50 year evaluation of St Louis' Gateway Arch

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Stainless steel's corrosion resistance made it a natural choice to achieve the desired longevity and aesthetic requirements of the exterior of the Gateway Arch in St. Louis, USA. While it is celebrated for its elegant symbolism and amazing size, many people do not realise that it was also visionary and innovative as the world's first large structural application for stainless steel. This article summarises a metallurgical investigation, historic review and current site assessment, which had the goal of determining the structural performance and integrity of the Gateway Arch's exterior stainless steel plate and welds.

While it was not possible to locate the original plate or weld filler metal chemical certifications in the Gateway Arch archives, Type 304 was specified during design. 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. 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 archives did not identify the source of the filler metal.

The stainless steel used for this project predates the installation of the first AOD (Argon Oxygen Decarburisation) furnace in the United States in 1974. AOD furnaces very efficiently remove impurities, including carbon and sulfur, and make overall chemistry control easier. Metal produced prior to their widespread use typically had 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 (3.2 mm) in thickness or greater today.

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 Type 304 and other common stainless steels were moved to ASTM A240 many years ago and A167 was recently withdrawn.

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). It was not clear whether either was a final procedure. Both indicated that MIG welding was to be used with different argon-CO_2 helium cover mixtures for each joint orientation. Weld clean up was to be with a wire brush, and 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.

Electrolytic cleaning wands are commonly used to remove heat tint today. 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, a phosphoric acid based cleaner that is still sold today, was used to clean and degrease the surface prior to welding. Both AWS and ASME code Section IX were referenced in the weld procedures.

Weld sample collection and analysis

Five approximately 0.75 inches (19 mm) diameter weld samples were obtained from the North leg of the Arch after examination of the welds using a lift. Larger weld beads, obvious weld repair or the other areas with visual cues that might indicate a possible imperfection were selected. All of the samples came from the lower sections of the North leg and a mixture of 'field' and 'shop' welds were selected.

During the second site visit, the architect's daily reports were found in the archives. A 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 weld penetration at these joints was found during 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 levels N63 and S63.

These records implied that most if not all of the carbon and stainless steel below these levels was re-welded 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 relative to the thickness of the plate. The metallographic weld cross-sections were mounted and polished and examined using optical light microscopy. Some of the samples were also examined using SEM/EDS to confirm findings.

Even with today's low-carbon levels, the high levels of heat input associated with repeated welding of plate could cause sensitisation (precipitation of carbides at grain boundaries), which decreases the corrosion resistance of the stainless steel plate adjoining the weld. Sensitisation 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 sensitisation-related corrosion. Given the high carbon levels typical of stainless steel produced prior to the introduction of the AOD, the sensitisation observed during weld cross sectioning is not surprising. Since the samples were from an area known to have been repeatedly re-welded, we cannot be certain that welds higher on the structure were also sensitised. After 50 years of service, the lack of the characteristic pattern associated with sensitisation related corrosion indicates that Type 304 is suitable for the environment.

SEM/EDS confirmed the presence of manganese sulfides in the base metal. Sulfides were seen in all the samples and can make the stainless steel more susceptible to pitting corrosion if the surface is not chemically passivated. The post-fabrication cleaning procedures indicated that passivation was to be done although we did not find confirmation of it. This would have removed surface sulfides and improved corrosion resistance.

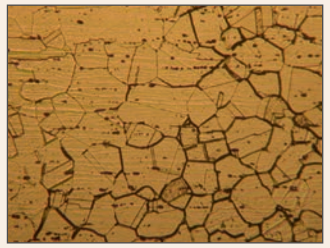

Figure 1(left) Micrograph of W1 in the etched condition showing sensitised grains (right) and grains that are not sensitised (left). (256x). Figure 2 (right): Micrograph of a plate inclusion, W1, as-polished condition. (517x) (Photos taken by TMR in 2014).

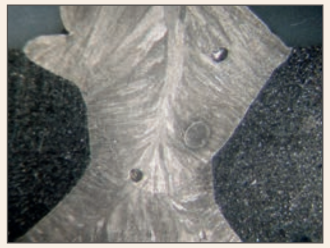

Figure 3: Micrograph of manganese sulfide stringers in the plate, W1, as-polished condition. (256x). Figure 4 (right): Macrograph, W4, etched condition, showing the most significant weld porosity found in any sample. The largest void near mid thickness has an approximate diameter of 0.04". (Photos taken by TMR in 2014)

All of the sample welds appeared to be full penetration. Numerous weld imperfections were documented during visual examination and microscopic evaluation of the weld samples, including small areas of porosity, weld spatter, weld slag and a shallow weld undercut. No cracking or significant corrosion was found at these imperfections after 50 years of service so they were not considered a concern. Figures 1 through 5 provide representative images of these imperfections, the inclusions and the sensitisation.

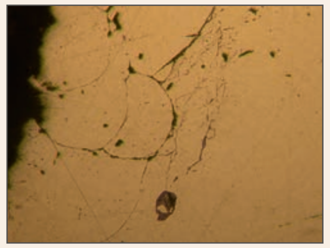

Figure 5: Micrograph W5 at the weld crown shown in the as-polished condition showing the sub surface weld slag. (256x) (Photo taken by TMR in 2014).

Table 1. SEM/EDS Chemistry Evaluation

Sample	Description	SEM/EDS Data for Primary Elements (Mass %)				
		Si	Cr	Mn	Fe	Ni
ASTM A167-1963	Type 304	1.00	18.00-20.00	2.00	Rem	8.00-12.00
A240/ A240M-2015	Type 304	0.75	17.5-19.5	2.00	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.

Plate and weld chemistry

The weld samples made it possible to determine the approximate chemistry using SEM/EDS. 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. 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. Neither carbon nor sulfur levels can be accurately measured so neither element was included in Table 1 where the samples are identified based on weld sample number. Carbon levels measurements done with SEM/EDS are typically much higher than what is physically possible due to surface contamination. 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 than they actually are.

The plate appears to be the specified Type 304 with an appropriate matching chemistry filler metal. If the carbon had been eliminated from the analysis, they should meet 1963 requirements. Even if some plates or filler metal were outside of the required chemistry range, there has been no significant corrosion problem after 50 years of service and remedial action, such as plate identification and replacement, is not reasonable.

Surface deposits and site corrosion assessment

Samples were collected between September 29 and October 1, 2014 from the lower areas of the North leg, which were reachable by foot or lift and by the inspectors climbing down the North leg between October 14 and 21, 2014. Gunshot residue kits, which were developed for law enforcement use, are specialised SEM/EDS sample collection tapes that can pull fine particles from the surface for analysis. Data analysis identified specific compounds associated with different types of industry.

Very minor amounts of deicing salts (chlorides) were found at all heights on the surface along with industrial particulates (i.e. fly ash, ferrochrome oxide, iron and steel slag, iron, copper, copper zinc, lead, and titanium), and soil constituents. Soil consists of 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 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.

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 of the surface deposits 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 surface deposits, included several steel mills; 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.

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Fly ash (SiO_2, and CaO) is also known as flue-ash, and is one of the residues generated in combustion. 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). It used to be released into the environment and would have been present for much of the Gateway Arch's service life. In recent decades, scrubber systems have been mandated and fly ash is no longer released into the environment.

The iron rich particles were mainly ferrochrome or iron and steel slag. Ferrochrome (FeCr) is an alloy of chromium and iron containing between 50% and 70% chromium. Steel production is the largest consumer of ferrochrome, especially stainless steel. The particles contained iron and chromium but no nickel; and therefore did not appear to be Type 304 stainless steel from the Gateway Arch. Iron and steel blast furnace slag is similar to fly ash in composition but it contains iron. There were also iron particles found on the surface, which could have been from manufacturing operations or nearby construction.

Figure 6. Superficial corrosion staining at the base caused by deicing salt exposure. (Photo taken by author in 2014).

Chlorides from deicing salt were found on the surface in very small concentrations at all sample heights. Highways surround the site and they are within the documented distance that deicing salt can travel. The high winds documented at elevated levels indicate that most of the structure is probably well rain-washed. It is not possible to determine how high deicing salt concentrations are in the winter and early spring but studies conducted by Argonne National Laboratory and by other researchers indicate that concentrations would be relatively low.

Other than very small, localized areas, the only corrosion staining observed on the surface was at the base, which would not be as effectively rain-washed as elevated areas. This light superficial staining was caused by microscopic deicing salt related pitting and could easily be removed. The environment is not corrosive enough for any of these deposits to have caused more than superficial discoloration after 50 years, so their presence is a purely aesthetic issue. Figure 6 shows superficial corrosion staining at the base.

Embedded iron contamination

There were scratches on Arch's base, which contain embedded iron particles from carbon or alloy steel. The largest of these extends 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 to deicing salt increases the corrosion rate. This contamination should be removed from the deep scratches 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.

Alloy selection

Overall the Gateway Arch is in very good condition. The service environment is less corrosive now than it has been historically due to the dramatic reduction in pollutants from heavy industry. Deicing salt has been added to the environment since the Arch's construction but surface concentrations were very low and only identifiable through SEM/EDS. The high winds combined with rain washing and a mechanically polished surface finish that is finer than most No. 4 polished plate today have made rain-washing effective for most of the surface. Type 304 appears to have been an appropriate alloy for this project. Cleaning could remove the existing discoloration.

Based on the assumption that corrosion staining is undesirable and there will be little or no maintenance cleaning, the stainless steels that would be most commonly specified today for low to moderate salt exposure or heavily polluted environments with little or no cleaning would be Type 316/316L or the duplex alloys UNS S32101 or S32304, because typically rougher finishes than a relatively smooth No. 4 are specified for monuments and sculptures. Duplex UNS S32205 provides substantially more corrosion resistance and is suitable for higher levels of industrial pollution and salt exposure, when rougher finishes are specified, or where natural heavy rain cleaning is less frequent.

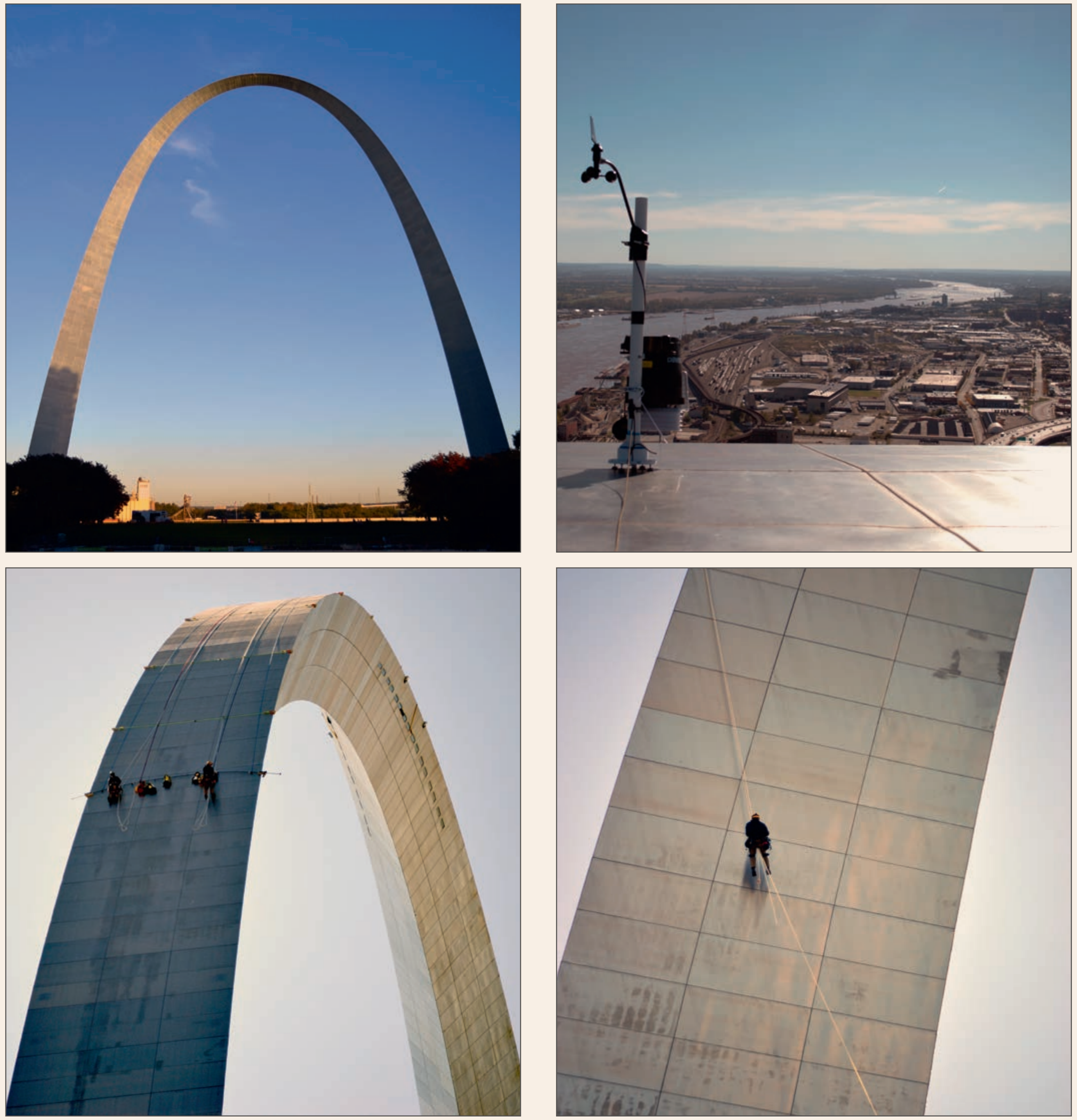
Memorial and sculpture use

The first large structural stainless steel non-industrial projects to use this research were the 1964 Unisphere sculpture (World's Fair, New York City) and the following year's Gateway Arch, which were both Type 304. Because it is in a coastal environment, cleaning of the Unisphere has been necessary to maintain its appearance, and it would have been constructed from Type 316L if it had been designed today. The 266 ft (81 M) sculptural flagstaff on the Australian Parliament building is also Type 304L. Canberra is an inland location with low pollution levels.

The 1986 restoration of the Statue of Liberty used Type 316L and the high strength proprietary duplex stainless steel UNS 32550 to replace much of the original iron support framing. It was the world's first known large non-industrial duplex structural application. There are many other examples of stainless steel's use in sculpture, memorial and building restoration throughout the world. Restoration of the Atomium in Brussels, which was built for the 1958 World's Fair and originally clad in aluminum, began in 2001, and Type 316L stainless steel was chosen to replace the poorly performing aluminum.

More recent examples of duplex stainless steel use include the large moving flag sculpture inside the entrance of the Smithsonian National Museum of American History in Washington, DC where its' high strength permitted structural section and weight reduction. A proprietary cast duplex stainless steel was used for the Pentagon 9/11 Memorial because added corrosion resistance was needed due to deicing salt exposure. By far, the largest construction-related structural application for duplex alloys (not including industrial buildings) has been pedestrian bridges.

Type 316L has been the most commonly used stainless steel for exposed structural sculpture and memorial section applications because it provides better resistance to corrosive coastal and deicing salts and pollution than Type 304/304L. Examples in the US include the US Air Force Memorial, Chicago's Cloud Gate, and the New Jersey, New York and Connecticut 9/11 Memorials. Stainless steel concrete reinforcement is used in restoration projects as well including the replacement of failing carbon steel in the seawalls around the Sydney Opera House (316L) and the Hassan II Mosque in Morocco (2205 duplex).



Inspectors used gunshot residue kits with specialised SEM/EDS sample collection tapes to gather samples from the surface of the Arch.