination that was visible on the weld surface. (Photo taken by authors in 2014)

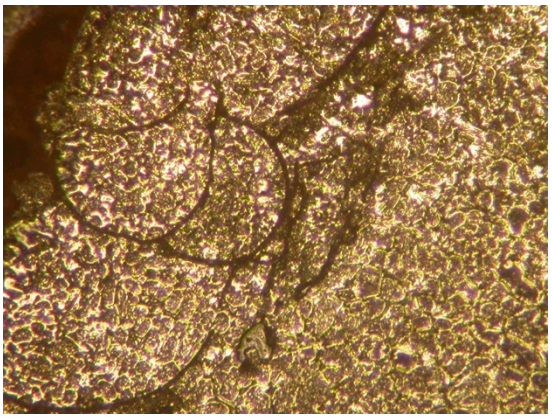


Figure A36: Micrograph of W5 same area, weld crown in the etched condition with sub surface weld slag. (256x) (Photo taken by authors in 2014)

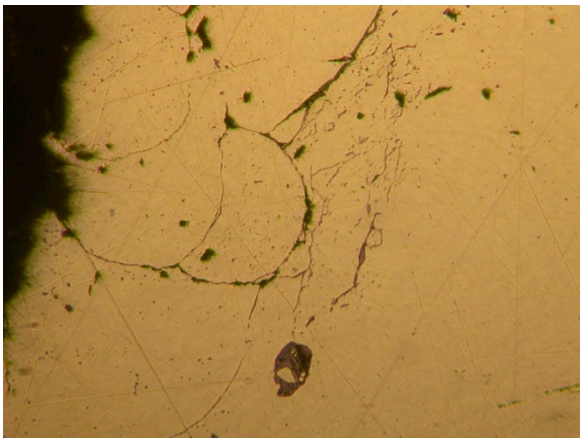
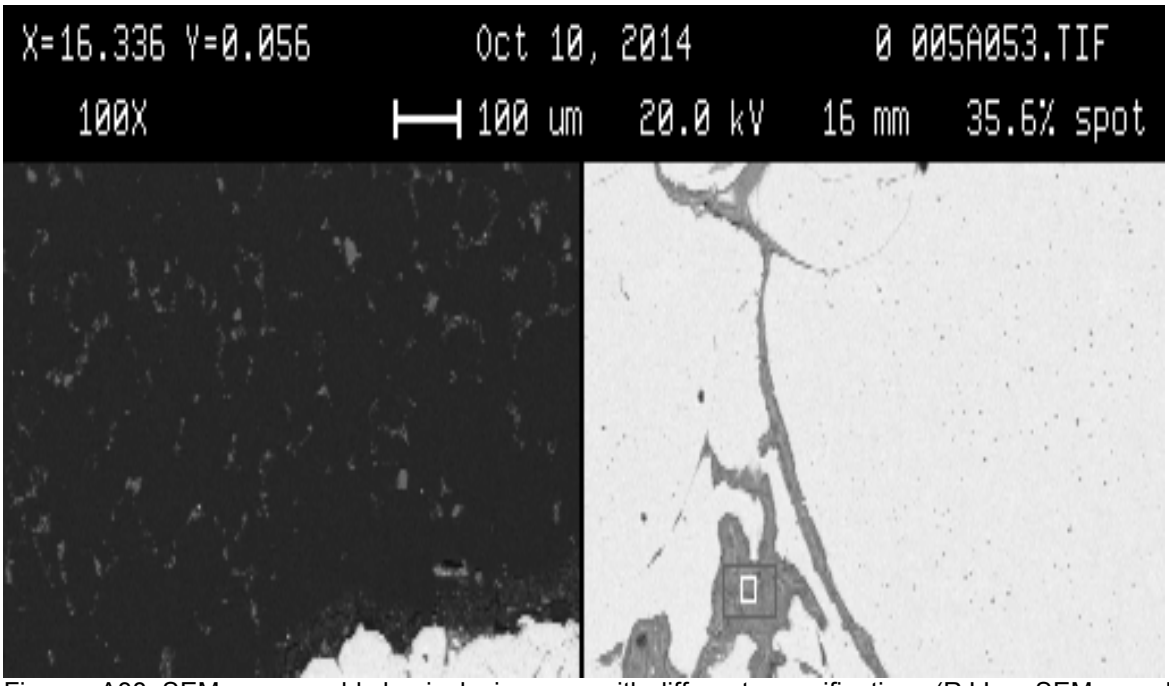


Figure A37: Micrograph W5 at the weld crown shown in the as-polished condition showing the sub surface weld slag. (256x) (Photo taken by authors in 2014)



Figures A38: SEM, same weld slag inclusion area with different magnifications (RJ Lee SEM sample scans 2014)

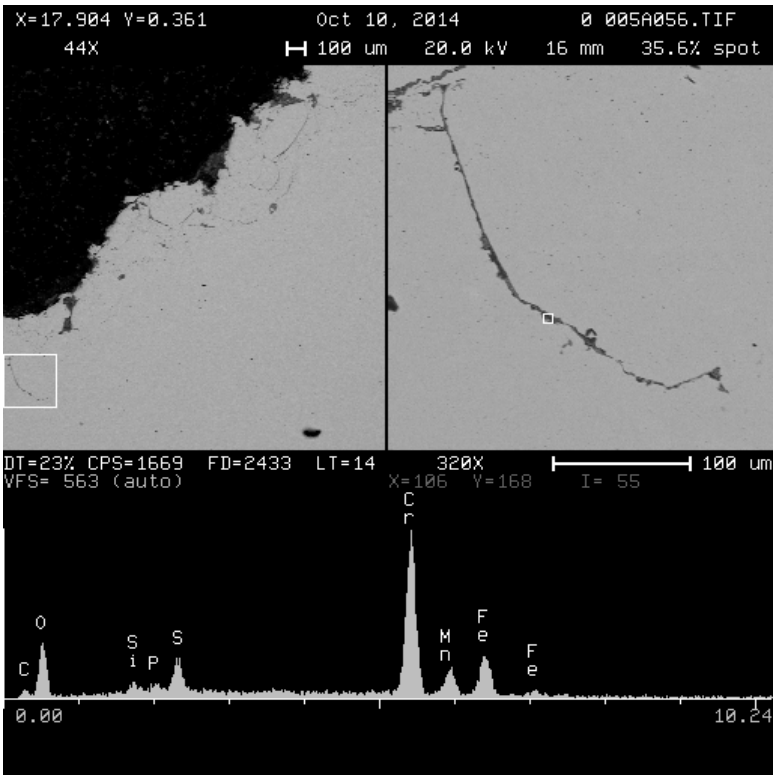


Figure A39: SEM micrograph, sample 5 same area, documenting that the observed linear areas are CrO and not cracks in all areas. No corrosion was observed. (RJ Lee SEM sample scan 2014)

Appendix B: Reference Examples of Typical Weld Imperfections

Several common weld imperfections were documented in Appendix A. TMR Consulting was asked to provide a reference Appendix describing the common weld imperfections. None of the pictures in this section were taken from Gateway Arch samples. They are for reference purposes from an industry suppliers guide.

This image is representative of the ideal appearance of a stainless steel weld: uniform with a relatively smooth, consistent, not overly large weld bead. There were many welds with this overall appearance on the Arch, particularly at elevated levels, although many had some weld spatter.

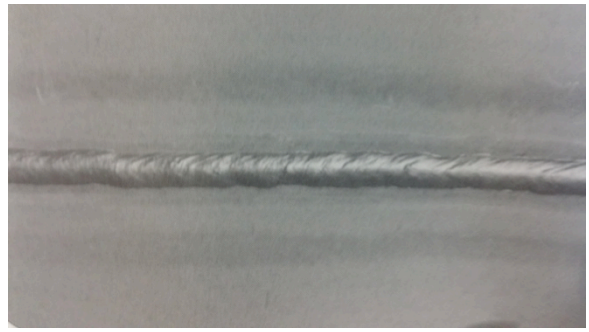


Figure B1: Ideal stainless weld appearance (Photo taken by authors, archive)

Porosity

It is not unusual to occasionally find porosity within weld beads. It can occur during all welding processes and is of greatest concern when it breaks the surface, where there are larger clusters, or when the area of porosity is large relative to the material thickness. Considerable areas of porosity maybe allowed if it is isolated and the affected areas are small relative to the thickness..

Only small isolated small areas of porosity were found within the Gateway Arch weld samples and they were not considered a problem.

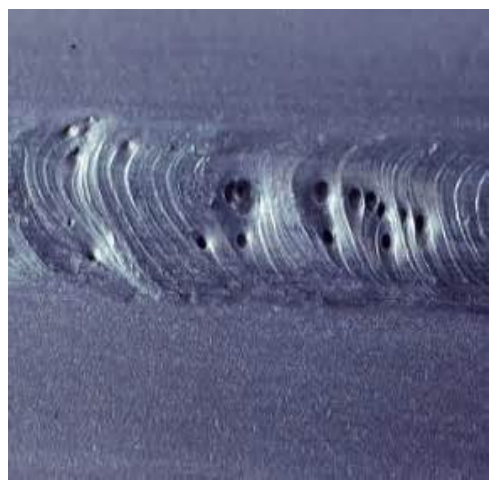


Figure B2: This image is representative of clusters of porosity breaking the surface. Nothing this severe was documented on the Arch. (Photo Avesta Welding Manual)

Weld Spatter

Some level of weld spatter (small raised areas where molten metal hit the surrounding surface) is likely with the welding method used on the Arch. Its acceptability is dependent on a specific projects aesthetic and corrosion requirements. Its presence on the Arch indicates that it was apparently considered acceptable by the inspectors.

Weld spatter can be an initiation point for corrosion and can increase surface deposit build up. Surface deposits can also cause corrosion or surface discoloration. Generally, it should be removed.

Weld spatter was documented on many of the Arch's welds although there was a great deal of variation seen. In some areas, it was obviously associated with increased surface deposit accumulation and discoloration. The image shows the typical appearance of this imperfection.

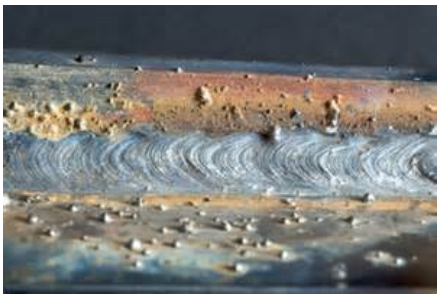


Figure B3: Weld spatter. (Photo Avesta Welding Manual)

Weld Slag Islands and Inclusions

Weld slag can be found on all weld types. Carbon and silicon are associated with these inclusions when analyzed using SEM/EDS. Small, spherical inclusions within the weld cross section are generally acceptable. The size and length of the inclusions is another factor in acceptability and potential impact on structural integrity.

Slag "islands" occur in the surface of the weld and can be a location where corrosion can initiate. Slag "islands" generally cannot be removed by brushing but light grinding is typically sufficient. Both types of imperfections were identified in the weld samples.

Figure B3: Weld slag inclusion (Photo Avesta Welding Manual)

Figure B4: Weld slag on the surface (Photo Avesta Welding Manual)

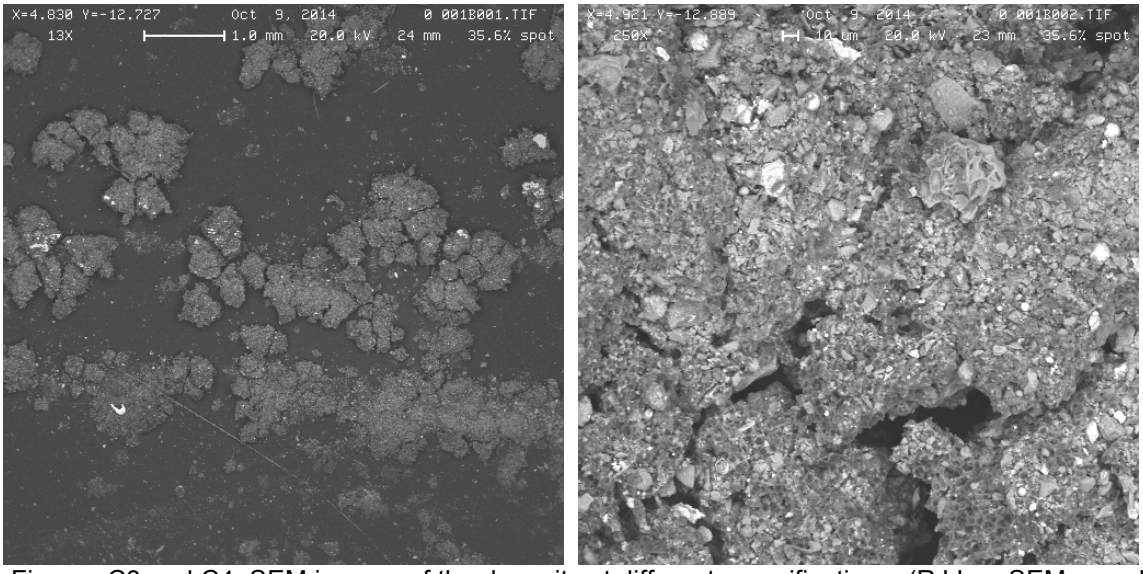
Appendix C: Surface Sample Analyses

The following SEM/EDS scans of particles found on the GSR sample strips are a representative sampling of a much larger number of scans documenting particle chemistry. See Table 4.

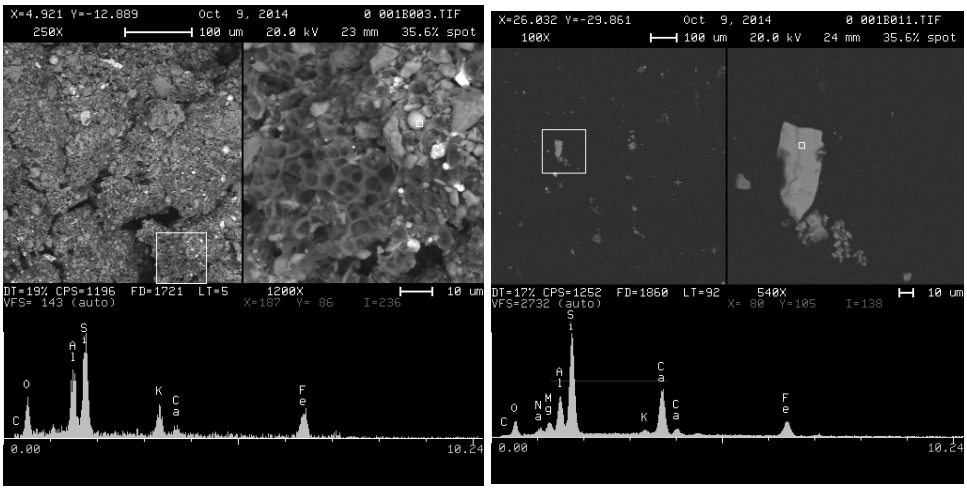
Representative SEM/EDS Scans of particles 1B and 2B

Both samples were dark in color and nearly identical in appearance and analysis. The only variation was the size of the deposit. The deposit appeared to mainly consist of particle agglomerations (Figure C1) and was largely removable with a wet cloth (Figure C2). This was representative of the appearance of the dark deposits found around welds.

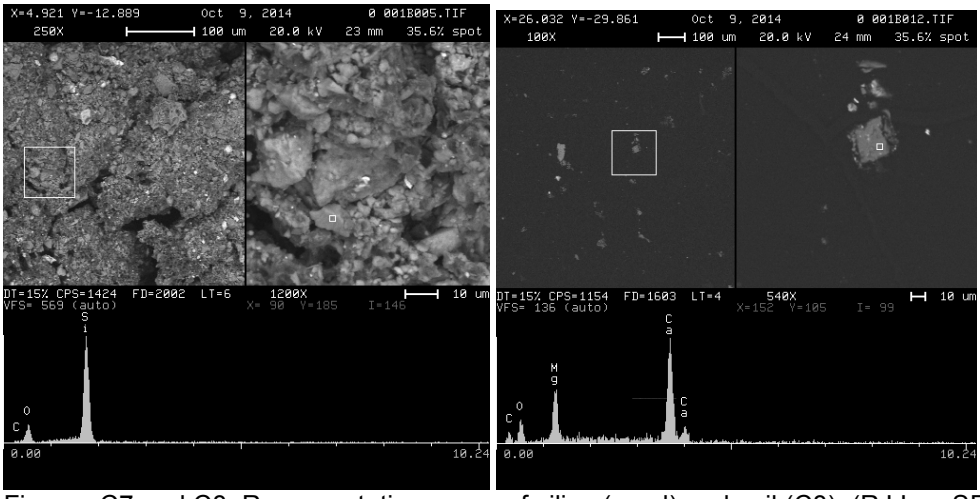
Figures C1 and C2: Dark deposit accumulation around and extrados weld, before collection of sample 2B (C1, left) and after sample collection and additional cleaning with an alcohol dampened cloth (C2, right). (Photo taken by authors in 2014)



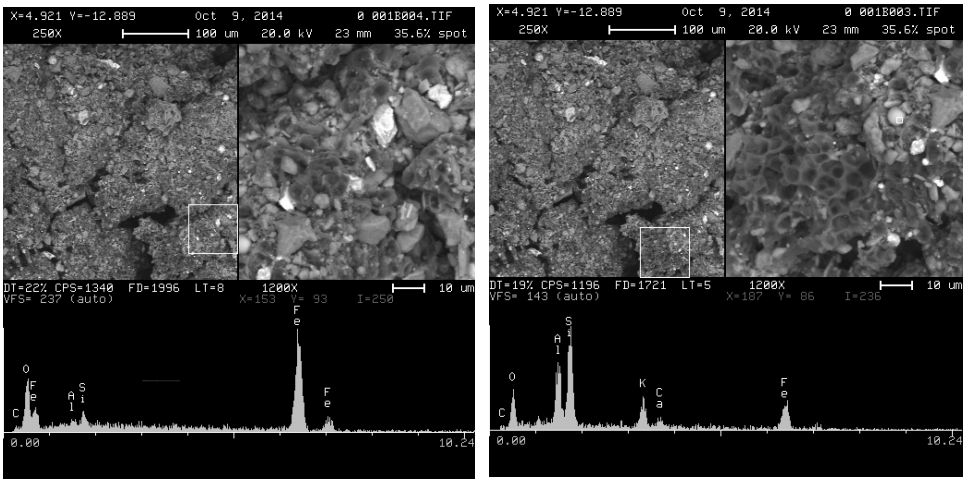
Figures C3 and C4: SEM images of the deposits at different magnifications. (RJ Lee SEM sample scans 2014)



Figures C5 and C6: Representative particles of what appears to be electric arc furnace slag from steel production or fly ash with some iron particles trapped in it. (RJ Lee SEM sample scan 2014)



Figures C7 and C8: Representative scans of silica (sand) and soil (C8). (RJ Lee SEM sample scans 2014)



Figures C9 and C10: (C9) Iron particle from carbon or steel manufacturing or fabrication combined with oxygen (corrosion) and (C10) soil combined with iron. (RJ Lee SEM sample scans 2014)

Figure C11 and C12: Weld spatter differences in areas with minimal versus significant surface deposits. (Photos taken by authors in 2014)

Representative SEM/EDS Scans of particles 3B and 4B

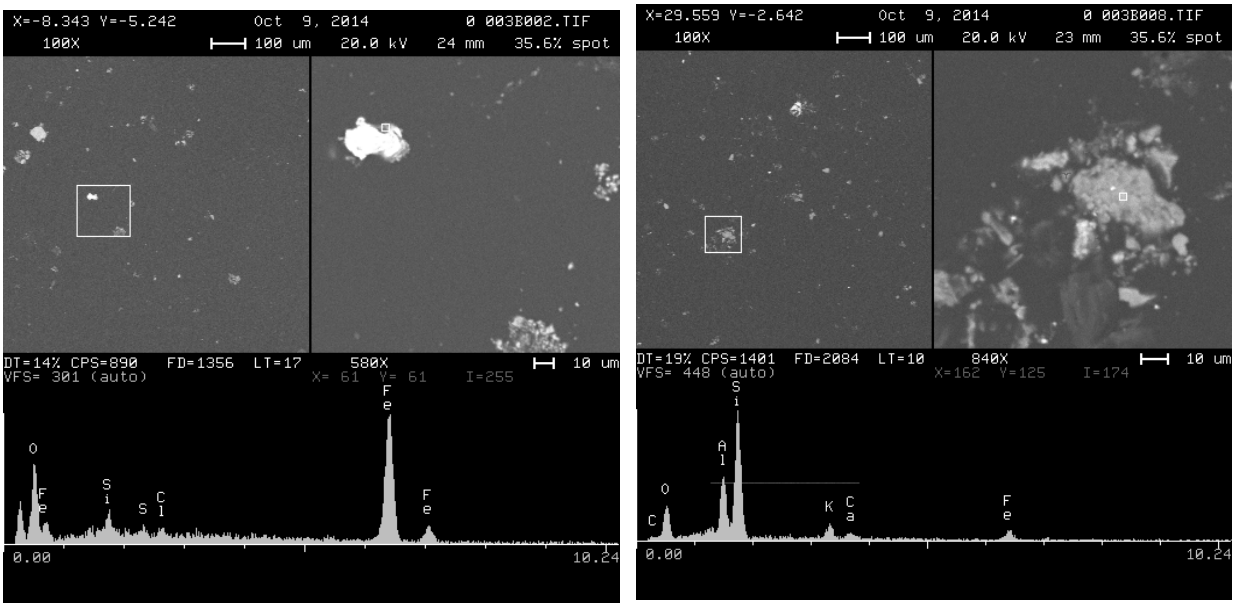


Figure C13 and C14: Iron with small amounts of silica and chlorides (left, C13) and soil with a small amount of iron (right, C14). (RJ Lee SEM sample scans 2014)

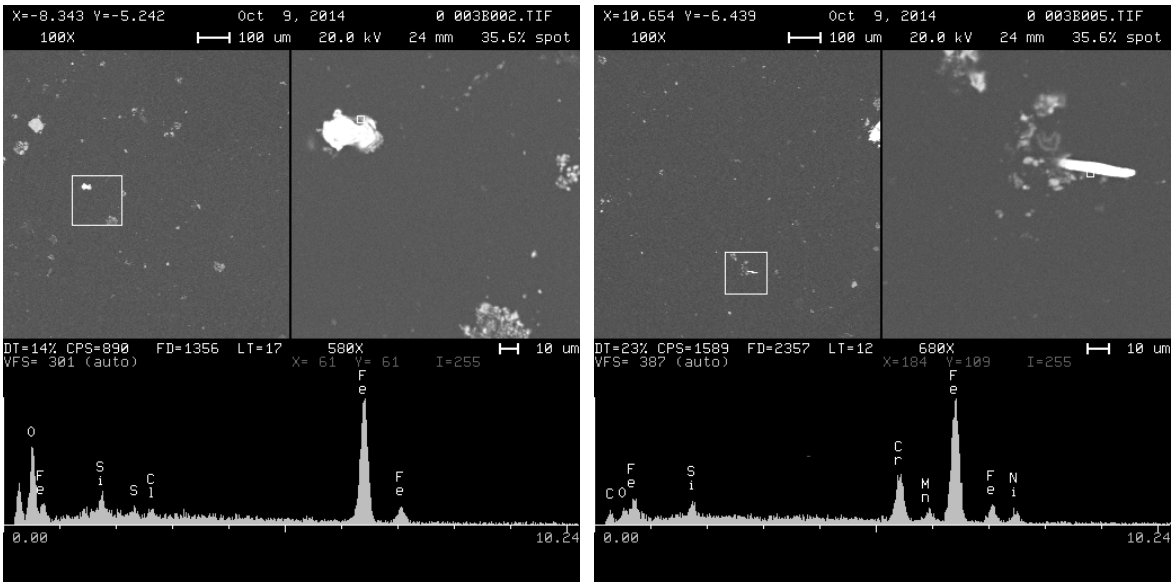


Figure C15 and C16: Iron with small amounts of soil (left, C15) and a stainless steel particle (no oxygen so it is not corrosion product) (right, C16). (RJ Lee SEM sample scans 2014)

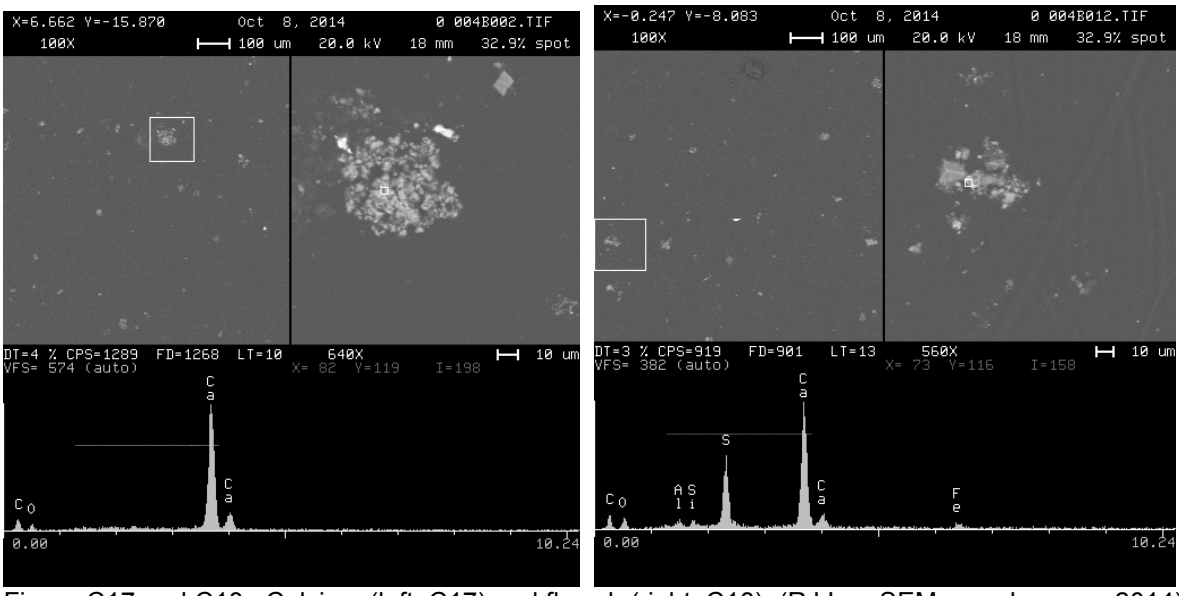


Figure C17 and C18: Calcium (left, C17) and fly ash (right, C18). (RJ Lee SEM sample scans 2014)

Representative SEM/EDS Scans of particles 5B and 6B

Many of the particles were sand or fly ash as documented in the other samples.

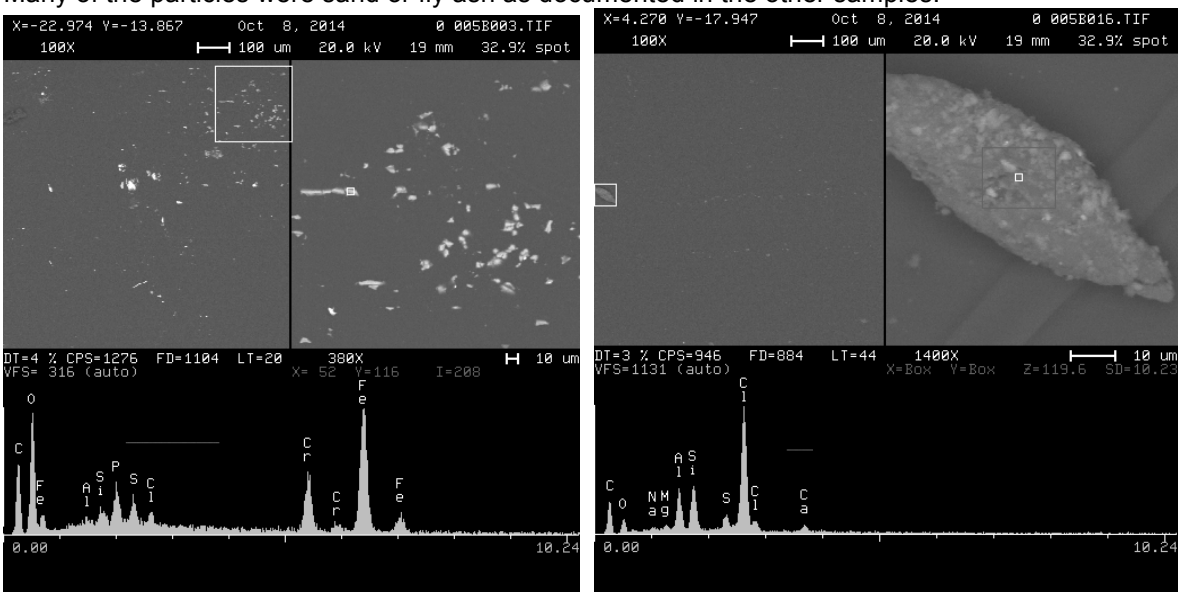


Figure C19 and C20: Ferrochrome with small amounts of chlorides and soil (left, C19) and chlorides mixed with soil (right, C20). (RJ Lee SEM sample scans 2014)

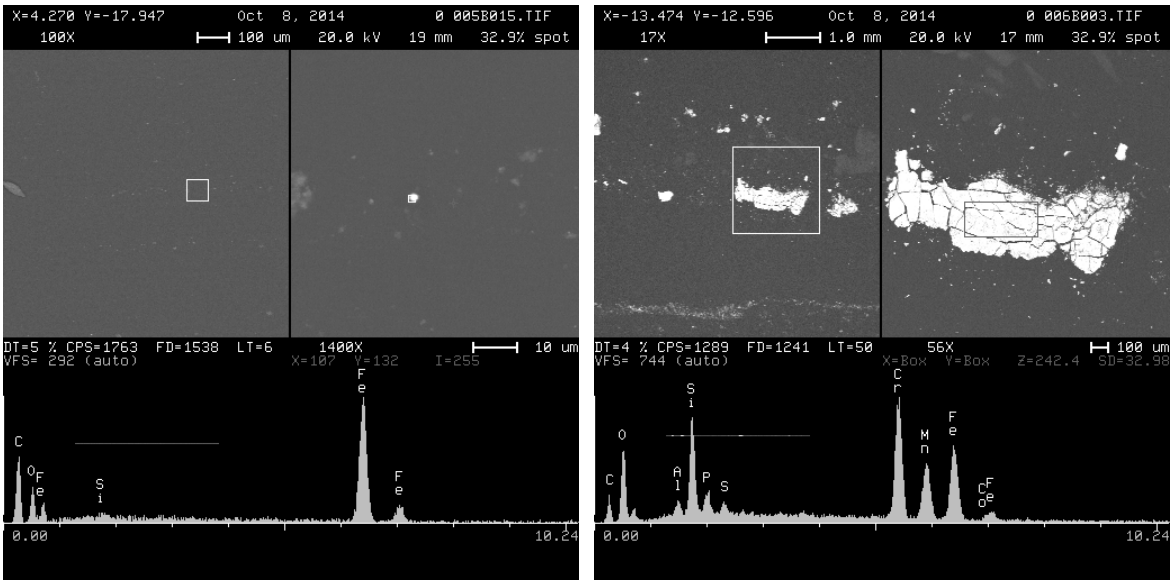


Figure C21 and C22: Iron particle (left, C21) and iron or steel slag with some soil (right, C22). (RJ Lee SEM sample scans 2014)

Representative SEM/EDS Scans of particles 7B and 8B

These scans were essentially identical.

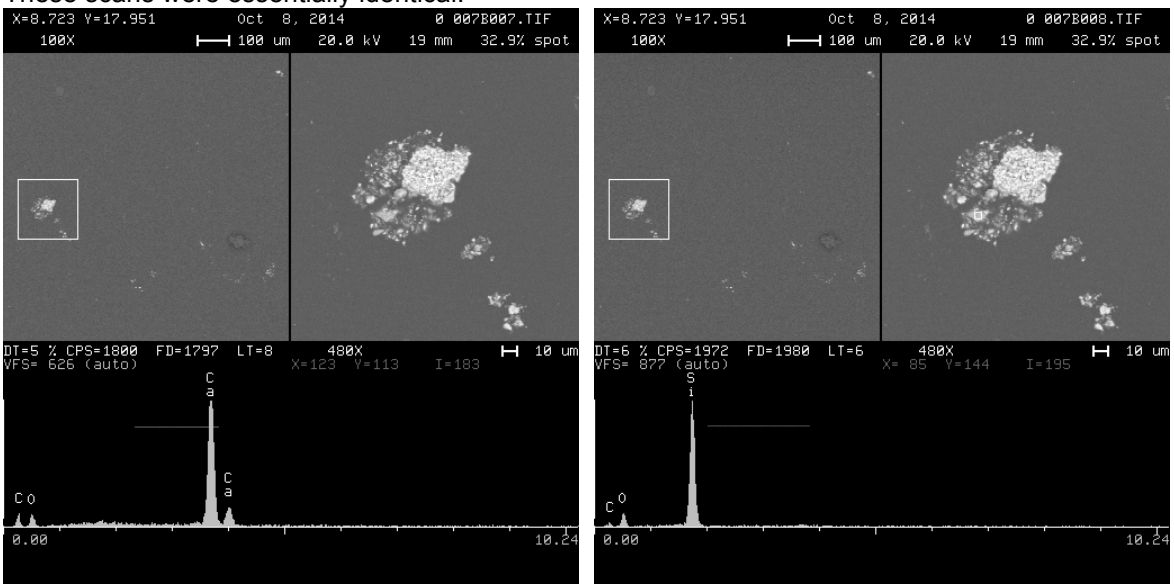


Figure C23 and C24: Calcium particle (left, C23) and silica (right, C24) (RJ Lee SEM sample scan 2014)

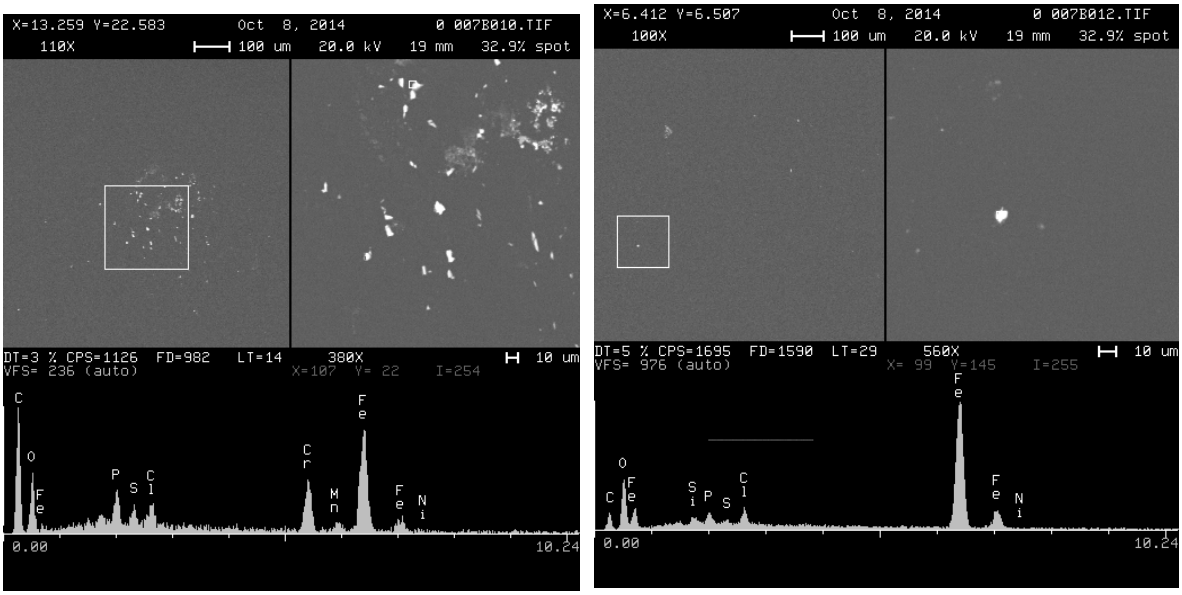


Figure C25 and C26: Probably ferrochrome with chlorides with carbon rich organics (left, C25) and iron with small amounts of chlorides and soil (right, C26). (RJ Lee SEM sample scan 2014)

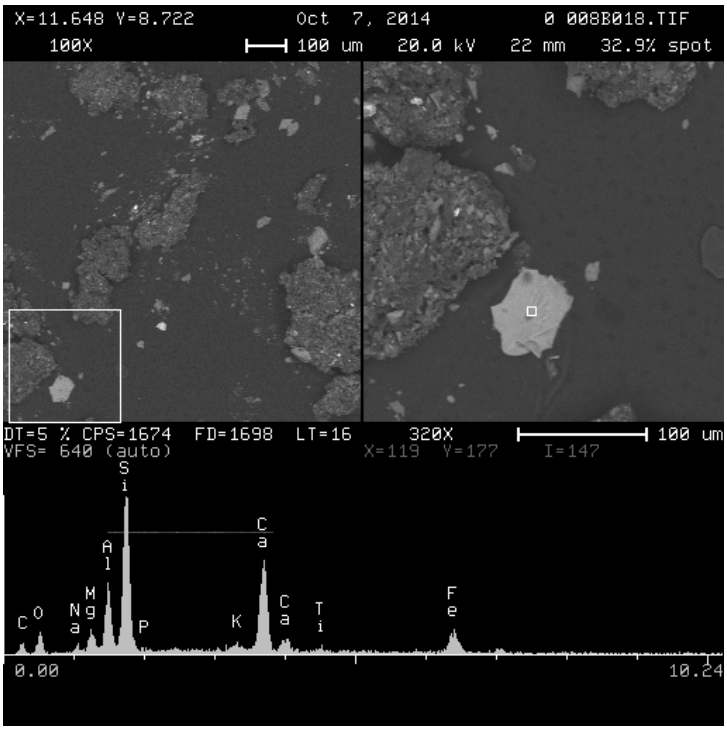


Figure C27: Fly ash, soil and a small amount of iron. (RJ Lee SEM sample scan 2014)

Representative SEM/EDS Scans of particles in Sample 4C

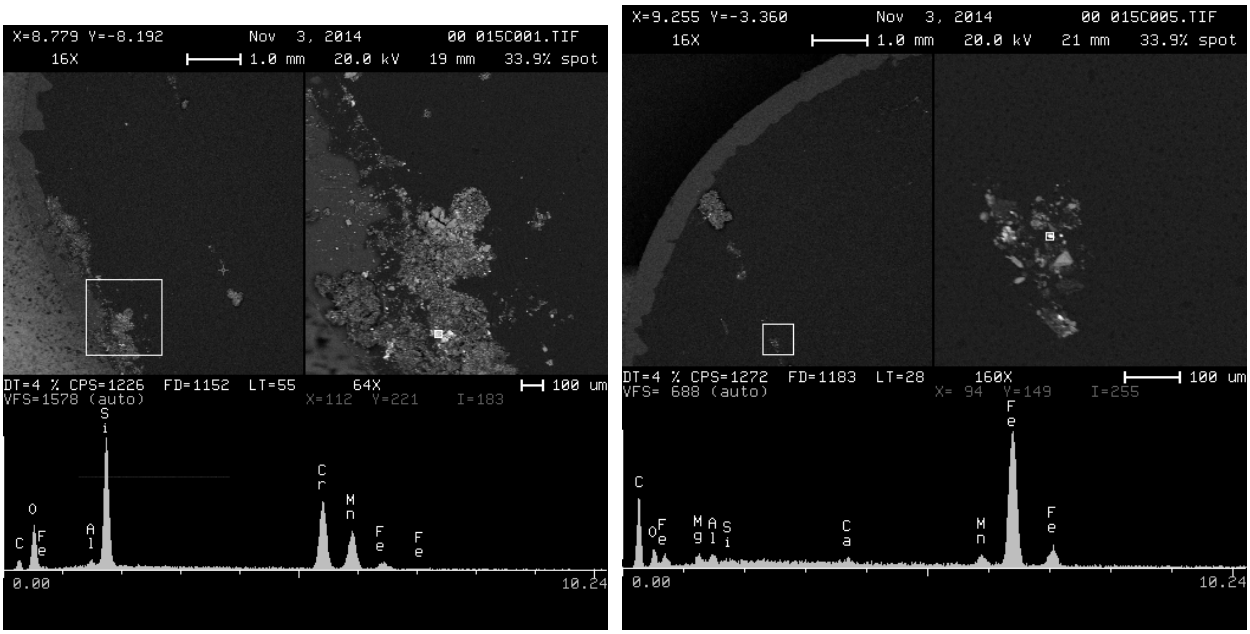


Figure C28 and C29: (left, C28) Slag from iron or steel production and (right, C29) iron with small amounts of soil and iron with soil. (RJ Lee SEM sample scans 2014)

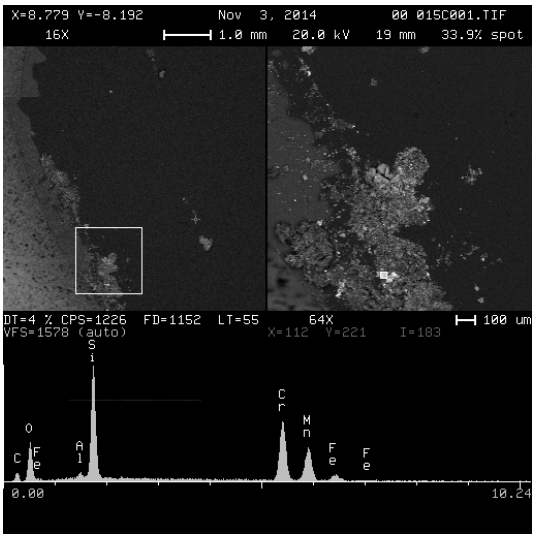


Figure C30: Soil and ferrochrome particles. (RJ Lee SEM sample scan 2014)

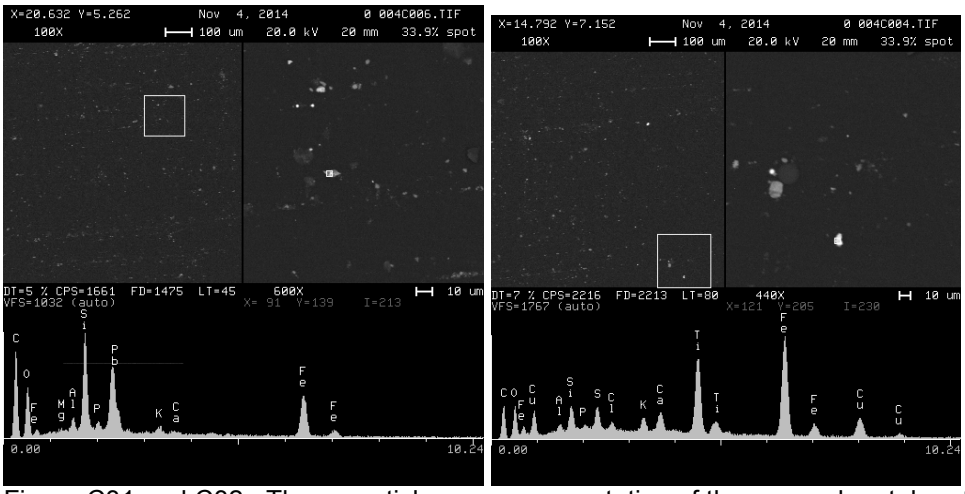


Figure C31 and C32: These particles are representative of the unusual metal particle combinations found on this sample including lead, iron, soil and carbon organics (left) and titanium with iron and smaller amounts of copper, chlorides, and soil (right). (RJ Lee SEM sample scan 2014)

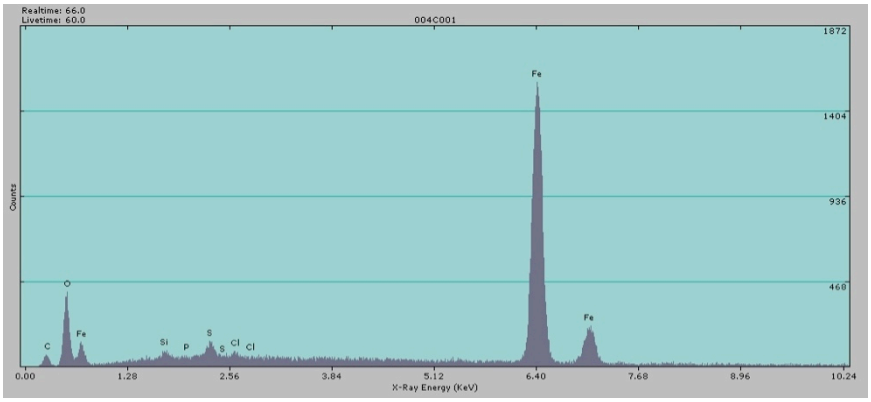


Figure C33: Iron particle with oxygen (corrosion). (RJ Lee SEM sample scan 2014)

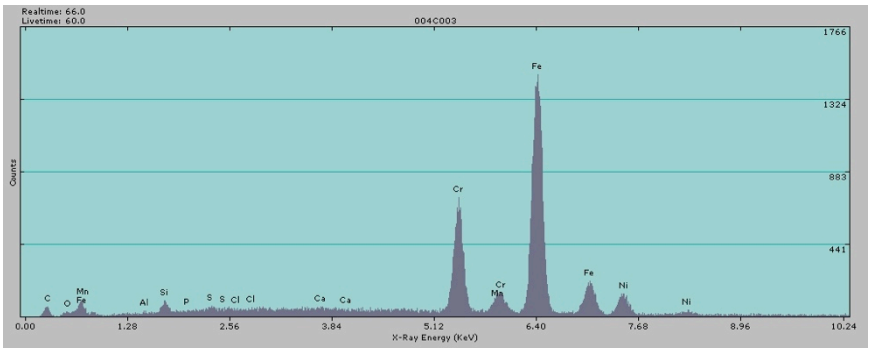


Figure C34: Stainless steel particle with no oxygen (corrosion) with minor amounts of chlorides (salt) and soil. (RJ Lee SEM sample scan 2014)

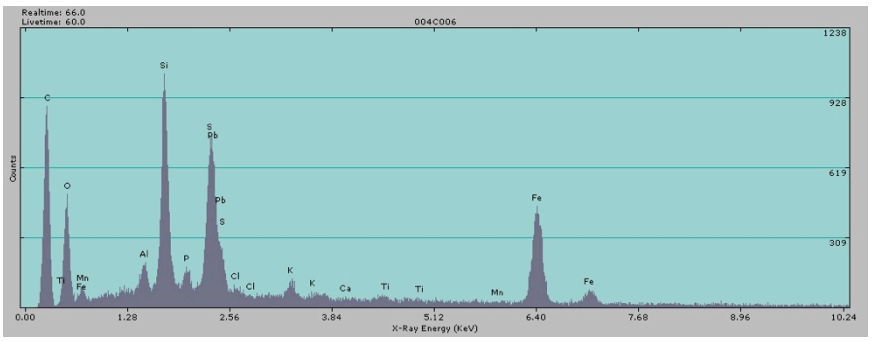


Figure C35: Soil combined with iron and steel slag and some lead. (RJ Lee SEM sample scan 2014)

Representative SEM/EDS Scans of particles in Sample 5C

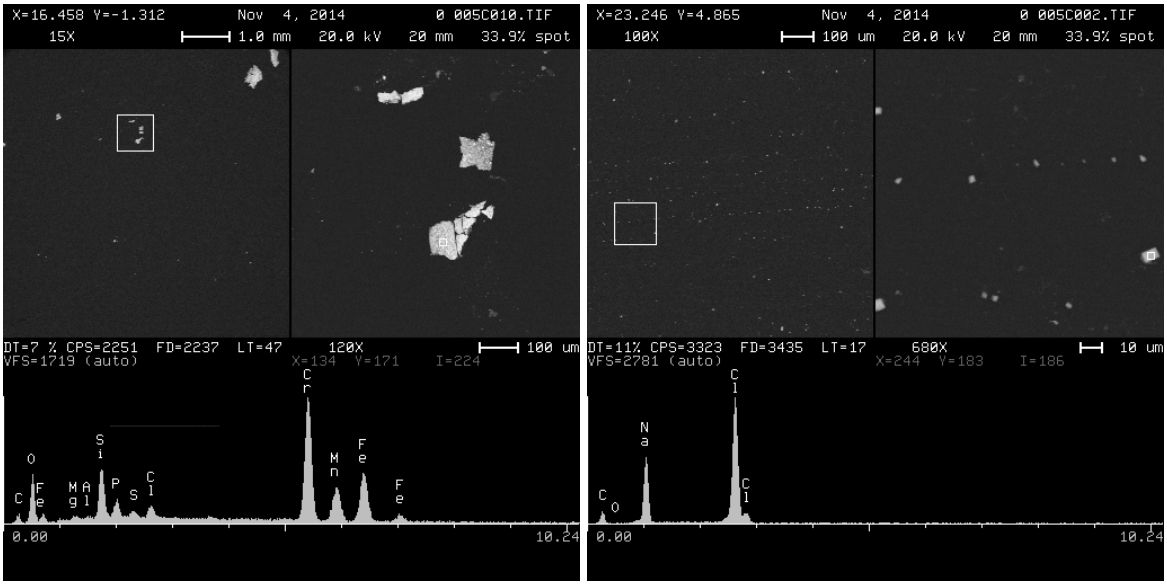


Figure C36 and C37: These were typical of the oxidized (corroded) steel or iron slag (left) and many small sodium chloride particles (deicing salt, right) on the lift. (RJ Lee SEM sample scans 2014)

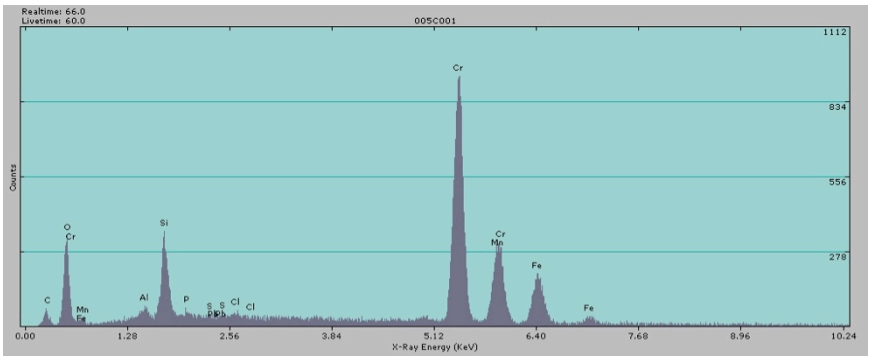


Figure C38: Ferrochrome and fly ash. (RJ Lee SEM sample scan 2014)

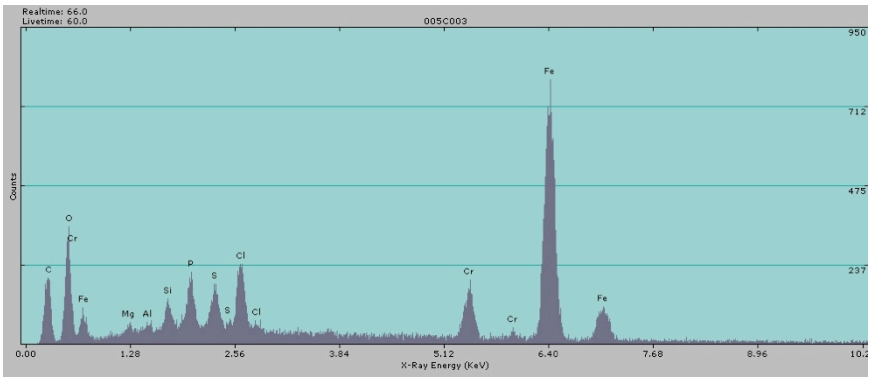


Figure C39: Ferrochrome, chlorides (salt), and soil. (RJ Lee SEM sample scan 2014)

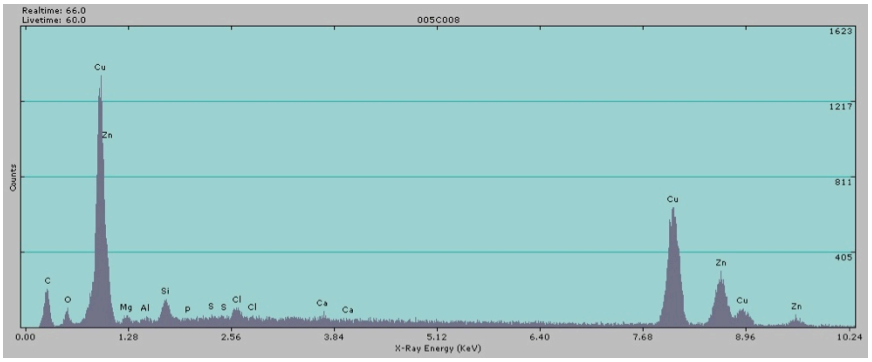


Figure C40: Copper zinc alloy particle with minor amounts of chlorides (salt) and soil. (RJ Lee SEM sample scan 2014)

Representative SEM/EDS Scans of particles in Sample 6C

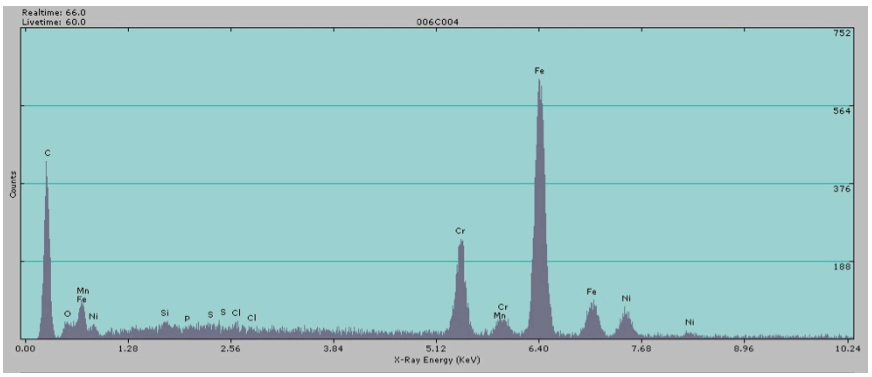


Figure C41: Most of the particles were ferrochrome combines with carbon rich organics (i.e. spores and pollen) with very small amounts of soil and chlorides (salt). (RJ Lee SEM sample scan 2014)

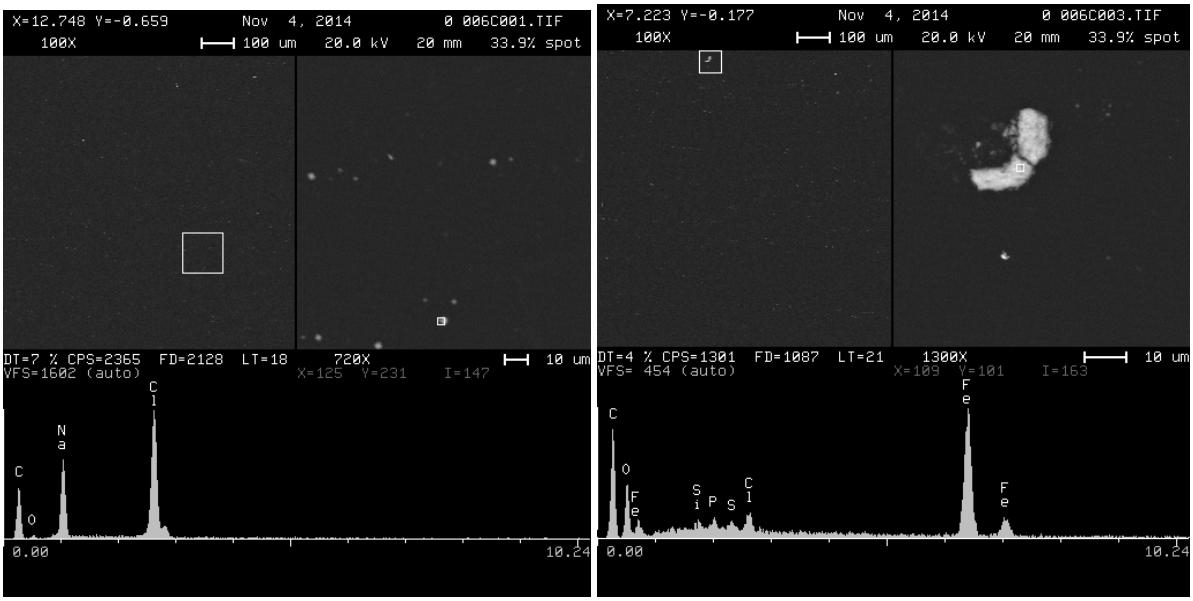


Figure C42: Sodium chloride (deicing salt) was found in combination with clay and iron/chloride/carbon organic particles were also found. (RJ Lee SEM sample scan 2014)

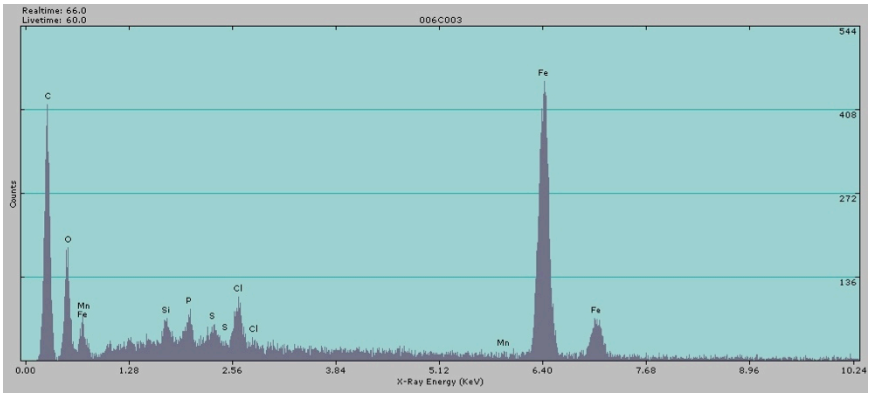


Figure C43: Iron particle combined with carbon rich organics (i.e. pollen and spores) and smaller amounts of chlorides (salt) and soil. (RJ Lee SEM sample scan 2014)

Representative SEM/EDS Scans of particles in Sample 13C

This sample was particularly chemically diverse with numerous metals that were probably from industrial emissions held together by soil or fly ash. The following scans are representative of the range of metals found.

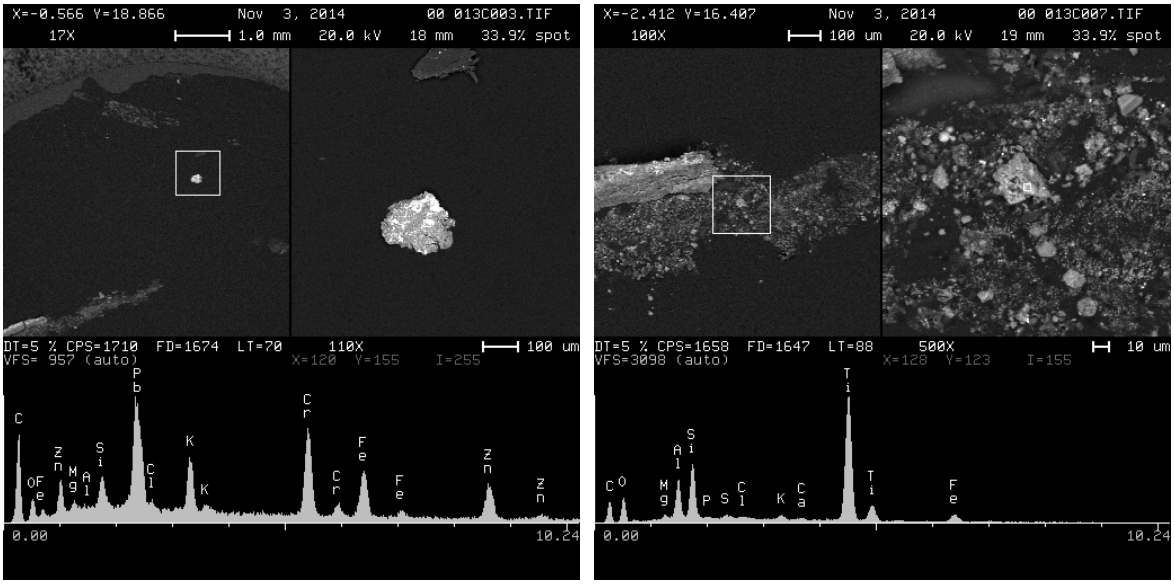


Figure C44 and C45: Iron or steel slag, zinc, lead, and potassium chloride (left) and titanium with soil and a small amount of iron and chlorides (right). (RJ Lee SEM sample scan 2014)

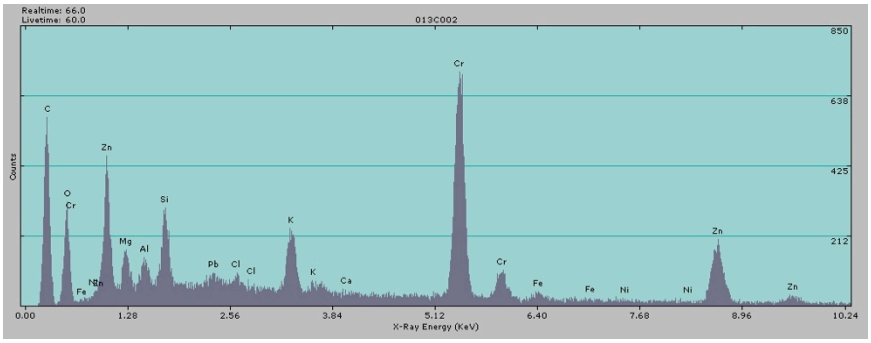


Figure C46: Carbon rich organics (i.e. pollen), chromium, zinc, and soil constituents. (RJ Lee SEM sample scan 2014)

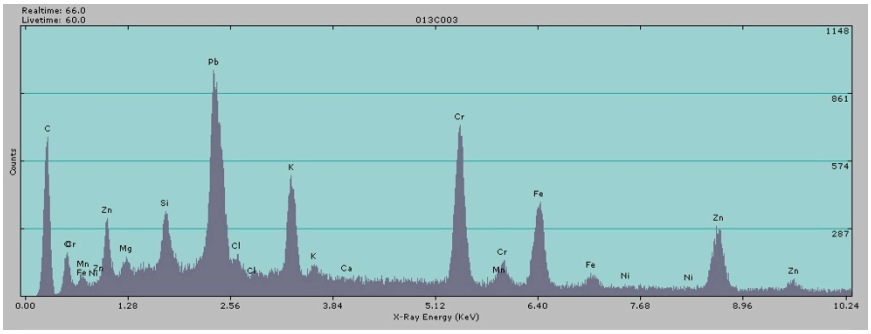


Figure C47: An amalgam of lead, chromium, zinc, iron, carbon rich organics, potassium and fly ash. (RJ Lee SEM sample scan 2014)

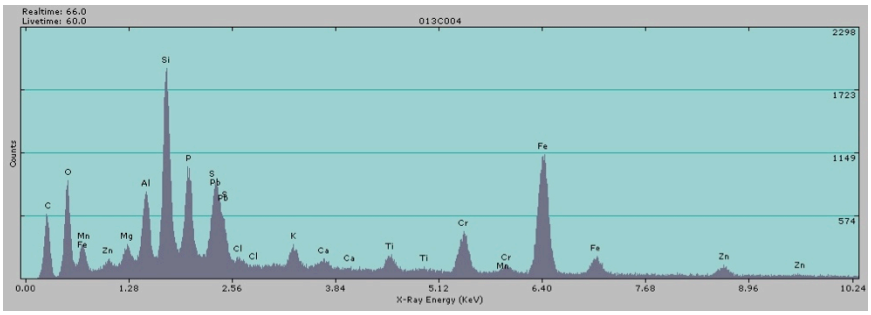


Figure C48: Ferrochrome, soil, potassium, zinc, and soil. (RJ Lee SEM sample scan 2014)

Representative SEM/EDS Scans for Sample 14C

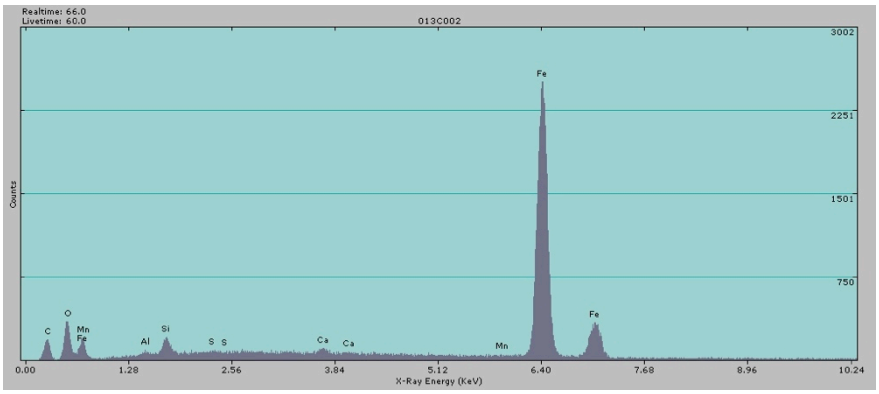


Figure C49: Iron particle with small amounts of soil. (RJ Lee SEM sample scan 2014)

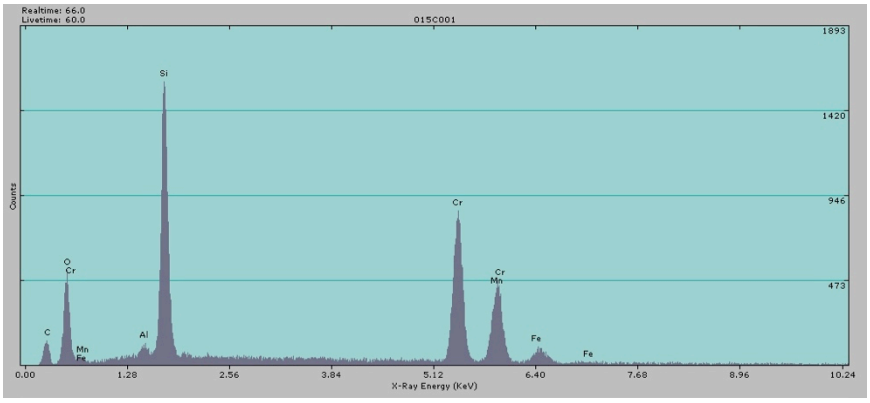


Figure C50: Ferrochrome combined with soil. (RJ Lee SEM sample scan 2014)

Representative SEM/EDS Scans of particles in Sample 15C

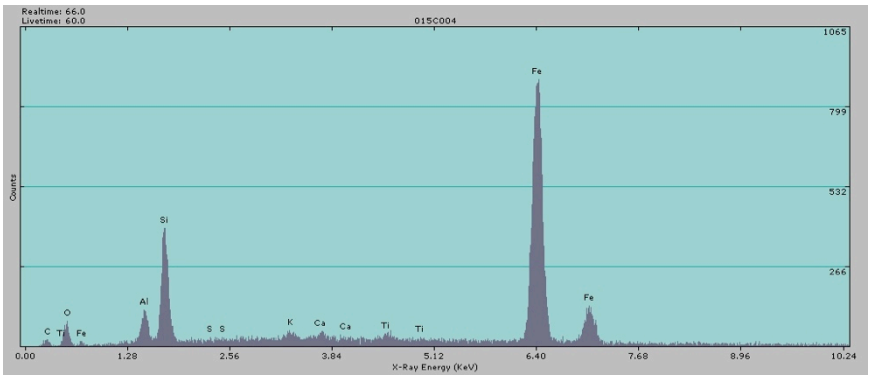


Figure C51: Most of the particles were iron combined with soil and some fly ash. (RJ Lee SEM sample scan 2014)

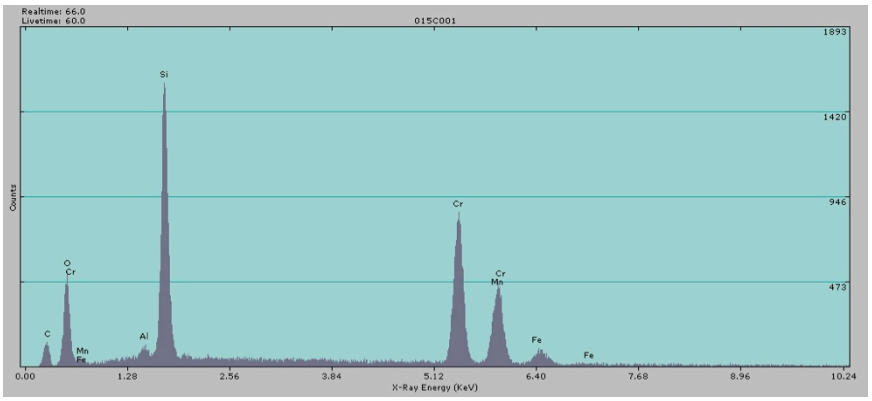


Figure C52: Ferrochrome combined with soil. (RJ Lee SEM sample scan 2014)