Alternative Methods for Sealing Overlapping Steel Members with Narrow Gaps During Galvanizing

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Abstract

Narrow gaps in overlapping structural steel surfaces are problematic when being hot-dip galvanized due to the potential for trapped cleaning solutions between the surfaces. A seal-weld is often used to prevent the cleaning solutions from penetrating this gap. However, these welds are not necessary used for strength, and add fabrication costs because of the additional weld. The purpose of this research is to provide alternatives, which fall under two major categories, to the seal-weld fabrication process. The first one was motivated by the steel fabrication industry and uses a commercial silicone caulk to seal the narrow gap instead of a seal-weld. The second was motivated by the galvanizing industry and increases the narrow gap to a minimum of 3/32 in. to allow free flowing of the liquids including viscous molten zinc. 45 specimens in six different overlapping configurations were tested. Three experimental tasks were performed as part of this research: two different types of silicone caulks were used to partially substitute the seal-weld to prevent fluid penetration; an accelerated corrosion test was performed to determine the long-term corrosion resistance of each configuration; and a coating layer evaluation was performed to investigate the bond of the metallurgical layer between the steel and the coating. Results indicate that silicone only partially prevented the penetration of the cleaning solutions into the gap but performed poorly when fully galvanized. Also, the accelerated corrosion and coating investigations indicated that the suggested caulks and the 3/32 in. gap were not as efficient as the seal-weld solution.

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General Audience Abstract

Hot-dip galvanizing is a corrosion protective process for steel. The process involves dipping the base material into a series of different baths. The first set of baths are the cleaning baths and the last bath is the zinc coating bath. In the cleaning baths, certain chemicals are applied to clean the steel surface from oxides and rusts and to prepare the steel for a better zinc coating. When steel members that are fabricated with narrow gaps between overlapping surfaces are subjected to the galvanizing process, the quality of the zinc coating is often inferior along the interface between the two surfaces. This problem occurs because the cleaning solutions—which have a lower viscosity than zinc—get trapped inside the gap while the molten zinc cannot galvanize narrow gaps due to its high viscosity. For this reason, overlapping steel members are seal-welded to prevent such issues. Since seal-welding is not efficient from a fabrication standpoint, the purpose of this research is to provide alternative geometrical overlapping surface configurations. These configurations were subjected to the galvanizing process. To evaluate their performance, three separate tasks were applied through this investigation. The first task involved sealing the gap with commercial silicone sealants instead of a seal-weld, the second task was an accelerated corrosion test, and finally a bond investigation of the coating of the overlapping surfaces was performed. Results have shown that the proposed alternatives did not provide an improved detail for overlapping steel surfaces compared to the existing seal-weld.

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Chapter 1: Introduction

1.1 Background

Hot-dip galvanizing (HDG) is a corrosion protection method for steel. It has been used widely and extensively since the 18th Century. It provides a zinc layer which offers a protective barrier, as well as cathodic protection. This system can significantly increase the service life of steel members when detailed correctly. The process, while differing slightly from one industry plant to another, consists of dipping steel members (beams, plates, etc.) into a series of four different baths. The first three are cleaning baths and the last one consists of a molten zinc bath. Each bath has a different chemical property and viscosity intended to prepare the material appropriately. Although HDG is currently utilized extensively for steel structures due its ability to increase the service life of structures, it has some significant challenges when used for certain geometrical configurations. One such configuration is overlapping surfaces which is the focus of this study.

For the purposes of this research, overlapping surfaces are considered simply as two adjacent planar steel surfaces that are either welded or bolted together. They are common in many structural steel applications. For this project, the focus is highway bridges; specifically, lateral bracing systems (cross frames). Cross frames are used for stability and stiffness needs. For steel bridges, they often consist of angles (surface 1) fabricated and attached diagonally to gusset plates (surface 2), as shown in Figure 1. This geometrical configuration between the two surfaces causes an overlapping surface.

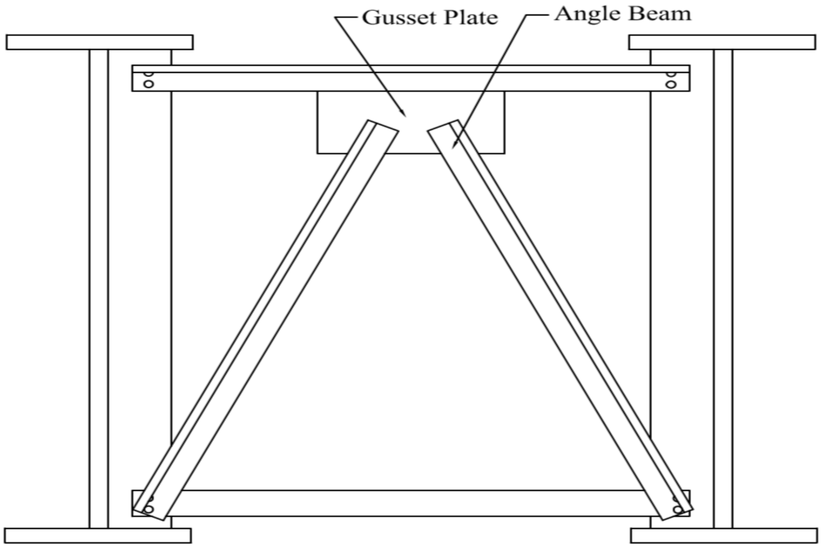


Figure 1: Overlapping Surfaces Between the Angle Beam and the Gusset Plate

Overlapping surfaces have a very narrow gap in between, this gap can cause coating quality issues in the localized area around the gap. This is due to the difference in viscosity between the cleaning solutions and the molten zinc. The cleaning solutions can leach into small gaps, whereas the zinc cannot due to its high viscosity. When fluids leach into this gap it can cause unseen internal corrosion between the surfaces that can result in red 'rust bleeding' as moisture leaches from the gap during service. Additionally, the cleaning solutions can trap between the overlapping surface inside the gap from the HDG process, this causes safety issues to the workers when the solutions are steamed instantly by the high temperature of the hot molten zinc bath. In order to overcome these problems, the galvanizing industry requires the fabricators the use of a seal-weld around all of the edges between the contacting surfaces to cover the gap and prevent the ingress of moisture. This is typically considered an unnecessary excessive weld, from a strength perspective, and results in additional fabrication time because the full weld area is not required for structural purposes. Additionally, if the overlapping surface area is large (higher than 16 in. square), the galvanizing industry and the American Society of Testing and Materials (ASTM) require the use of holes between the surfaces to appropriately vent the area and accommodate the flow of the zinc inside the surface, which is also considered extra fabrications. This thesis will investigate the problem of overlapping surfaces and investigate alternative economical solutions.

The proposed solutions were obtained from recommendations from fabricators and galvanizers. These include developing different fabrications between the contacting surfaces, such as using different gap locations, different gap widths, and commercial silicone caulk instead of the extra weld if welding is not required for structural purposes. Each solution was investigated to determine whether the result was an improvement over current methods.

1.2 Objective and Scope

The objective of this research was to investigate the overlapping surface by testing 45 steel specimens. These specimens were fabricated as similarly as possible to bridge braced frame components overlapping gusset plates. The 45 specimens were composed of six different configurations and each configuration had a different geometrical detailing. The first configuration was a control configuration. In this configuration, the specimens were seal-welded in all the edges. The rest five configurations fall under two categories. The first one, which was recommended by the fabricators, was to have specimens with open edges (no weld-edge) to be sealed with commercial silicone instead of using a weld. The second category, which was recommended by the galvanizers, was having specimens with a minimum of 3/32 in. gap between the overlapping surfaces. The distinction between each configuration was the gap or the open edge location with respect to the overlapping surface.

This research was performed with three major tasks and each task sought a specific objective. The first task was to test the feasibility of silicone caulk for the open edge specimens to determine if it can be a substitute for the welds. This was done by having steel specimens go through part of the HDG process. The second task was to test the specimens using accelerated corrosion tests to compare the long-term corrosion results of the recommended specimens with the seal-weld specimens (control specimens). The third task was to have a detailed assessment of the zinc coating adjacent to the gap in certain locations. This was observed by cutting the specimens in half and using a microscope when necessary to better understand the bond of the zinc.

1.3 Thesis Organization

This thesis has a total of five chapters. The first chapter introduces the problem and the motivation of this thesis. The second chapter reviews the literature around this corrosion phenomena, describes the hot-dip galvanizing method to prevent it, and explores the issues with hot-dip galvanizing, presents current solutions to the problems of HDG and provides alternatives solutions. The third chapter presents in detail the alternative solutions and illustrates the methods used to implement these alternative solutions. The fourth chapter includes the results along with a discussion. Because the nature of this study involves many pictures and figures, the discussion and the results are combined to enable the reader to more easily extract and directly connect them. Lastly, there is a conclusion chapter that gives the concluding thoughts of the thesis along with future recommendations.

Chapter 2: Literature Review

2.1 Corrosion

Overview

Corrosion can potentially cause catastrophic failures. In 1985, a roof collapsed in a swimming pool causing 12 fatalities (Maurath, 1989). Evidence has shown that the reason behind the failure was stress corrosion cracking, which occurred in the rods supporting the roof. Also, a study was conducted on prestressed beams bridges with corrosion rates of 5% and 10% and with normal non-corroded bridges. The fatigue life of the bridges with 5% and 10% corrosion rates decreased by 53.5% and 96.7%, respectively (Wang, Liu, Wei, Zhang, & Wang, 2017). In sum, corrosion, similar to other natural challenges such as earthquakes and wind, should be considered carefully in structural design.

Corrosion is the natural deterioration process of a metal due to an electrochemical reaction between the metal and the environment. The electrochemical reaction occurs when the metal surface undergoes oxidation reaction. An oxidation reaction is the process of losing electrons of the metal from the contribution of oxidizing agents, typically oxygen. For steel specifically, when encountering such a loss of electrons, ferrous ions are formed, which is the actual metal loss. The ferrous ions can potentially react and combine with hydroxyl ions, which are formed from the reaction of oxygen from the environment with the electrons from the metal, creating a reddish to brown rust (Young, Mindess, J. Gray, & Bentur, 1997). The schematic picture shown in Figure 2 illustrates the process of the general corrosion case.

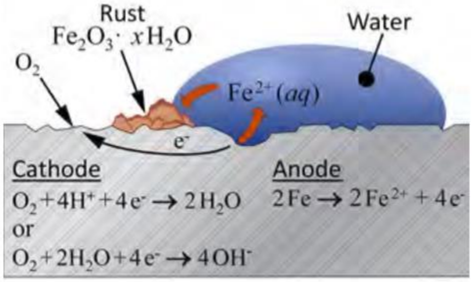


Figure 2: A General Electrochemical Reaction on a Metal Surface (NACE International, 2012)

Four chemical equations can summarize the general corrosion process described above. First, the anodic reaction at the steel surface:

$$2Fe - 4\ electrons \rightarrow 2Fe^{++}$$

The second reaction is the cathodic reaction. This reaction can occur in the same surface, but with a different electrochemical potential. Alternatively, it can occur with a dissimilar metal with electrolytes as a medium transferring ions/electrons.

$$O_2 + 2H_2O + 4\ electrons \rightarrow 4OH^-$$

The third equation creates the precipitate of ferrous hydroxide.

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2$$

Lastly, the hydrous ferrous oxide is oxidized to form hydrous ferric oxide $(Fe_2O_3 \cdot nH_2O)$, which is rust.

The corrosion of steel is an inevitable mechanism and it has many forms. In part, it can occur in a regular uniform condition under a normal environmental circumstance where the oxygen from the air and water from the rain are present; it can be localized, such as pitting corrosion where the presence of chloride is required; it can occur through crevice corrosion, where a limited flow of air can establish a potential difference; or it can be load induced corrosion, in which corrosion is affected and accelerated by the stress or loads, such as corrosion fatigue and stress corrosion cracking.

Preventative Measures

There are several preventative measures to impede or control the corrosion that occurs. The ultimate goal for these measures is to provide a layer on top of the steel that acts as a first line of defense against the corrosive attack. For example, one of the commonly applied methods is painting, as shown in Figure 3. Painting provides a protective barrier between the steel and the surrounding environmental factors, such as moisture, oxygen, and chlorides or salts. This preventative wall between the steel and atmosphere delays the attack of corrosion on steel. Painting is estimated to give 10–15 years of additional service life (Young et al., 1997).

Figure 3: Painted Girders and Bracings in a Bridge (Highway 460, Blacksburg VA)

Another common example is galvanizing the steel. Hot-dip galvanizing is one of the most common methods of galvanizing steel and is explained in detail in the next section. Galvanizing the steel provides a gray looking thin zinc coating layer as shown in Figure 4. Zinc acts as the anode and, when coated on steel, corrodes first, impeding the corroding of steel. Lastly, one preventative measure, which differs from coating methods, is having corrosion-resistant steels. These steels are self-resistant. The method to achieve such resistance is by changing some of the composition of alloying elements of the steelmaking. Some elements, such as copper, phosphorus, and aluminum, are known for their corrosion resistance (Young et al., 1997).

Figure 4: Galvanized Bridge Components (Goshen Land Company Bridge, VA)

2.2 Hot-Dip Galvanizing

History

Zinc coating has been used for corrosion mitigation since the 18th Century. Because there was no proper surface cleaning of steels at that time due to the high cost of the process (Maaß, Peißker, & Ahner, 2011), zinc coating was on small local scales, and the term galvanizing was not yet introduced. At that time, dipping steel into the molten zinc was a phenomenon that protected steel products. However, the explanation for this chemical protection was unknown. After several attempts by scientists and chemists, the cause of the steel protection was revealed by immersing two different metals in water and connecting them with a wire, which resulted in one corroded and one protected metal. This little experiment is now known as the galvanizing cell. After the discovery of surface preparation of the steel (pickling), a process that removes the oxides from the surface, the galvanizing cell developed into hot-dip galvanizing and gained interest in the industry around the 19th century (Maaß et al., 2011).

Hot-dip galvanizing has many benefits. First, it provides barrier protection in which the moisture and oxygen cannot penetrate the steel. Second, it can provide cathodic protection where the zinc, which is one of the least noble elements, acts as an anode, allowing the steel to act as a cathode, resulting in stabilized steel. Lastly, it provides zinc patina, which decelerates the corrosion rate of steel. For these reasons, hot-dip galvanized steels that have been utilized in various ways, including bridges, buildings, and automobiles, have a service life that can reach 50-75 years.

Process

In general, HDG is a dipping process where steel is immersed into multiple baths in a sequential order. Each bath has a different chemical formula that provides the appropriate need for steel preparation and protection. The key to having a uniform and efficient zinc coating is to provide a proper surface cleaning. The steel preparation has three stages: caustic cleaning/degreasing, pickling, and fluxing. Figure 5 illustrates the HDG process and shows each bath with the cleaning solution chemicals and temperatures.

Starting with the degreasing process, the steel is immersed in an alkaline solution bath (typically NaOH) that helps remove soil contaminates such as dirt and oil. Degreasing improves the efficiency of the pickling bath. It is recommended that the degreasing bath maintain a temperature of 122°F or higher (Kuklík & Kudláček, 2016). Second is the pickling bath, which is an acid solution bath (typically HCl) that removes the corrosive products such as stains, rust, and scale (oxidation surface). The efficiency of pickling is a function of the temperature of the pickling bath, the concentration of the HCl, and whether or not the steel has been degreased. A study has shown that the optimum pickling time changes when these parameters change, it was also found that the optimum pickling time occurs around 1.5-3 minutes for HCl that is 10% concentrated at room temperature or around 104°F (S. Sarhan, 2000). The last cleaning stage is the fluxing bath. It contains salty aqueous solutions such as zinc chloride and ammonium chloride. These chemical solutions are responsible for having a prepared steel surface to get the proper metallurgical reaction with the molten zinc bath. Also, the bath prevents any oxidation to the steel that might occur before galvanizing it with the molten zinc. The temperature of this bath is recommended to be below 122°F (Kuklík & Kudláček, 2016).

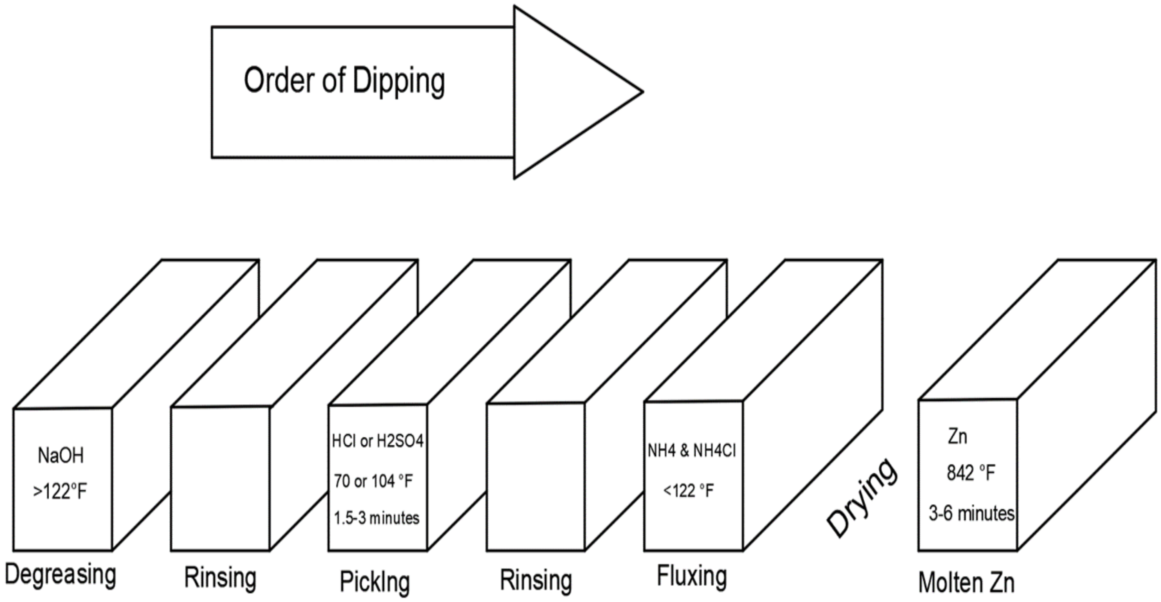


Figure 5: Hot-Dip Galvanizing Typical Process

The final bath of the process is the molten zinc bath. It has a temperature of around 850°F and a purity of zinc of at least 98% (ASTM B6, 2013). Many factors affect the immersion time such as the thickness of the steel, the bath's temperature, and the zinc content. The molten zinc reacts with the steel and provides the protective coating layer. A typical microscopic metallurgical reaction layer between the steel and the molten zinc is shown in Figure 6. Each phase has a different crystal structure and different zinc weight percentages. In Phase 1, gamma, the closest to the base steel, has approximately 75% zinc and 25% iron. In Phase 2, delta, has around 90% zinc and 10% iron. In Phase 3, zeta, has around 94% zinc and 6% iron. The layer above 3 is a pure zinc (Marder, 2000).

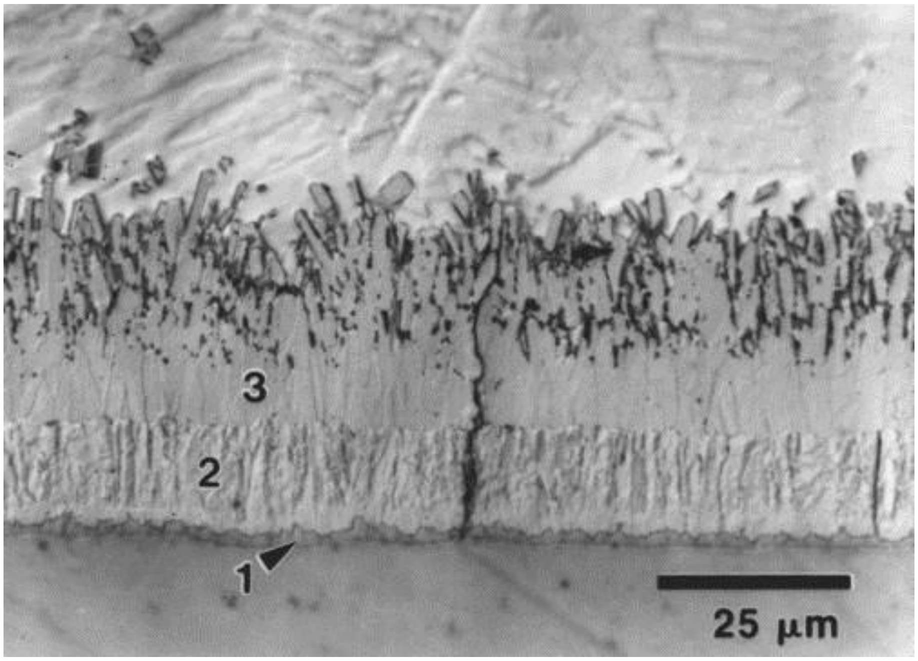


Figure 6: Typical Layers Of (1) Gamma, (2) Delta, (3) Zeta Found After HDG (Marder, 2000)

Although degreasing, pickling and fluxing are the major steel treatments, rinsing and drying are crucial as well. Between the three stages, the steel is rinsed. Because each bath has a different solution and steel is withdrawn and then dipped into a separate bath, rinsing helps diminish any excessive cleaning solvent. As a result, it contributes to maintaining the chemical properties of the solutions in the baths (Hochstein, 2016). Lastly, if the steel is dipped into the molten zinc immediately after fluxing, splashing will occur. For safety and quality issues, the steel is dried before entering the hot molten zinc bath (Kuklík & Kudláček, 2016). The process of HDG described here is the general case, meaning individual industrial plants may have slightly different procedures, chemical concentrations or temperatures.

Defects of Zinc Quality Coating

While HDG is considered one of the best corrosion protection methods, it has some defects. These defects could originate from the process itself, the geometry of the metals that are being dipped, the surface covering the metal (oil, grease, slags, etc.), or from transport, storage and assembly (Maaß et al., 2011). The major focus of this study involves the geometry of the metals that are being dipped, specifically overlapping surfaces which are commonly found in cross frames. Since the HDG process involves dipping steel articles into different baths, in which each bath has a different viscosity, temperature, and chemical formula, steel articles that involve moving parts, threaded items, overlapping surfaces and other geometries result in a low-quality zinc coating and safety concerns.

In addition to the defects originating from the geometry of the metals, defects from the process are important as it is expected to have such defects through this investigation. These could be improper cleaning of the metals, high or low content of a chemical in the bath, fast or slow speed of withdrawal from a bath, and much more. The severity and the damage vary depending on the causes. Some quality coatings are susceptible to rejection, while others may require preliminary retreatments. The common quality defects from the process of the HDG and the complex geometry metals are bare spots, spike drainages, and pimples. Bare spots are simply spots that did not get coated. This could be due to the improper cleaning of the steel surface, zinc not able to reach to certain locations, or high aluminum content in the baths. Spikes or drainage runs, as the name indicates, these are solidification of zinc making spikes at the bottom of the metals being dipped, most likely, due to the fast withdrawal of the metals from the zinc bath. Pimples are small pumps in the coating, these are due to byproducts from the zinc and iron that exist on top of the bath zinc and deposit on the coating, or they could be due to iron-aluminum content in the baths (Maaß et al., 2011).

Corrosion Products of Hot-Dipped Galvanized Steel

It is essential to quantify the corrosion products on galvanized coated steel to help analyze the results of this investigation. The basic premise of zinc corrosions is that zinc acts as the sacrificial layer against corrosion of steel as it reacts with oxygen from the atmosphere, leading to zinc oxides. Then, zinc oxides become zinc hydroxide after being subjected to moisture. Lastly, there is the formation of zinc patina, which is zinc carbonate that is produced from the reaction of zinc oxide and zinc hydroxide with carbon from the air (Azizinamini et al., 2013).

To increase the level of sophistication of this process, after a review of several publications regarding the corrosion of HDG steel, it was found that three main corrosion product compositions were frequently observed in zinc coated steel. These product compositions are zinc oxides (ZnO), hydrozincite ($Zn_5[OH]_6[CO_3]_2$), and simonkolleite ($Zn_5[OH]_8Cl_2H_2O$) plus sulfate products. These products are not necessarily typical in all cases, however. Several factors, such as the location of the exposure, the alternating events of the atmosphere (relative humidity and temperature), and the geometry of the coated steel (edges, small gaps and the like), all play a significant role in determining the quantity, type, and uniformity of corrosion products on a galvanized steel surface.

One of the influential factors of the formation and type of corrosion products is the location of the steel. A study was conducted using HDG steel to be exposed in the environment in different countries. One of the findings is that mass losses varied in the different countries (Persson, Thierry, & Karlsson, 2017). For example, pure marine and marine/urban/industrial sites experience high mass loss compared to industrial/urban sites. Also, regarding the proportionality of the corrosion products, it was found that zinc hydroxide is abundant in marine sites with low sulfate corrosion products, whereas high sulfate corrosion products were found in industrial/urban sites.

Another crucial factor is the geometry of the steel structure. Steels that are confined or have narrow gaps may experience different corrosion products, concentrations and uniformity. For example, a study was done on confined HDG coupons, test specimens, using accelerated corrosion tests, tests that accelerate the corrosion of steel and are described in detail in Chapter 3, it was found that crevice surfaces experience non-homogenous distribution of corrosion products (Thierry & LeBozec, 2009). It was concluded that the drying process of crevice surfaces was relatively slower than on open surface steels. This leads to the separation between anodic and cathodic reactions which increases the corrosion attack. The same study also found that zinc oxides were abundant in cathodic sites while simonkolleite formed in anodic regions after a period of testing.

2.3 Bridge Cross Frames Fabrications

Overview

Many steel highway bridges in the United States use bracing systems to achieve stability and transfer lateral loads. Figure 7 shows several K-bracings of one span of the Lee Highway Bridge in Radford, VA. These systems are usually composed of bracing angles or steel bars connected to gusset plates by welding or bolting. This configuration creates an overlapping surface as shown in Figure 8. These overlapped surfaces create a very small gap between surfaces. When galvanizing, this gap can cause interior corrosion that can lead to rust bleeding and stains.

Figure 7: K-Bracing Systems Welded to Gusset Plates (Lee Highway Bridge, Radford)

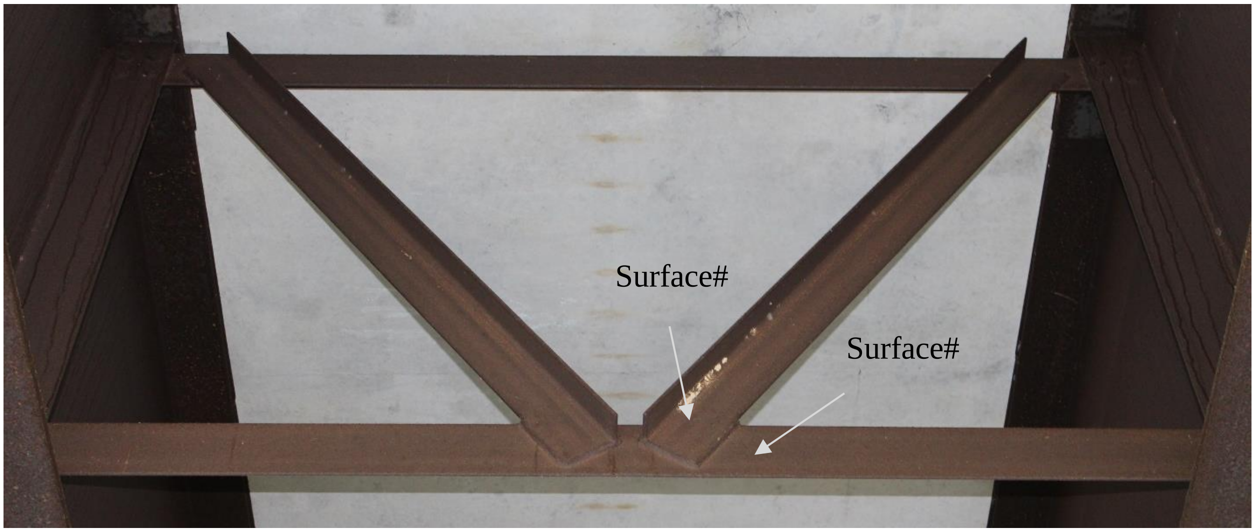


Figure 8: Angle Beam (Surface 1) Overlapping with a Steel Bar (Surface 2) (I-81 Bridge, Blacksburg VA)

HDG versus Overlapping Surface

Because the viscosity of the cleaning solutions (degreasing, pickling, and fluxing) are less than the viscosity of the molten zinc, gaps in overlapping surfaces can be problematic when hot-dipped galvanized. To illustrate, because the gap is too small, pickling or cleaning solutions can penetrate through the gap and be trapped inside. Meanwhile, the viscosity of molten zinc prevents the zinc from entering a gap that is smaller than 3/32 in. Hence, when the steel with trapped cleaning solutions is dipped into the hot molten zinc at a temperature of around 850°F, several effects may occur:

- The trapped cleaning solutions turn to steam, causing high pressure between the contacting surfaces which in turn may lead a burst of escaping steam, sending molten zinc into the air and creating safety issues as well as damage to the zinc coating nearby (ASTM A385, 2010)
- Because of moisture, the trapped cleaning solutions may cause corrosion issues later due to the leaching or ‘bleeding’ of the chemicals within the cleaning solutions when exposed to the atmosphere (ASTM A385, 2010). Figure 9 shows a typical ‘rust bleeding’ that was caused by the interior corrosion of the overlapped surface due to the trapped cleaning

solutions. Although the member shown is riveted, which is not the focus of this research, it illustrates the concept of the potential problems with overlapping surfaces.

Figure 9: Rust Bleeding (Goshen Land Company Bridge)

2.4 The Standard Specification

Overview

Fortunately, the industry is aware of the issues that occur in such narrow gaps. Thus, after a literature review, publications and design guides indicated that there are two major existing recommendations to this fabrication design issue. One solution is seal-welding all the edges of the overlapping surface. The second solution is to provide a vent hole over the overlapping surface. Galvanizers usually reject overlapping configurations, to the fabricators, that do not meet these specifications.

Seal-Weld

Seal-welding is simply welding all of the edges of the overlapping surfaces. The purpose of seal-welding is to prevent the cleaning solutions from the HDG process from entering the tight surfaces by eliminating the existence of the gap. Figure 10 shows an example of a typical seal-weld between two plates in which the weld continues to the edges. When the research team visited several bridges around the area of Montgomery County, such as Route 460, Interstate 81, and Lee Highway, it was found that most of the bracings were seal-welded. Figure 11 shows an example of a seal-welded bracing. Although seal-welding is proven to be an effective method to prevent the penetration of cleaning solutions, it requires time and excessive welding when used in cross frames.

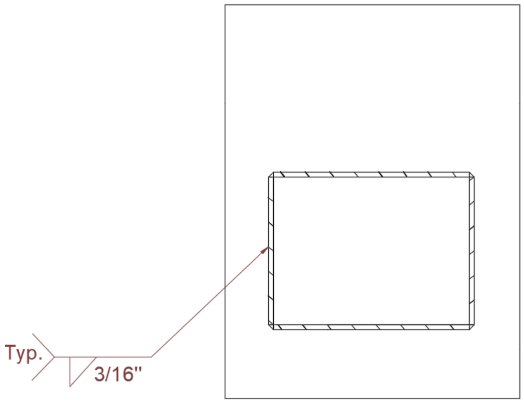


Figure 10: Typical Seal-Weld Example

Figure 11: Seal-Welded Bracing to a Gusset Plate (Lee Highway Bridge)

Since cross frame angles are extended beyond the gusset plate, a fillet weld is typically required on the back-side of the frame. An example in Figure 12 shows the back of bracings welded to a plate as indicated by the arrow. Since the transverse weld is in the other side of the overlapping surface, it requires flipping and rotating of the cross frame by cranes in the fabrication shops to account for it. From a fabrication standpoint, omitting the back weld can reduce the handling and lifting of cross frames during the fabrication. To reemphasize, for instance, according to the California Department of Transportation, it was stated in their design guidelines for cross frames that "…all welding during fabrication should be done from one side to minimize handling costs." (Duan, Saleh, & Kim, 2015), this is to eliminate the transverse weld.

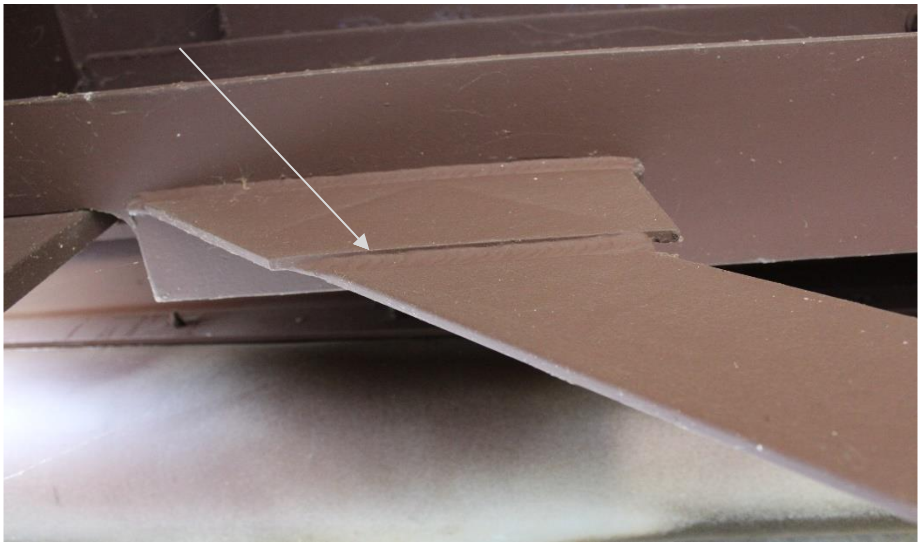


Figure 12: Transverse Weld (Lee Highway Bridge)

This transverse weld is either used for structural needs or galvanizing purposes. A study was published by Texas Department of Transportation (TxDOT) testing the fatigue limit of different bracings (Battistini et al., 2014). Part of the tests included having some cross frames welded with the transverse weld, and some without, for different cross frame geometries (K-frames and X-frames). It was concluded that the back weld did not contribute to the fatigue life failure of the K-frames, but it did affect the X-frames' fatigue performance negatively. To summarize, if welding is not necessary at the back of the bracing for K-frames for structural purposes, meaning the cross frames are adequate to provide stability when welding with the top side only, having the transverse seal-welding only for the purpose of galvanizing may be inefficient when constructing a bridge with numerous bracings.

Weld Cost

As previously stated, the excessive weld requires unnecessary time and cost. Although many factors affect the economy of welding, such as labor experience, size of weld, length of the weld, time to prepare electrodes, time to remove slag, time for tuck-up etc., the concern of this research lays on the extra length of welding. To illustrate, since seal-welding requires welding the four edges (three on top and one transverse weld) when only two or three edges are required for structural purposes, this additional welding, when considering a whole bridge structure, could have a significant effect on the cost.

A small cost estimation was performed for a highway bridge in Blacksburg, VA. The purpose of this estimate was to provide a tangible sense of the economics behind having seal-weld on the edges. It does not provide an actual cost estimation of welding steel members since there are many factors that affect the overall cost of the weld. Rather, it simply provides the deposited material of the electrode consumed by the welds and the time used when using seal-welding vs welding three and two edges.

The study was done for the Prices Fork bridge over the State Highway 460, located in Blacksburg. Plans and drawings were obtained from VDOT. The plans showed that there is a total of 164 K-cross frames in the nearly 250 ft long bridge. Figure 13 shows the drawing of the cross frames. The red circle represents the angle beam, which is L5x3x3/8 in. according to the plans, welded to the steel bar. As can be seen from the figure, the transverse weld indicated at the back of the beam to be 5/16 in.. Although there is no indication of welds in the other three edges as seen from the figure, a VDOT representative verified that the contacting lengths between the two frame members were welded in the fabrication shop. Figure 3 shows the cross frames same bridge, where it can be seen clearly that the contacting surfaces were welded.

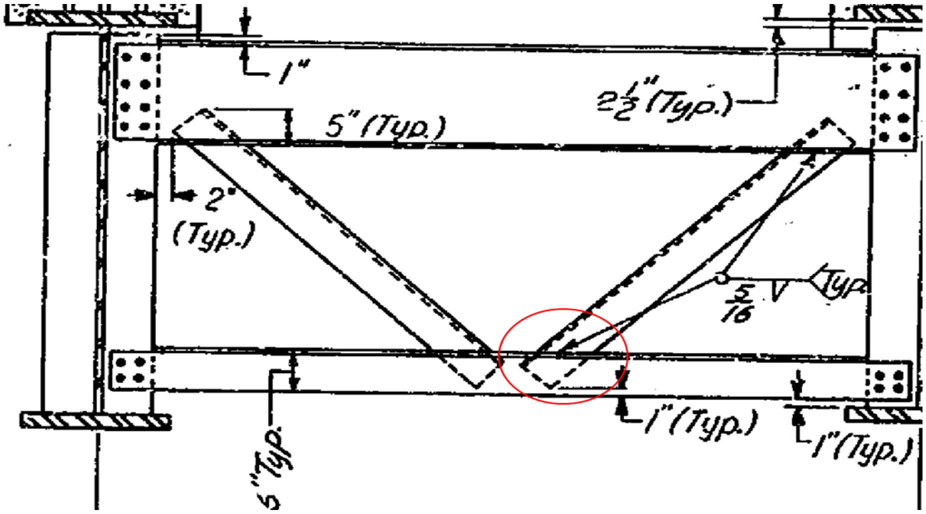


Figure 13: Prices Fork Bridge (460 highway, VA) (Sutherland-VDOT, 1977)

The weld material deposited (volume of welds) and the time utilized for the welding can be estimated given the rate of weld application and the length of the contacting surfaces. According to a journal from the American Welding Society, it requires 99 seconds for a 5/16 in. fillet weld that is 1 ft long (Barckhoff, Kerluke, & Lynn, 2010). The weld length for the given K-frames were estimated using simple geometry obtained from the plans. Figure 14, which is a simplification of the red circle from the previous figure, shows each side and the estimated lengths. The only assumption made for determining the lengths is the angle of the oriented angle beam to the horizontal, which is 45°. Given the dimensions, the total length of the weld length is 21.2 in. for four edges, 14.1 in. for three edges, and 9.1 in. for two edges, for one overlapping surface. Note that three edges means omitting the 7.07 in. back weld, and the two edges is omitting the back and the top (7.07 in. and 5 in.) leaving the two sides only.

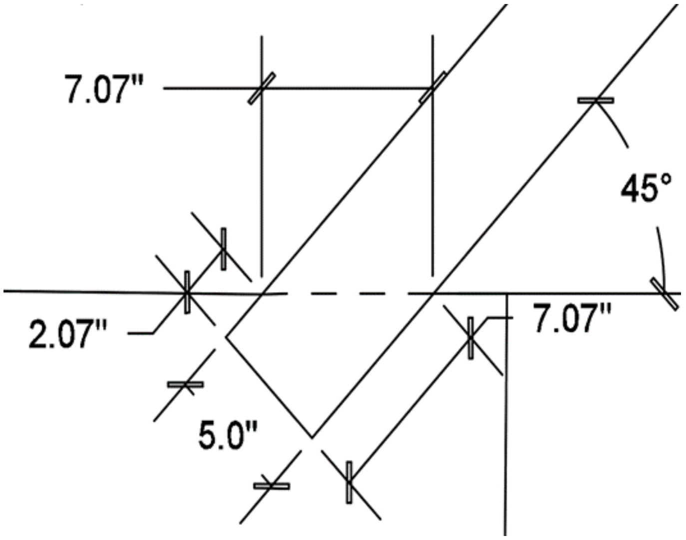


Figure 14: Lengths of the Contacting Surfaces.

Given the 164 K-frames, and the fact that there are four overlapped surfaces in each cross frame, Table 1 summarizes the time and the material deposited for the four, three and two edges. It can be seen that the savings in time and deposited material reaches to 56% if two welds were used, and around 33% if three welds were used. For more information regarding the calculations, refer to appendix E. To summarize, if two or three welds meet the strength and stiffness requirements for highway bridges, having a full seal-weld for galvanizing purposes only may significantly increase the cost and labor of cross frames.

Table 1: Time and Deposited Volume of Weld for Different Edges

Edges Included	Time (hours)	Deposited Volume (in^3)
four	31.9	681.8
three	21.3	454.5
two	13.7	293.8

Vent Hole

The other solution that was investigated to overcome the previously mentioned issues with galvanizing overlapping surfaces is to have holes in the overlapping surfaces when their contacting area is large, as shown in Figure 15. The purpose of these holes is to smooth the flow of the cleaning solutions, the rinsing water, and the molten zinc. This in return drains out the cleaning solutions, which prevents a high-pressure liquid collecting inside the contacting surface. The vent hole size(s) are a function of the overlapping surface area. To illustrate, as the overlapping surface area or the contacting surface increases, the diameter of the hole increases as well. ASTM A385 and many other technical practical design reports from the galvanizing industry have standards for the hole's dimension, as shown in Table 2.

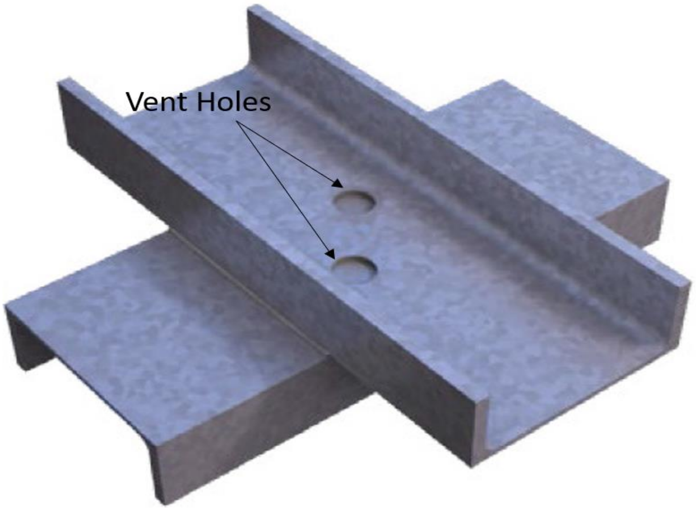


Figure 15: Typical Vent Holes for Overlapping Surfaces (GAA)

Table 2: Hole Dimensions for Overlapped Surfaces (ASTM A385, 2010)

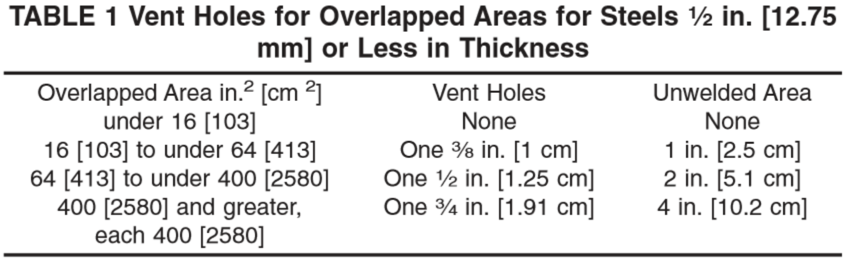
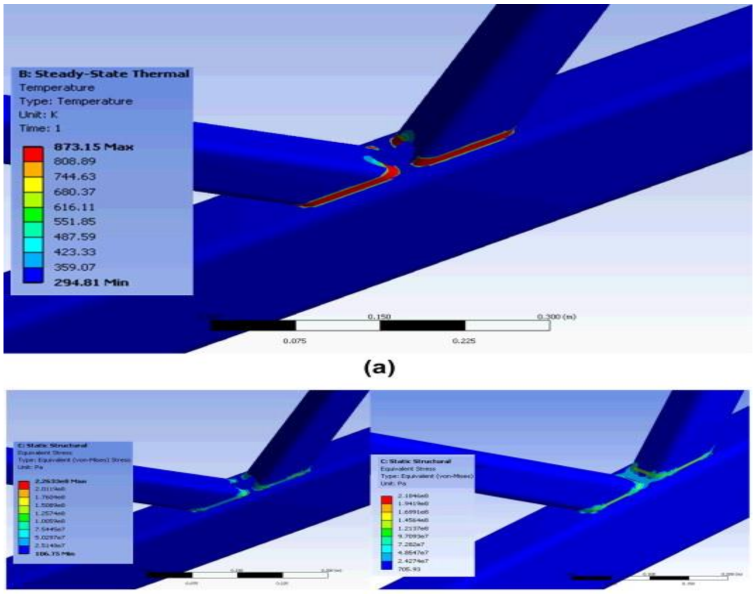


TABLE 1 Vent Holes for Overlapped Areas for Steels ½ in. [12.75 mm] or Less in Thickness

Overlapped Area in.^{2} [cm ^{2}]	Vent Holes	Unwelded Area
under 16 [103]	None	None
16 [103] to under 64 [413]	One ⅜ in. [1 cm]	1 in. [2.5 cm]
64 [413] to under 400 [2580]	One ½ in. [1.25 cm]	2 in. [5.1 cm]
400 [2580] and greater, each 400 [2580]	One ¾ in. [1.91 cm]	4 in. [10.2 cm]

Holes, however, may introduce new potentials for failure. Although a numerical study published the effect of circular, semicircular and V-notched holes of K-joints, as shown in Figure 16, it was concluded that these small holes do not have a significant influence to the strength of the member (Serrano-López, López-Colina, Díaz-Gómez, López-Gayarre, & Iglesias-Toquero, 2015), the study did not consider the fatigue limit state, which is a significant factor in the bridge design industry for bracing systems. Additionally, like the welding solution, these holes require extra fabrication, eventually increasing the cost. Also, the hole size requirements and recommendations originated empirically from the practice of galvanizing; there is no clear guidance or code that relates strength with the fabricated holes for designers. For these reasons, further research must be performed to obtain alternative solutions.



(a)

(b) (c)

Figure 16: K-joint Test Study (Serrano-López et al., 2015)

2.5 Alternatives

The proposed solutions are mainly a function of alternate fabrications of steel members. These fabrications undergo the HDG process to yield different results. The primary goal of this research was to determine which alternative fabrication detail has the best coating and less corrosion damage.

Silicone

Because seal-welding the gap is not efficient, one of the major goals of this research was to identify an alternative and efficient way or material to prevent the pickling/cleaning solutions from penetrating the gap, which is the original problem that led to seal-welding all of the edges of two overlapping surfaces. Given the circumstances and the nature of the galvanizing process and the fabrication of cross frames, commercial silicone caulk sealants were thought to be the best alternatives to replace the welds. Figure 17 shows where the bead of the sealant is applied instead of the weld on the top edge. Silicone sealants are easily and quickly applied, no prior experience is needed, and they are ultimately more economical than welding. These advantages favored using silicone sealants instead of other materials.

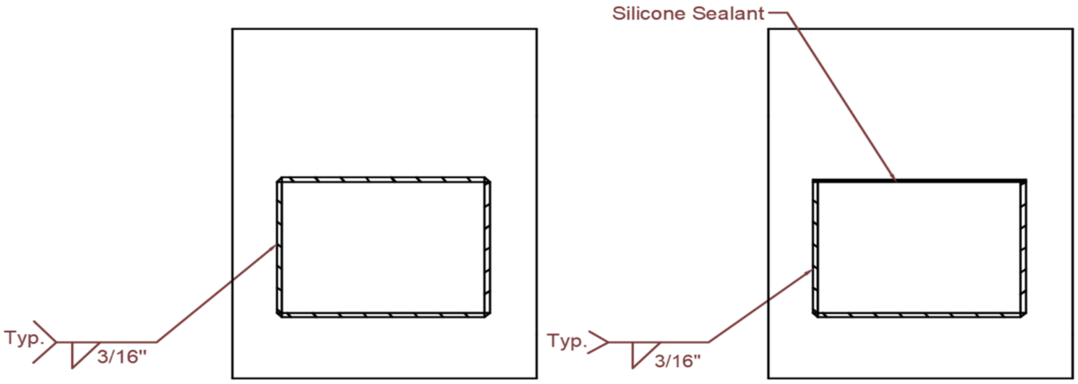


Figure 17: Comparison of Welding and Caulking Overleaped Surfaces

To choose the right silicone caulk sealants, one important criterion must be met. That is, the silicone caulk must have a melting temperature that is above the temperature of the various cleaning solutions from the HDG baths, yet less than the molten zinc bath. The reason for such a requirement is to enable the sealants to withstand the cleaning solutions while also allowing the zinc to melt off the sealants and coat the surface. A concern that this study should answer is, what happens to the bare steel that was covered by the caulks and that did not get cleaned but was galvanized. To acquire more data and increase the chances of a successful sealant proposed solution, two types of silicone were chosen.

A study was conducted using 15 different types of materials to prevent the zinc from adhering to flat steel and a steel bolt (Langill & Duran, 2010). The materials were applied prior to the HDG process. Some of them succeeded in preventing the galvanizing to adhere to the steel surface, while others failed. The study was helpful when choosing the sealants for this research. GE 100% Silicone Caulk and DAP Adhesive Silicone Sealant were chosen because they succeeded the experiment from the study and were easy to apply and remove. Both of the sealants meet the temperature requirement. Although this research is focused on a gap application, which is different from the application of the study mentioned, theoretically, the sealants must still achieve the same goal. Note that the DAP Silicone has a clear color and the GE has a white color.

Wide Gap

In addition to the recommended use of silicone by the fabricators, galvanizers, on the other hand, recommend using a minimum of 3/32 in. gap between the overlapping surfaces, as shown in Figure 18. The main purpose of this gap is to allow the thick zinc leach through the gap to galvanize the surface. Additionally, it allows adequate cleaning and rinsing of the cleaning solutions between the overlapping surfaces as well as letting them escape easily. Thus, preventing the existence of bare spots, internal corrosion and splashes of the molten zinc. The gap is simply constructed using a shim between the overlapping surfaces when welding them together.

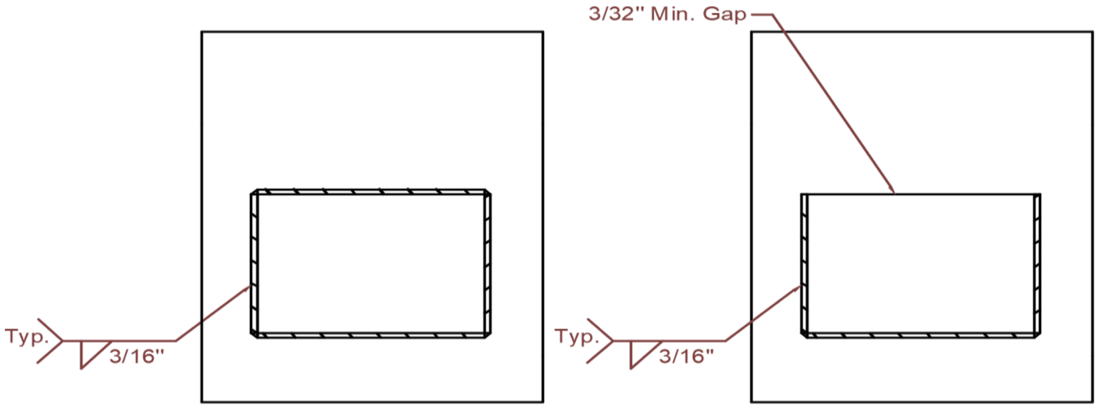


Figure 18: Comparison of Welding and Wide Gap Overlapped Surfaces

Different Fabrications

Another goal of this research is to develop different configurations of overlapped surfaces. The purpose of these different fabrications was to obtain alternative results and thus maximize the chances of having alternatives that result in good quality zinc coating. The next chapter details these fabrications, along with the methods to validate such alternatives in the experiment.

Testing Procedures

Briefly, there are three major tasks that were done in order to quantify the feasibility of the alternative ideas. It is important to note that these tasks were applied after galvanizing the specimens. The first task was to verify whether the caulks could withstand degreasing, pickling, and fluxing. The second task was an accelerated corrosion test, using the Surface Vehicle Standard SAE J2334, to better investigate the specimens. Lastly, there was a head-to-head comparison between specimens of different configurations, which includes cutting the specimens and investigating the bonds between the metal and the zinc.

Chapter 3: Experimental Methods

3.1 Materials & Fabrications

These materials are described geometrically in detail in this section and were used for three different tasks that are described in the following sections.

Overview

The materials and fabrications determined for this research were targeted to be similar to the lateral bracing systems of bridges. Therefore, overlapped surfaces of steel plates were the best representatives of cross frames. A sample of the specimens is shown in Figure 19. The bigger plate (6x8x1/2 in.) is the gusset plate, and the smaller plate (4x3x3/8 in.) represents the bracing bar. In addition, there is a 1/2 in. diameter hole on top to help galvanize the specimens by having steel hooked through the hole. The overlapped surface area was chosen to prevent any vent holes as required by ASTM A385, in which any overlapped surface areas that are 16 in^2 or less do not require vent holes (ASTM A385, 2010). A 1/2 in. thickness of the bigger plate was preferred to prevent any warping during galvanizing, as recommended by the galvanizers. Lastly, a typical fillet weld of 3/16 in. was chosen as it is common in bracing systems in highway bridges. The steel plates were donated and fabricated by Hirschfeld.

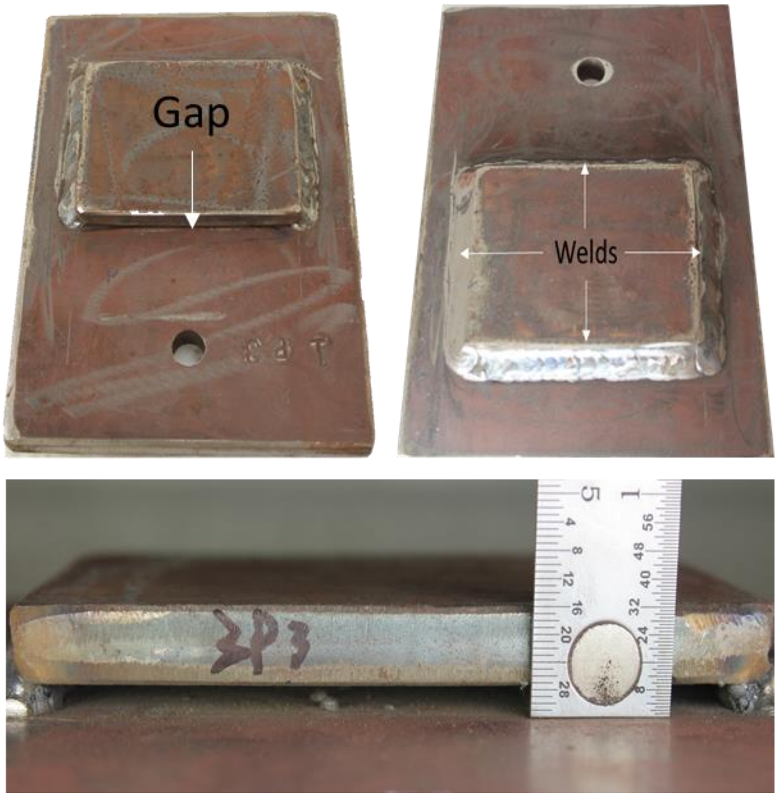


Figure 19: Sample Plate Specimens

There were a total 45 steel plates, all of which had the same dimensions but different configurations. There were six different configurations, as seen in Figure 20 and Figure 21. Each configuration was fabricated to achieve a specific purpose. The main difference between each configuration was the existence of the gap, the width of the gap and the location of the gap. Given the nature of this study, the configuration type, quantity, mark of each specimen, and the tasks, all can be found and summarized as a guide in Table 7 in Appendix A.

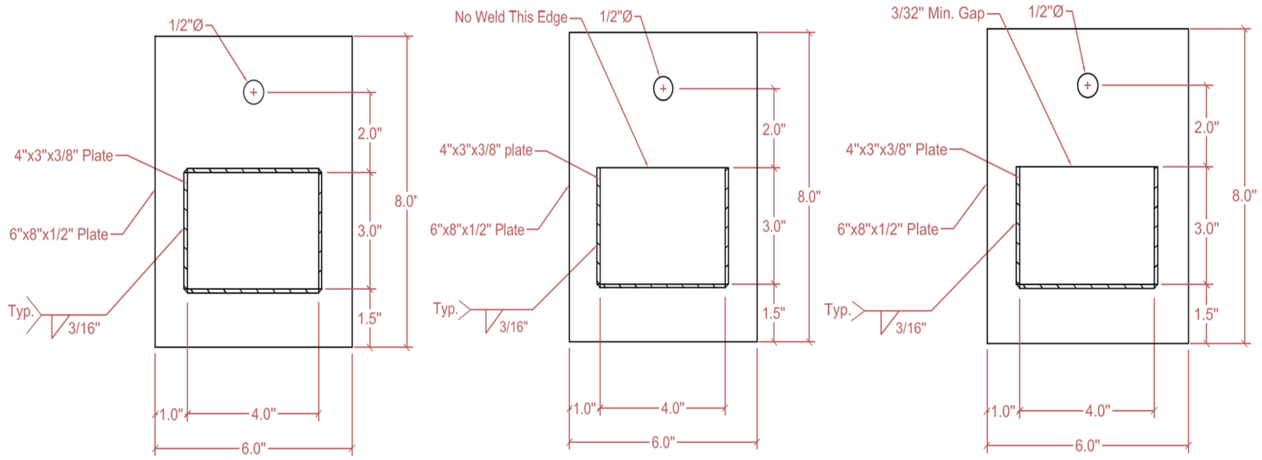


Figure 20: Steel Plates (configuration 1, 2 & 3, respectively from left to right)

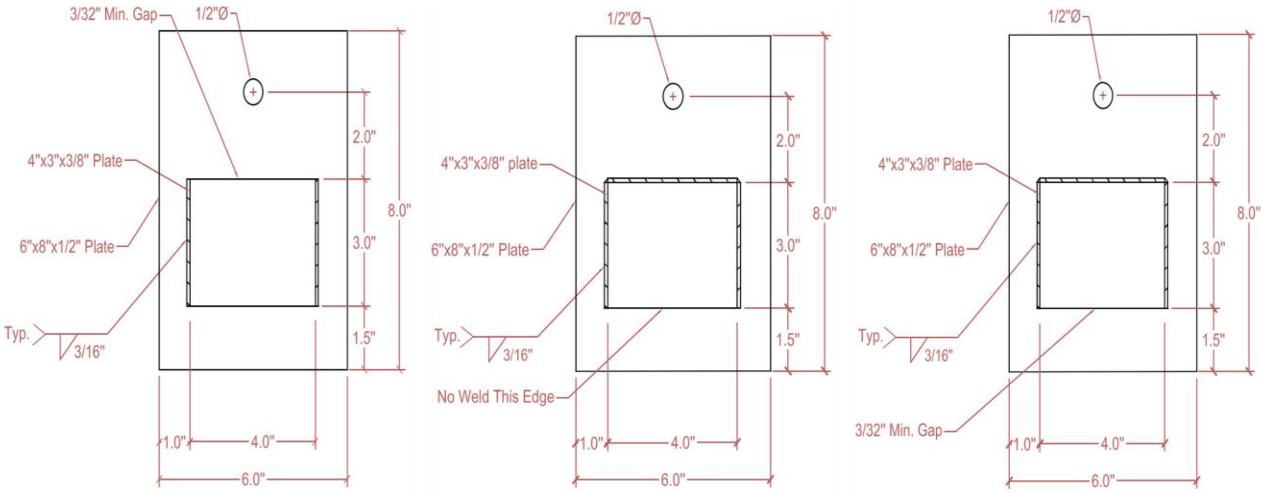


Figure 21: Steel Plates (configuration 4, 5 & 6, respectively from left to right)

Configuration 1

This was the control configuration, to which the other proposed specimens were compared with. This configuration is what was seen in the bridges that the researcher visited where the bracing bar is welded on all of the sides (four sides). Figure 22 shows one specimen of Configuration 1.

Figure 22: Configuration 1 (welded in all sides)

Configurations 2 and 5

Configurations 2 and 5 were almost identical except that the open edge in 2 was on top relative to the immersion path while it was on the bottom in 5, as shown in Figure 23. In both configurations, the remaining three sides were welded. The reason behind having different location of the gaps was to determine if the orientation of dipping plays any factor in the coating quality of the galvanizing of overlapping surfaces. Figure 24 shows where the circular holes were attached to the hook cranes to immerse the specimens vertically. As seen, the open edge of the left specimen is facing upward whereas the open edge of the right specimen is facing downward. By analogy, an open pocket is used to collect and keep articles whereas an upside open pocket cannot hold items. In this case, Configuration 2 represents the open pocket whereas Configuration 5 represents the upside down open pocket.

Figure 23: Configuration 2 (top) and Configuration 5 (bottom)

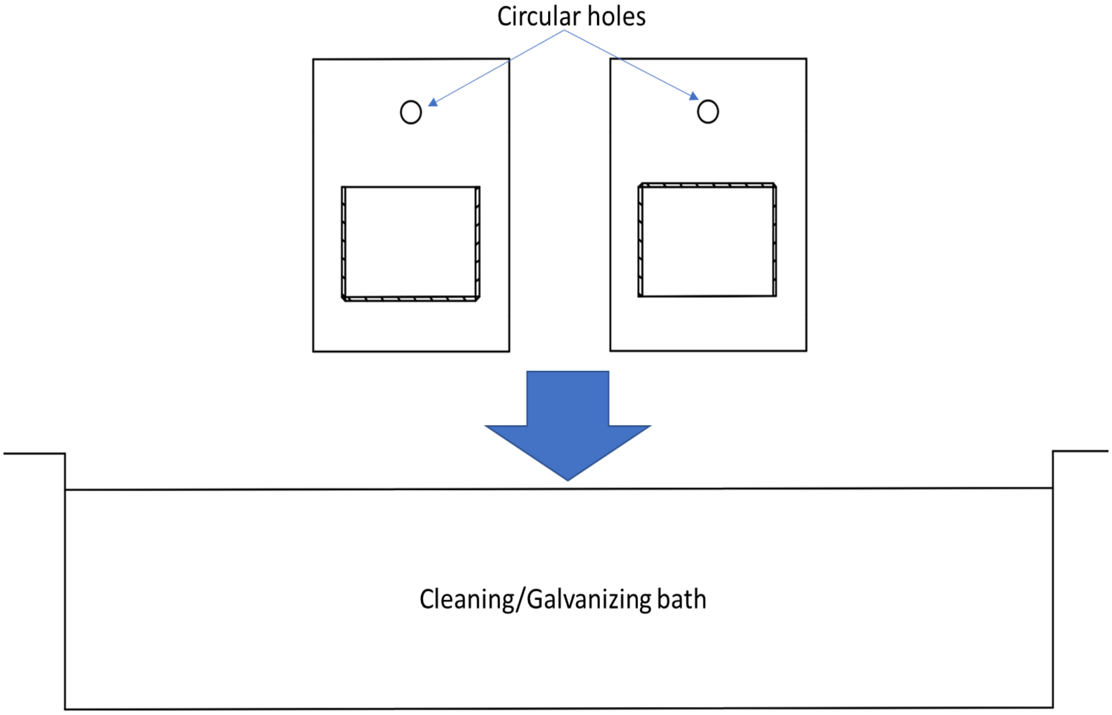


Figure 24: Different Orientation Immersion Diagram

Configurations 3 and 6

Similarly, Configurations 3 and 6 were almost identical to the analogy of Configurations 2 and 5, except that the gap was fabricated to be 3/32 in. or more, as shown in Figure 25. This gap width is recommended by galvanizers in the industry. This was to allow not only the cleaning solutions to penetrate between the gap, but also the relatively thick zinc to flow inside and coat the interior surface.

Figure 25: Configuration 3 (left) and Configuration 6 (right)

Configuration 4

Unlike the others, Configuration 4 had only two welds on the side, with a minimum gap of 3/32 in., as shown in Figure 26. The motivation behind this geometry was to have the cleaning solutions as well as the zinc flow between the overlapping surfaces.

Figure 26: Configuration 4 (top and bottom views)

3.2 Gap Measurements

The gap measurement was the first type of documentation and it was an important feature to document. In the event that the specimens were galvanized, it is essential to investigate and determine whether the gap width can be correlated to the coating performance of the specimen. Although the drawings of the specimens specified the gap to be larger than 3/32 in. in Configurations 3, 4 and 6, and no gap in Configuration 2 and 5, the gap widths were not consistent throughout the fabrications. In other worlds, the gap of the specimens varied slightly due to some fabrication error.

The measurements were taken in three separate locations using a feeler gauge, as shown in Figure 27. The reason for having these three locations was to determine if the gap measurement could be related to performance of the specimens in the HDG process. Configurations 3, 4, and 6 were verified to be more than 3/32 in. (0.09375 in.) as required, except one specimen from Configuration 3 where the gap measured was 0.0930 in., which is almost equal to the required 3/32 in.. Most of the gaps in Configurations 2 and 5 could not be measured by the least unit of the feeler gauge, which is 0.0015 in., due to the gap tightness. In other words, there were no gaps between the overlapping surfaces in these configurations. Some difficulties arose when measuring some of the specimens, due to the slags and spatter of the welds stuck between the overlapping surfaces, preventing the movement of the feeler gauges. All of the measurements for the 45 specimens can be found in Table 8 in Appendix A. Note that from the table, edge 1 refers the left circle, edge 2 refers to the middle, and edge 3 refers to the right circle.

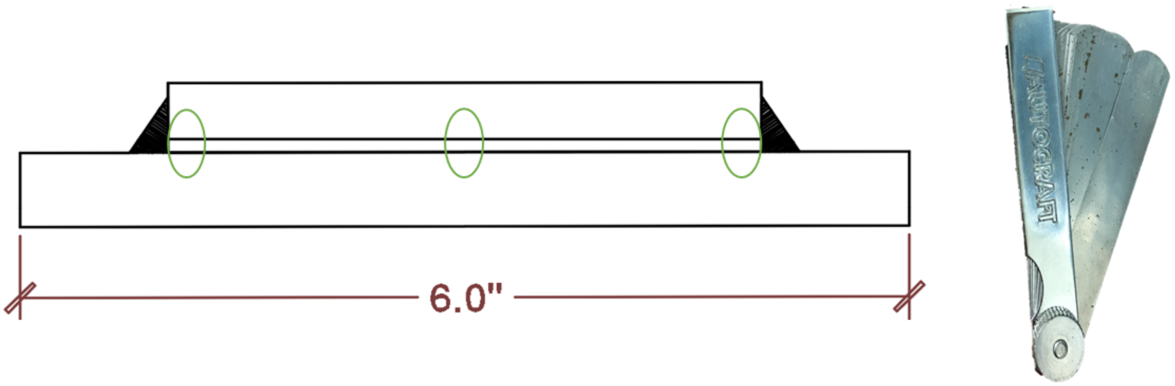


Figure 27: Three Circles Representing Location of Measurements (top view of a specimen (left) and feeler gauge (right))

3.3 Silicone Verification (Task 1)

Overview

Since the cleaning solutions are the primary cause of inadequate quality coatings in open gap overlapping surfaces and rust bleeding, the goal of this task was to apply and verify that the sealants would withstand the cleaning solutions. This was done by having steel specimens sealed with silicone (GE or DAP) in the open edges instead of the welds to complete the process of dipping in the degreasing, pickling, and fluxing baths. Note that in this task the specimens were not dipped into the molten zinc because, had the silicone failed in the process of HDG and provided poor galvanizing coatings, it could not be deduced whether the failure occurred in the cleaning baths or the zinc bath. The objective of this task was only to study the effect of the silicone caulk with the cleaning solutions.

Specimens

The goal of applying the silicone was to seal the open edge specimens. The application was initially a bit challenging. With the aid of a caulk gun, silicone was applied as thinly and sparingly as possible, as shown in Figure 28. To achieve this, tape was used adjacent to the gap, so that the silicone would not stick to or touch the steel surface other than the gap. However, the first attempted application of the silicone was done without the tape, which resulted in the removal and reapplication of the caulk for some of the specimens. Before application, the area adjacent to the gap had to be cleaned to improve the adhesion between the silicone and the steel surface. Figure 29 shows the sealants used along with the cleaner.

Figure 28: Configuration 2 Sealed with DAP Silicone (left) and Configuration 5 Sealed with GE Silicone (right)

Figure 29: GE Silicone (left), DAP Silicone (middle), and CRC Cleaner (right).

A total of 12 specimens from Configurations 2 and 5 were chosen to undergo this task. Table 3 shows a representation of this task. Configurations 2 and 5 were the optimized solutions of configuration 1, in which silicone is used instead of the excessive weld, as was shown previously in Figure 17. Therefore, the silicone was applied only to these configurations and not the others. As can be seen from the table, some of the specimens were only degreased, some were degreased and pickled, and some were degreased, pickled, and fluxed. This is to determine at which stage the silicone failed.

Table 3: Task 1 Specimen Study

Type of Specimen	Sealant	Process	Number of Specimens
Configuration 2	GE 100%	Degreased only	1
		Degreased and Pickled only	1
		Degreased, Pickled and Fluxed only	1
	DAP	Degreased only	1
		Degreased and Pickled only	1
		Degreased, Pickled and Fluxed only	1
Configuration 5	GE 100%	Degreased only	1
		Degreased and Pickled only	1
		Degreased, Pickled and Fluxed only	1
	DAP	Degreased only	1
		Degreased and Pickled only	1
		Degreased, Pickled and Fluxed only	1

Evaluations

This task was evaluated through visual observation. This was done using photographs of the sealants before and after the application of this task. In addition to the photographs, some specimens were sealed but did not go through the task (nothing done) as shown in Table 7. This was to have a physical silicone unharmed to compare it with the specimens that were used for this task.

3.4 Accelerated Corrosion Test (Task 2)

Overview

The second task was the accelerated corrosion test. Generally, corrosion requires moisture and salt to occur. Moisture was obtained by using a specific chamber called Cincinnati Sub Zero (CSZ) installed at the Virginia Tech Structural Lab that provided the necessary humidity/moisture. Meanwhile, soaking containers filled with certain chemicals were used to obtain the necessary sodium-chlorided solution. The purpose of this task was to validate which detail configuration had the better corrosion resistance behavior. This was done by having different configurations, where some were sealed and some were not, to undergo the process of HDG. Then these specimens were tested by the accelerated corrosion test.

As the name indicates, the acceleration corrosion test expedites steel corrosion. This is beneficial in determining the severity of corrosion in steel in a short time period. For example, a study was done in one of the steel bridges and it has shown that 100 day test cycles were equivalent to 20 years of in-field corrosion of mass loss of steel (Fletcher, 2011). Although there are numerous studies and guidelines available regarding accelerated corrosion tests, The Society of Automotive Engineers (SAE) J2334 was chosen due to its acceptable results with in-field corrosion and the availability of the materials in the structural lab to perform such a test. SAE J2334 provides certain guidelines and procedures regarding the accelerated test (SAE International, 2016).

SAE J2334

The SAE J2334 provides a clear laboratory procedure to process the accelerated test. The steel specimens must undergo a process referred to as test cycles. The cycles are a 24-hour test. In these 24 hours, the specimens were exposed to three main stages: the humidity stage, the salt application stage, and the dry stage. Figure 30 shows the repeated daily cycles with the time and temperature for each stage.

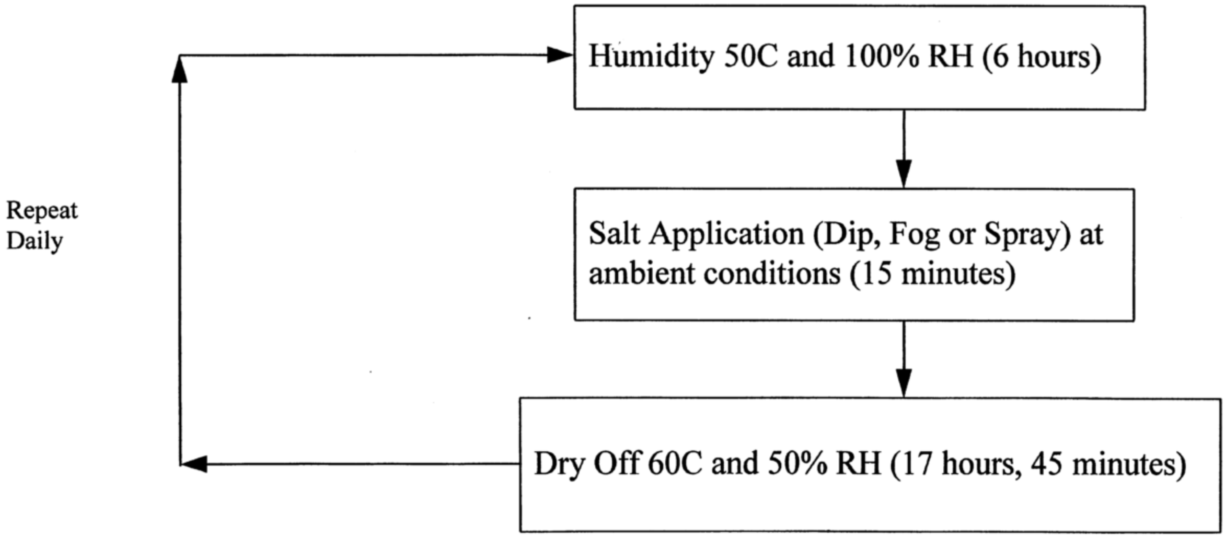


Figure 30: Corrosion Lab Cycles (SAE International, 2016)

The means to achieve these cycles were through the use of an automated chamber cabinet that provided the necessary temperature and moisture, in addition to an external salt application process. The (CSZ) chamber used and is in Virginia Tech’s Structural Lab. The CSZ can provide a relative humidity (RH) in a range of 10% to 98.5% and a temperature in a range of -30°F to +375°F. The CSZ can be controlled by a touch screen, called EZT-570i, attached to the chamber. This screen has all the ability of automating the chamber in terms of the timing, the temperature, the humidity and all other features. For more information regarding the humidity and temperature of the chamber, refer to Appendix B.

As shown in Figure 30, the salt application stage can be completed using either of three different methods: dipping, fogging, or spraying. Since the chamber does not have the feature of spraying or fogging, dipping was chosen. The process simply required a daily immersion of the specimens into the salt solution for fifteen minutes.

The highly corrosive salt solution was composed of reagent water diluted with three chemicals in soaking containers. The chemicals were sodium chloride, calcium chloride, and sodium bicarbonate with 5%, .1% and .075% concentrations, respectively. Although SAE J2334 uses .5% of sodium chloride, this test was modified to better match the atmospheric corrosion of steel, as recommended by an FHWA technical report (Fletcher, 2011). The resultant combination solution was 60 liters to accommodate for the mass concentration as shown in Table 4. It is recommended that this solution be replaced on a weekly basis. Certain measurements were taken to meet the specifications of the reagent water and the salt solutions such as the conductivity, resistivity and pH levels. The measurements and descriptions of the salt application are shown in Appendix C.

Table 4: Salt Solution Content

Chemical Name	Chemical Formula	Mass Concentration	Mass (g)
Sodium Chloride	$NaCl$	5%	3000 ± .5
Calcium Chloride	$CaCl_2$	0.10%	60 ± 0.1
Sodium Bicarbonate	NaHCO3	0.075%	45 ± 0.1

The process of accelerating the corrosion was done in 40 cycles. The steel specimens were first placed in the humidity chamber. At exactly 3:45 am, the chamber was automated to start producing a 100% RH for 6 hours in the humidity stage with a temperature of 122° Fahrenheit. Although the requirement is to have 100% RH, the chamber is unable to produce such a high percentage as it causes sensor reading issues. The chamber can provide 98% to 99% RH. Then, at 9:45 am, the specimens were withdrawn from the chamber and dipped into the salt soaking containers for 15 minutes. Before dipping the specimens, however, for the first 10 cycles and at intervals of 20, 30, and 40 cycles, pictures were taken of the specimens to document the corrosion process. Next, the specimens were returned to the chamber for the drying stage, which is a temperature of 140° Fahrenheit for 17 hours and 45 minutes with 50% RH, thus completing one cycle.

Specimens

A total of 19 specimens were evaluated for corrosion resistance, as shown in Table 5. Note that N/A means applying the sealants was not applicable, that is in Configuration 1, the control specimen, where all of edges were welded, and in Configurations 3, 4 and 6, where they had a minimum gap of 3/32 in. Also, ‘none’ means the there was no sealant applied, this was to compare the behavior of specimens with sealants vs specimens without sealants for the same configuration. For statistical purposes, two of each type of specimen (except the control specimen) were tested.

Table 5: Task 2 Specimens Study

Type of Specimen	Sealant	Number of Specimens
Configuration 1	N/A	1
Configuration 2	None	2
	GE 100%	2
	DAP	2
Configuration 3	N/A	2
Configuration 4	N/A	2
Configuration 5	None	2
	GE 100%	2
	DAP	2
Configuration 6	N/A	2

The specimens were hung vertically inside the chamber through the 1/2 in. hole. This was done by inserting steel bendable wires through the 1/2 in. hole to be hooked to PVC plastic pipes inside the chamber, as shown in Figure 31. The reason for choosing this setup was to allow leaching or bleeding of rust, and additionally, to prevent any runoff from the moisture or the salt solution that might occur between specimens if the specimens had been placed on top of each other.

Figure 31: Steel Specimens Hanged on PVC Pipes Inside the Chamber

Evaluations

Similar to the evaluation of the first task, photographs and pictures from the cyclic corrosion tests were the means of evaluation. Pictures were expected to provide progressive of corrosion products, the distribution of the corrosion products, and, most likely, rust bleedings. Photographs were taken in the first 10 cycles and then every 10 cycles until 40 cycles.

3.5 Cut Open (Task 3)

Overview

The third task was a head-to-head comparison between different configurations in certain locations in terms of bond quality between the zinc and the steel after hot-dip galvanizing the specimens. The specimens were cut in half using a band saw from the Virginia Tech Structural Lab, as shown in Figure 32.

Figure 32: Bandsaw Saw Cutting a Specimen

After obtaining the cuts, two areas were investigated as indicated in Figure 33 which shows a drawing of the cross section of a plate with the indications of the investigated areas. The first area is indicated by the top circle of the cross section and the second area is indicated by the bottom circle. The objective of investigating the top area was to determine the zinc quality adjacent to the gap. As stated, some of the configurations were sealed with silicone, and some of them had a minimum gap of 3/32 in.; thus, the zinc interface between the area adjacent to the gap and the surface of the gap was a question of reliability. To the left, the bottom investigated area of the overlapping surface was near the welds, as shown in the same figure. The motivation behind this spot was to determine if the zinc coating or cleaning solutions reached to the bottom given the small gap and, additionally, to determine the detailing of the interface between the weld and the zinc. After cutting the specimen, a microscope was used to determine the bond quality of the indicated areas. A typical metallurgical reaction layer was shown in Figure 6.

Furthermore, in addition to the two investigated areas, Configuration 3, 4 and 6 were cut in the edges to remove the smaller plate from the bigger plate, in other words, removing the overlapping surface, to view the zinc profile of the overlapping surfaces.

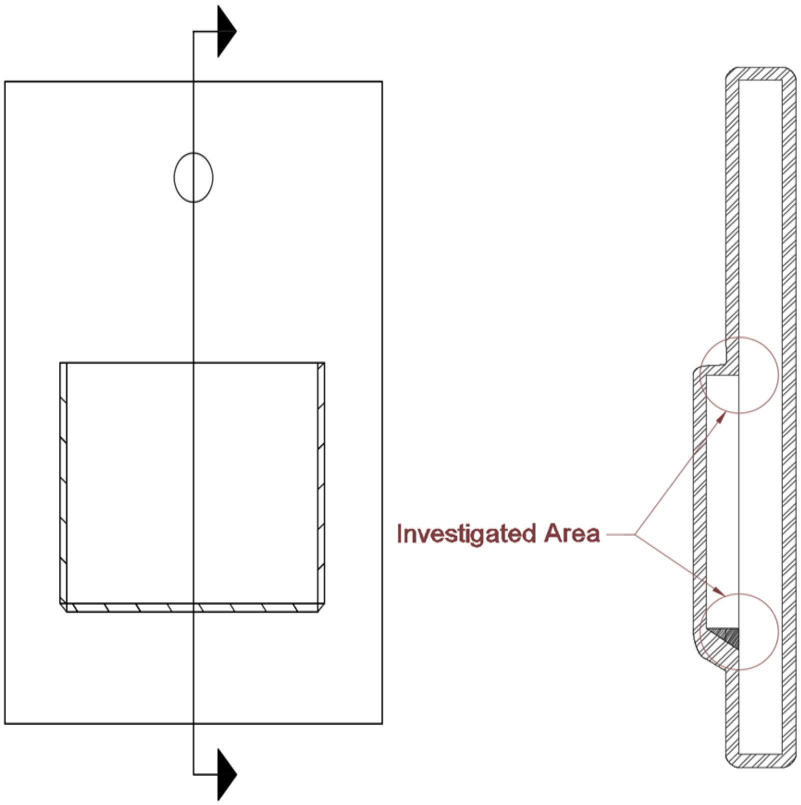


Figure 33: Steel Plate Cross-section Investigation Areas (all configurations except 4)

Since Configuration 4 had welds on two sides, the cut runs in the opposite direction of the previous figure, as shown in Figure 34. The purpose of this cut was to determine the quality of the zinc around the weld of this configuration.

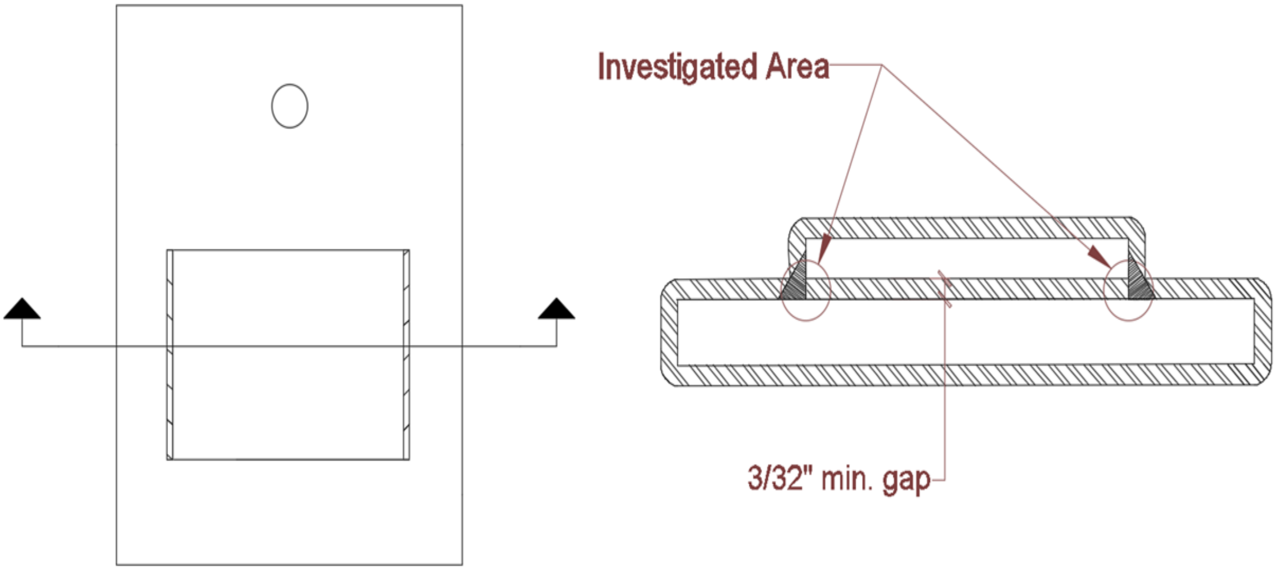


Figure 34: Configuration 4 Cross-section

Specimens

Ten specimens were cut and investigated as shown in Table 6. This includes one specimen in each configuration, with three specimens in configurations 2 and 5 due to the sealants. Again, some specimens with no sealants where N/A means sealing the seal-weld specimen with silicone was not applicable (Configuration 1), or sealing the wide gap was not applicable as well since the gap used for different purposes (Configurations 3, 4 and 6). Also, some specimens were not sealed as indicated by ‘none’, this was to compare sealant specimens with no sealant specimens for the same configuration (Configurations 2 and 5)

Table 6: Task 3 Specimens Study

Type of Specimen	Sealant	Number of Specimens
Configuration 1	N/A	1
Configuration 2	None	1
	GE 100%	1
	DAP	1
Configuration 3	N/A	1
Configuration 4	N/A	1
Configuration 5	None	1
	GE 100%	1
	DAP	1
Configuration 6	N/A	1

Evaluations

The means to achieve this task is by unaided visual observation or via microscope if required. The objective is to determine the quality of the zinc. Inferior quality may include cracks or voids in the microstructure of the coating or bare spots in the indicated areas. However, before using the microscope, it is necessary to polish and grind the spots to be investigated in order to determine the features and characteristics of the surface. These procedures are described in detail in Appendix D.

3.6 Hot-Dip Galvanizing

Overview

41 specimens were dipped at the AZZ galvanizing plant in Bristol, VA. The staff of the plant provided insightful knowledge about galvanizing in general and a tour with helpful tips and illustrations. Also, the research team explained the goal of the study to the staff for better performance.

As mentioned earlier, the process involves dipping the steel specimens into multiple baths. For this plant specifically, there was the degreasing bath, the pickling bath, and the fluxing bath, which are all considered cleaning solutions. The final bath was the galvanizing bath. Furthermore, there were two rinsing baths. One was after the pickling bath, which helps remove any excess acids on the steels being dipped, and one was after the molten zinc, which helps cool down the specimen.

Galvanizing Process

The steel specimens were hung on a large moveable crane using steel bendable wire hangers, as shown in Figure 35. The crane was used to dip the specimens into different baths. Since some of the specimens were to be degreased only, some to be degreased and pickled only, some to be degreased, pickled and fluxed only, and some to be fully galvanized, the specimens were spaced into four different batches in the crane for identification.

Figure 35: Steel Specimens Hung with a Moveable Crane

The first stage was the degreasing bath, as shown in Figure 36. Sodium hydroxide was used at a concentration of around 12-25%. The specimens were submerged for approximately five minutes. The temperature of the bath was about 160-180°F. After five minutes of immersion, the crane lifted the specimens and four specimens were withdrawn from the bath as specified for task 1, these specimens did not continue the HDG process. The four specimens were rinsed with water from a hose. Figure 37 shows the four specimens which were from Configurations 2 and 5 and were sealed with GE or DAP Silicone.

Figure 36: Degreasing Bath with the Chemical Composition

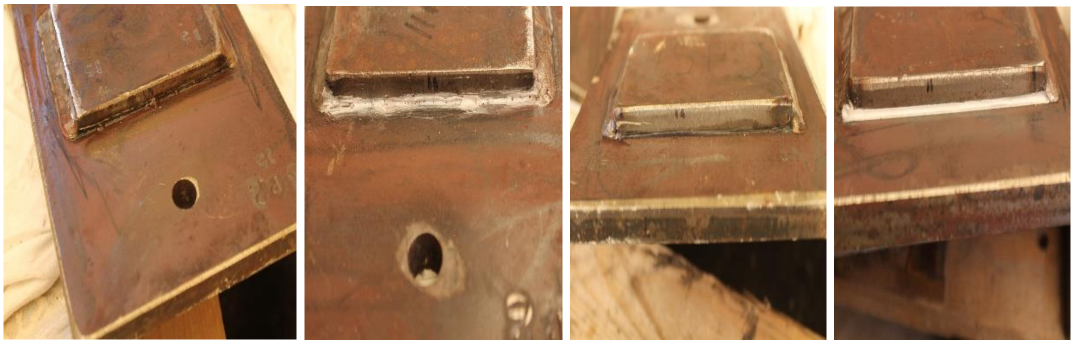


Figure 37: Specimens (Configurations 2 & 5) to Undergo the Degreasing Bath

The second bath was the pickling bath, as shown in Figure 38. The bath had the same ambient temperature with a 12% concentration of HCl. The dipping time initially took about 20 minutes. Then the specimens were checked, and it was determined that they were not cleaned enough.

They were dipped again in the same bath for around 12 minutes. After checking, they still were not cleaned enough so they had to be degreased again for about 2 minutes. After that, they were pickled a third time for 5 minutes. Next, they were rinsed with a water bath with an ambient temperature. After that, similar to the degreasing bath, four specimens were withdrawn from the bath. Similarly, two specimens from Configurations 2 and two specimens from Configuration 5 were withdrawn.

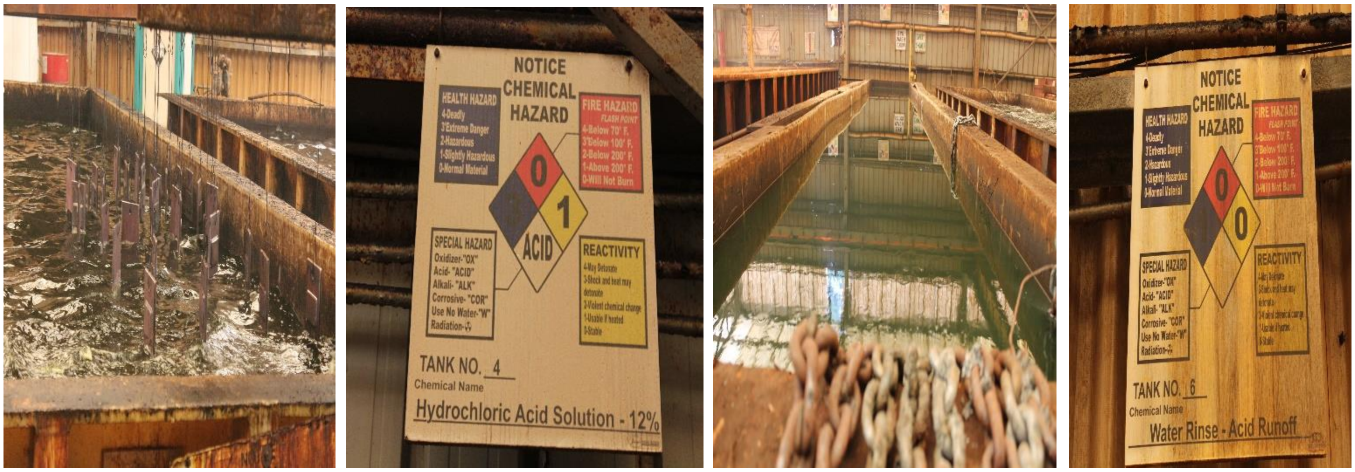


Figure 38: Pickling Bath (Bristol, VA)

The last bath of the cleaning solutions was the flux bath, which contained zinc ammonium as shown in Figure 39. The temperature of the bath was around 160-180°F. The dipping took 1-2 minutes, but it was done by multiple dippings, not a constant dipping as was the case for the other baths. Next, again, four specimens—two specimens from Configuration 2 and two specimens from Configuration 5, with each specimen either having silicone (GE or DAP), were withdrawn from the bath and rinsed by a water hose. After the fluxing bath, the specimens were dried and hung for about 3-4 minutes. The drying was crucial to prevent any splashing that result from dipping the specimens into the hot zinc later.

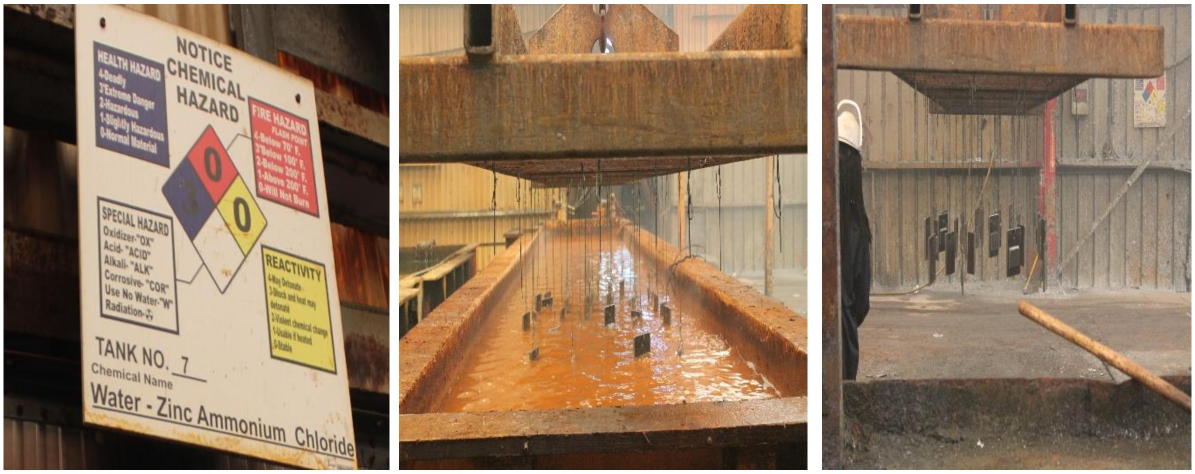


Figure 39: Fluxing Bath (Bristol, VA)

Lastly, the molten zinc with a temperature of about 835°F was the final bath. After taking 12 specimens out at the previous stages from the cleaning solutions for task 1, only 29 specimens were fully galvanized. The galvanizing took around 2-3 minutes. As expected, high pressure was developed for the specimens with small to no gaps, which damaged some of the plates. Once the specimens were lifted by the crane, they were poorly galvanized. Therefore, it was decided to re-galvanize some of the specimens. The specimens that were chosen to be re-galvanized were the ones with no sealants on them since galvanizing the sealant specimens twice could affect the caulks, which could risk changing the results. The specimens that were taken out were rinsed in a water tank. The primary purpose of the water was to cool down the specimens from the hot molten zinc. Figure 40 shows the zinc bath. Note the previously mentioned high pressure between contacting surface causing zinc splash as shown in the white circle.

Figure 40: Zinc (left) and Water (right) Baths

Thirteen plates were taken out although only 12 were caulked. Since some of the specimens were quite damaged and were difficult to identify, a mistake was made by pulling out one of the plates that should have been galvanized twice. Consequently, 16 specimens were re-galvanized. Similar to the previous stages (except the degreasing stage was not used), the process involved dipping the plates in the pickling bath for about 45 minutes this time. Then the plates were rinsed, fluxed, dried, dipped in the zinc, and finally water rinsed to cool down.

Chapter 4: Results

The results can be divided into four sections. The first presents the outcome from the galvanizing plant, the quality of the coatings, and some comparison between the configurations. The second section shows the silicone application and whether it passed the cleaning solutions unharmed. The third section presents the results from the cyclic corrosion study. Lastly, the fourth section shows the investigation of the zinc quality in the investigated areas indicated in section 3.5.

Although most of the corrosion analyses in other sources use average thickness loss to present corrosion results, this study used only photographs and visual observations. The purpose of this investigation was to visualize the severity of corrosion of the different alternative details, including poor bond of HDG in overlapped surfaces and rust formation, in order to determine the best corrosion resistance configuration. The long-term corrosion behavior of the material was the targeted result. Thus, thickness loss measurements including intermediate cleaning specifications and procedures of corroded specimens were not performed as they would deviate from the ultimate goal of this project. In addition to the thickness loss, the mil thickness of the zinc was not used as significant analysis factor for the results. This was due to the fact that the specimens were poorly galvanized as described in the following paragraph.

Generally, the overall coating result for all of the alternative details was not satisfactory. Although it was expected to have relatively bad coatings in certain specimens in certain configurations (near the gaps), the overall quality of the galvanizing did not produce acceptable results. Bare spots were observed in many specimens and in many locations, not only near the gaps but also, for instance, at the back of the specimens, which is unusual since the back of the specimen is just a plain rectangular steel. This made it difficult to distinguish between the poor galvanizing and the outcome results from the configurations of this research. Although re-dipping would better galvanize the specimens, it could affect the specimens that had moisture in them already, also, it could affect the silicone which was already comprised and charred at that point. Thus, re-dipping the specimens was not a viable option, and it was decided to continue along the research trajectory to attempt to see if any results were available based on the specimens – even in their poor condition. Many reasons could have affected the quality of galvanizing, such as the rate of immersion of the specimens, the quality of the zinc bath, improper cleaning or drying and much more contribute to the zinc quality.

4.1 Results from HDG Process

4.1.1 Silicone Test

Silicone was shown to pass the degreasing, pickling, and fluxing baths without any apparent issues, for both Configurations 2 and 5. Figure 41 through Figure 46 show four plates of Configurations 2 or 5, where the plates of the left column of the figures were sealed with GE Silicone and the right column were sealed with DAP Silicone. The top pictures are the ones before the cleaning baths while the ones on the bottom are after cleaning baths. It was apparent that, in general, the sealants were not negatively affected by the cleaning baths.

On a separate note, although the time which had elapsed between taking photographs before and after cleaning the specimen in the plant was short (2 to 3 days), the specimens corroded very quickly, especially the specimens that were tested in the pickling and fluxing baths, as shown below. This was due to the saltiness of the cleaning solutions that accelerated the corrosion of the specimens.

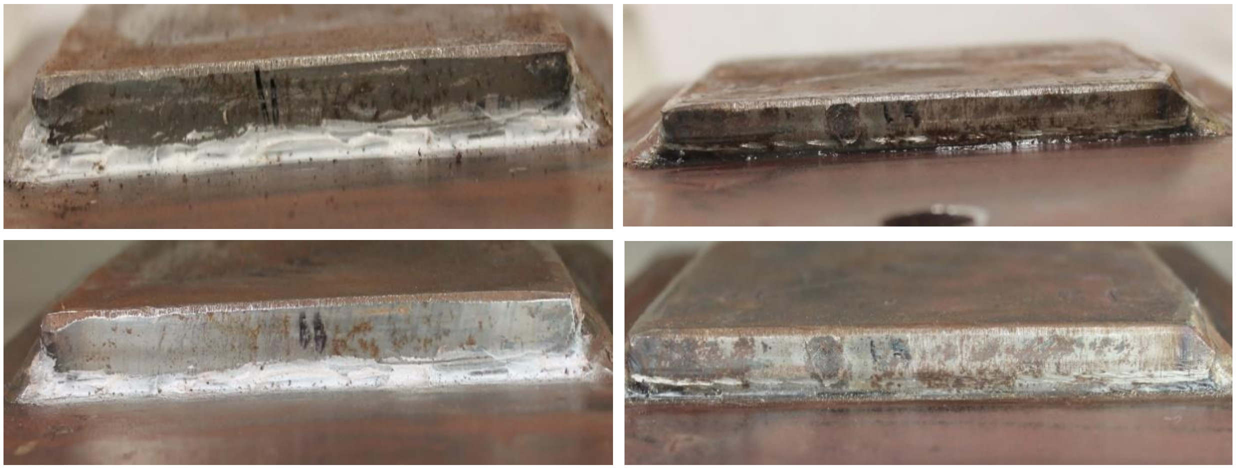


Figure 41: Before (top pictures) and After (bottom pictures) Degreasing for GE Silicone (left column) and DAP Silicone (right column) of Configuration 2

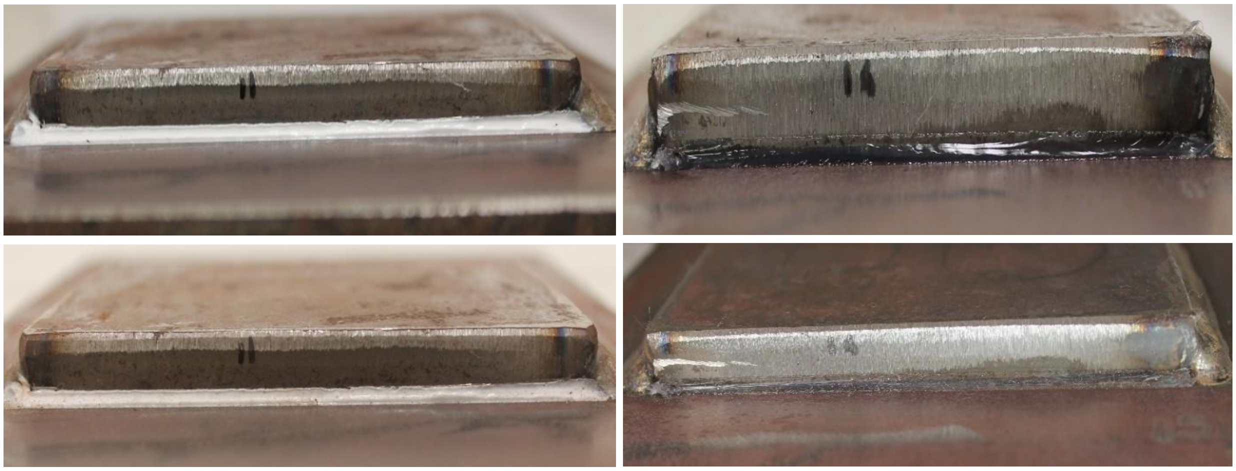


Figure 42: Before (top pictures) and After (bottom pictures) Degreasing for GE Silicone (left column) and DAP Silicone (right column) of Configuration 5

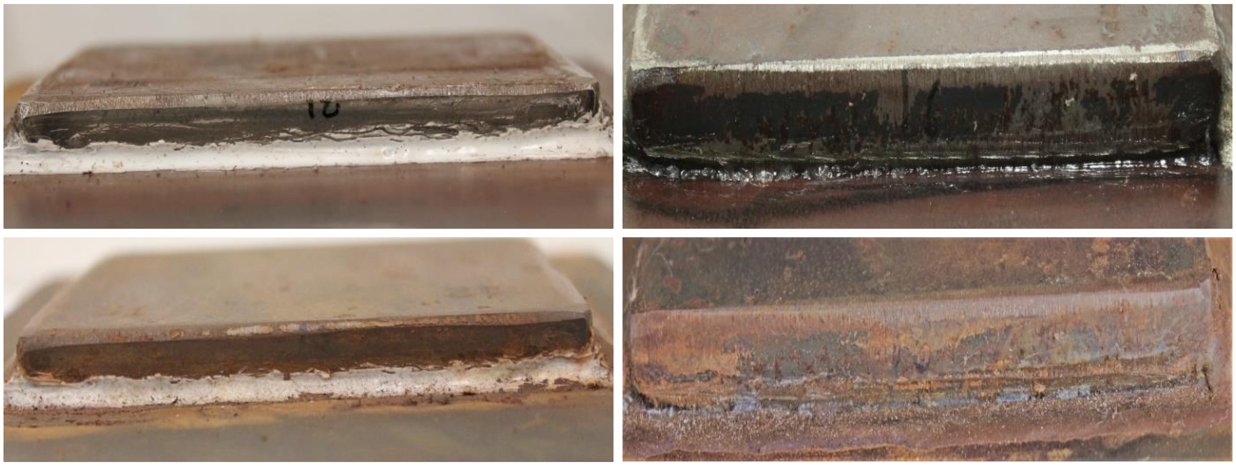


Figure 43: Before (top pictures) and After (bottom pictures) Pickling for GE Silicone (left column) and DAP Silicone (right column) of Configuration 2

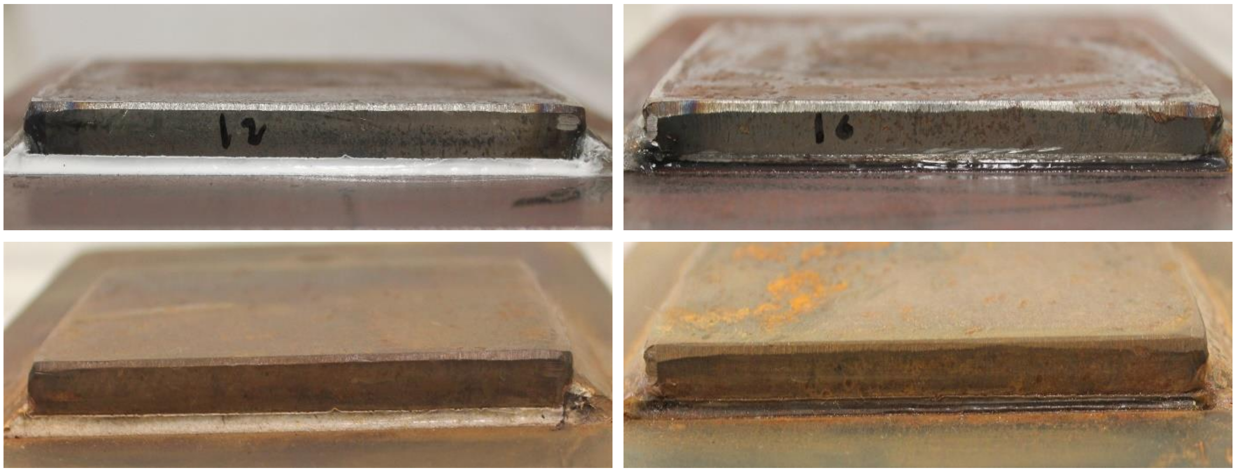


Figure 44: Before (top pictures) and After (bottom pictures) Pickling for GE Silicone (left column) and DAP Silicone (right column) of Configuration 5

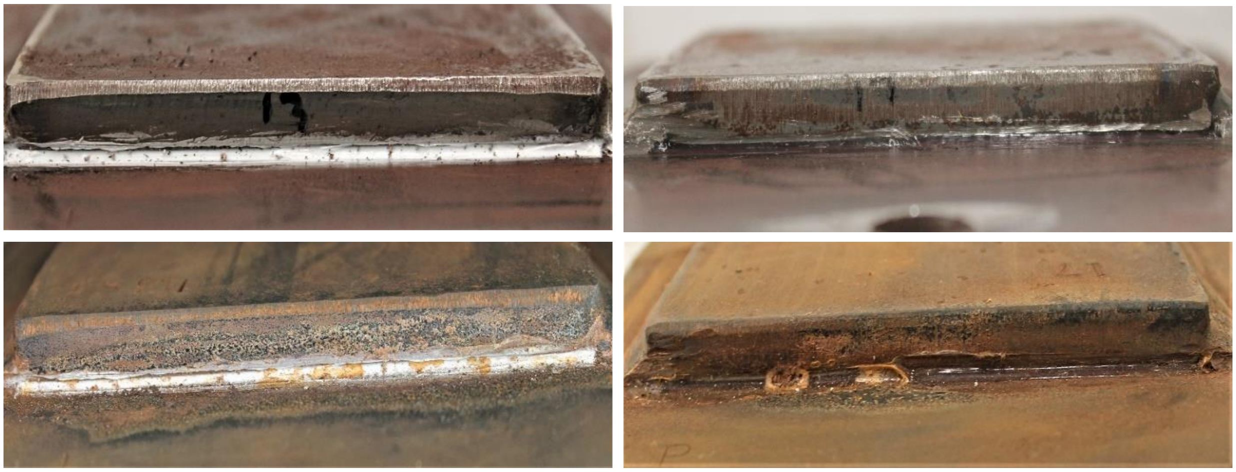


Figure 45: Before (top pictures) and After (bottom pictures) Fluxing for GE Silicone (left column) and DAP Silicone (right column) of Configuration 2

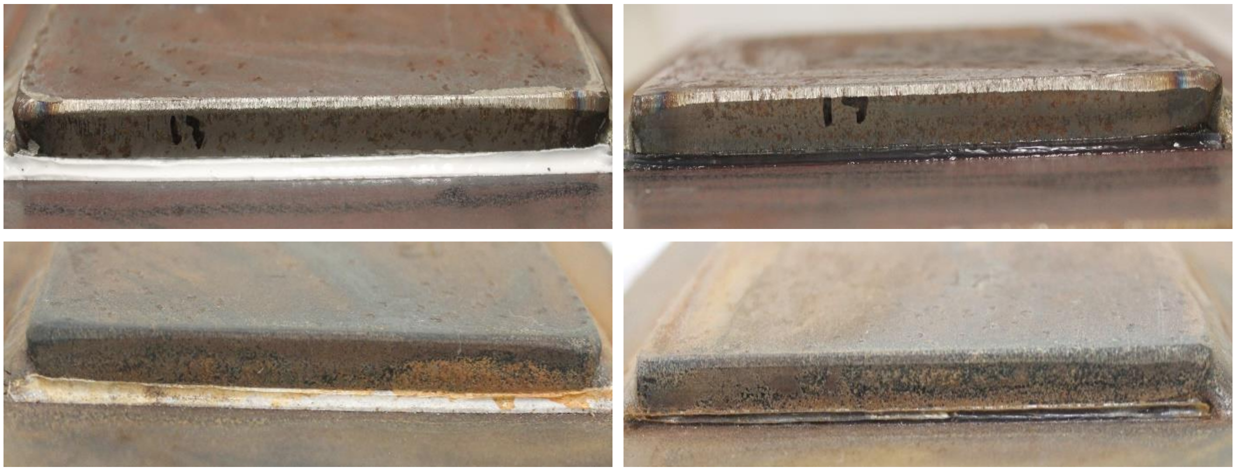


Figure 46: Before (top pictures) and After (bottom pictures) Fluxing for GE Silicone (left column) and DAP Silicone (right column) of Configuration 5

4.1.2 Specimens

As a general trend and before implementing the tasks, specimens from Configuration 2 yielded poor galvanizing whereas Configurations 1 and 4 yielded the best galvanizing, except some minor bare spots in 4. Configuration 5 experienced a relatively better coating than Configuration 2. At the gaps, however, both configurations 2 and 5 were damaged, whether sealed or unsealed. Configurations 3 and 6 had improved results but were still not acceptable for implementation due to the poor zinc bond and defects.

Even though the sealants passed the cleaning solutions unharmed, the specimens that were sealed and galvanized resulted in poor coatings in the adjacent areas near the gap. Surprisingly, the sealants did not melt off after the galvanizing. This was not expected based on the understanding of the melting points of the sealants. As a result, the specimens with silicone sealants were badly damaged near the gaps compared to the unsealed ones.

Configuration 1

This was the control specimen as shown in Figure 47, and it is also the configuration that is currently being designed in the industry. The two specimens from Configuration 1 yielded relatively satisfactory results compared to the other configurations. This was due to the fact that there was no gap at any of the edges. This prevented any collection of moisture or fluids between the overlapping surfaces. However, note the bare spot in the same figure (upper left of the left specimen), this indicates that the specimens were not appropriately galvanized, and not, however, a defect that resulted from this configuration. In addition to the bare spot, the difference in color (shiny silvery to matte gray) from within each specimen indicates an insufficient cooling rate of the specimens or probably a difference in the chemistry elements of the steel making (*Inspection of Hot-Dip Galvanized Steel Products*, 2016). Although the difference in appearance does not have an impact on the behavior of the coating, it gives evidence of the poor galvanizing that the specimens experienced.

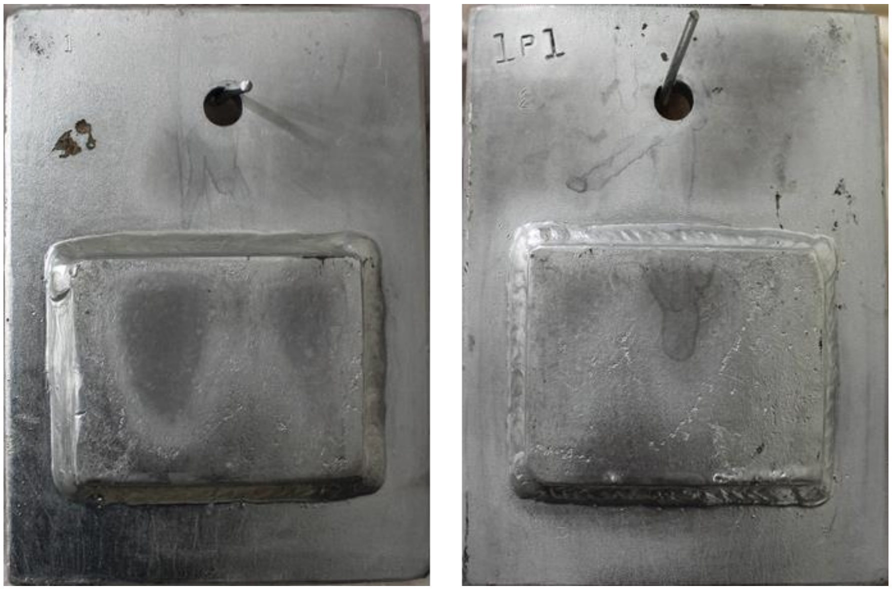


Figure 47: Configuration 1 Specimens After Galvanizing

Configuration 2

The results for Configuration 2 are shown from Figure 48 to Figure 51. As can be seen, the sealants did not contribute to having a better dipping performance. In fact, in general, specimens with no sealants performed better than the ones with the sealants as seen from Figure 48 and Figure 49 vs Figure 50 and Figure 51. However, among the three unsealed specimens, 1p2 was severely damaged, which had a small gap on the right edge, indicated by the arrow as seen in Figure 49. This gap was measured to be 0.0015 in., and it is likely that the gap collected some fluids from the cleaning solutions and damaged the coating for this specimen. The gaps for the other two unsealed specimens were less than 0.0015 in. as indicated by Table 8 from appendix

A. Even though the unsealed specimens performed relatively better than the sealed ones, they were not satisfying as there were bare spots near the open edge.

All of the gaps measured for this Configuration were less than 0.0015 in., except in two specimens. The first one, 1p2, was just discussed in the previous paragraph. The second one was sealed with GE Silicone, 2p2. The gap measured for this specimen was 0.07 in. on the left of the overlapping surface (left gap = right side from the front view of the specimen). Remarkably, as seen from , the bare spots were oriented on the right of the specimen, where the gap existed. This indicates that the silicone did not perform well during the HDG in spite of the fact that the silicone task was verified to withstand the cleaning solutions. Furthermore, although the gap in the sealed specimen (0.07 in.) was bigger than the unsealed one (0.0015 in.), this sealed specimen in particular performed relatively better than the unsealed one as shown in Figure 48 and in terms of the distribution and amount of the bare spots.

Figure 48: Configuration 2 (open edge on top, no sealants 1p2, 4p2, 5p2)

Figure 49: Gap View of Configuration 2 Before (left column) and After (right column) (1p2, 4p2, & 5p2)

Figure 50: Configuration 2 (GE Silicone Sealant, 2p2, 6p2, 7p2)

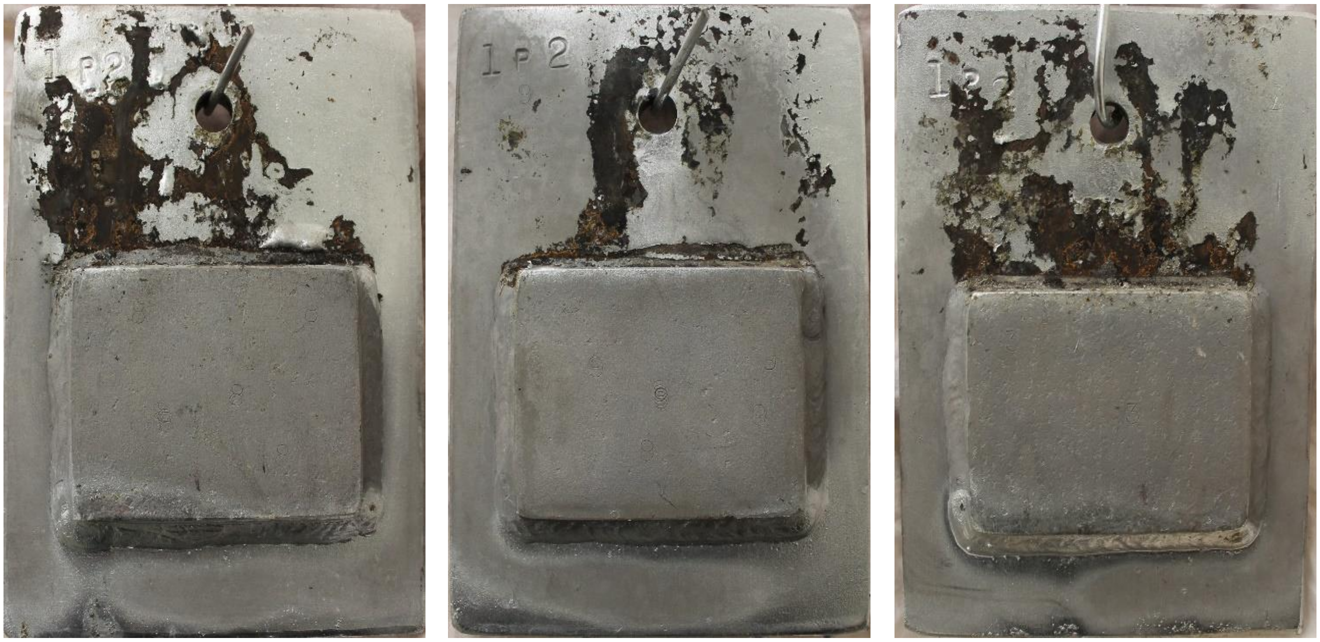


Figure 51: Configuration 2 (DAP Silicone Sealant, 3p2, 8p2, 9p2)

Configuration 5

Configuration 5 specimens (Figure 52 through Figure 54) yielded a better outcome than Configuration 2 (Figure 48 through Figure 51), in all three types of specimens (no sealants, GE Silicone, DAP Silicone). As a result, the orientation of the dipping has been determined to be a significant factor in the quality of the zinc on the surface. This is because the cleaning solutions could easily penetrate into the gap if it is on top but faces difficulty when it is at the bottom. An illustrative figure is shown in Figure 55, this was a Configuration 2 specimen in the plant during the HDG process, specifically, after the fluxing bath. As seen when the gap or the open edge is on top, the solutions were collected on top of the overlapping surface as indicated by the arrow. For Configuration 5, at the gaps, similar to Configuration 2, those that were not sealed had less damage, as shown in Figure 56.

Figure 52: Configuration 5 (open edge on bottom, no sealants 1p5, 4p5, 5p5)

Figure 53: Configuration 5 (open edge on bottom, GE Silicone Sealant 2p5, 6p5, 7p5)

Figure 54: Configuration 5 (open edge on bottom, DAP Silicone Sealant 3p5, 8p5, 9p5)

Figure 55: Configuration 2 Specimen Collecting Fluids Between Two Surfaces

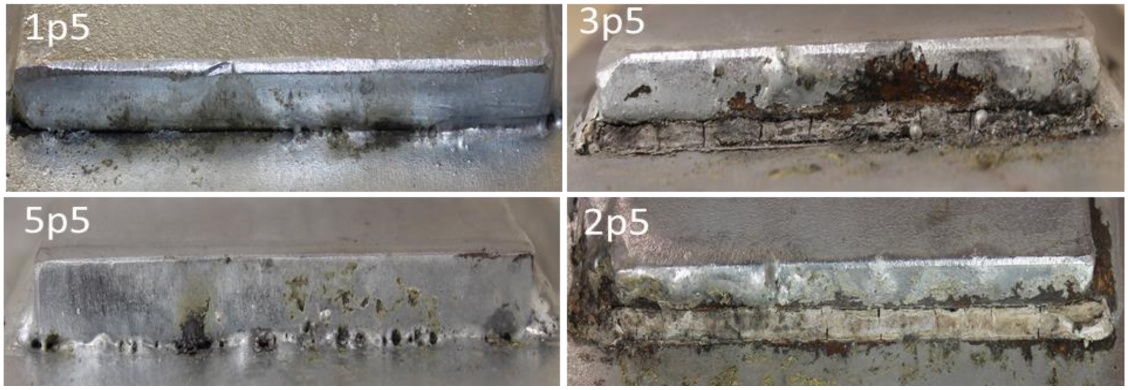


Figure 56: Sealed vs Unsealed Specimens

Configuration 3

Overall, Configuration 3 did not provide satisfactory results but yielded a better outcome than Configuration 2. There were some damaged areas on the upper side of the plates as seen in Figure 57, but they were not as severe as Configuration 2. It is difficult to conclude that the recommended minimum 3/32 in. gap was an inadequate solution for overlapping surfaces given that it provided unsatisfactory results for Configuration 3. Again, the bare spots observed in this configuration could be due to the poor HDG process. In fact, the bare spots for Configuration 2 were likely due to the open edge collecting fluids since they were initiated and extended from the open edge up to the upper side of the specimens, however, for Configuration 3, the bare spots were located only at the upper side of the specimens and no bare spots existed near the gaps. This favors the fact that the inferior coating found in Configuration 3 were due to the improper HDG process. In addition to the bare spots, this configuration experienced dots and rough surface, especially near the gaps in 2p3.

The orientation of dipping and the gap width contributed to having a filled zinc between the overlapping surfaces. The gap width can be correlated with the visualized zinc through the gap. The gap, although required to be larger than 3/32 in. (0.09375”), varied between the three specimens. The gaps were measured for the three specimens before galvanizing. They were, on average, 0.125, 0.0950, 0.130 in. for 1p3, 2p3, 3p3 respectively. This is shown in Figure 57, where the zinc in 3p3 can be visualized since this specimen had the widest gap.

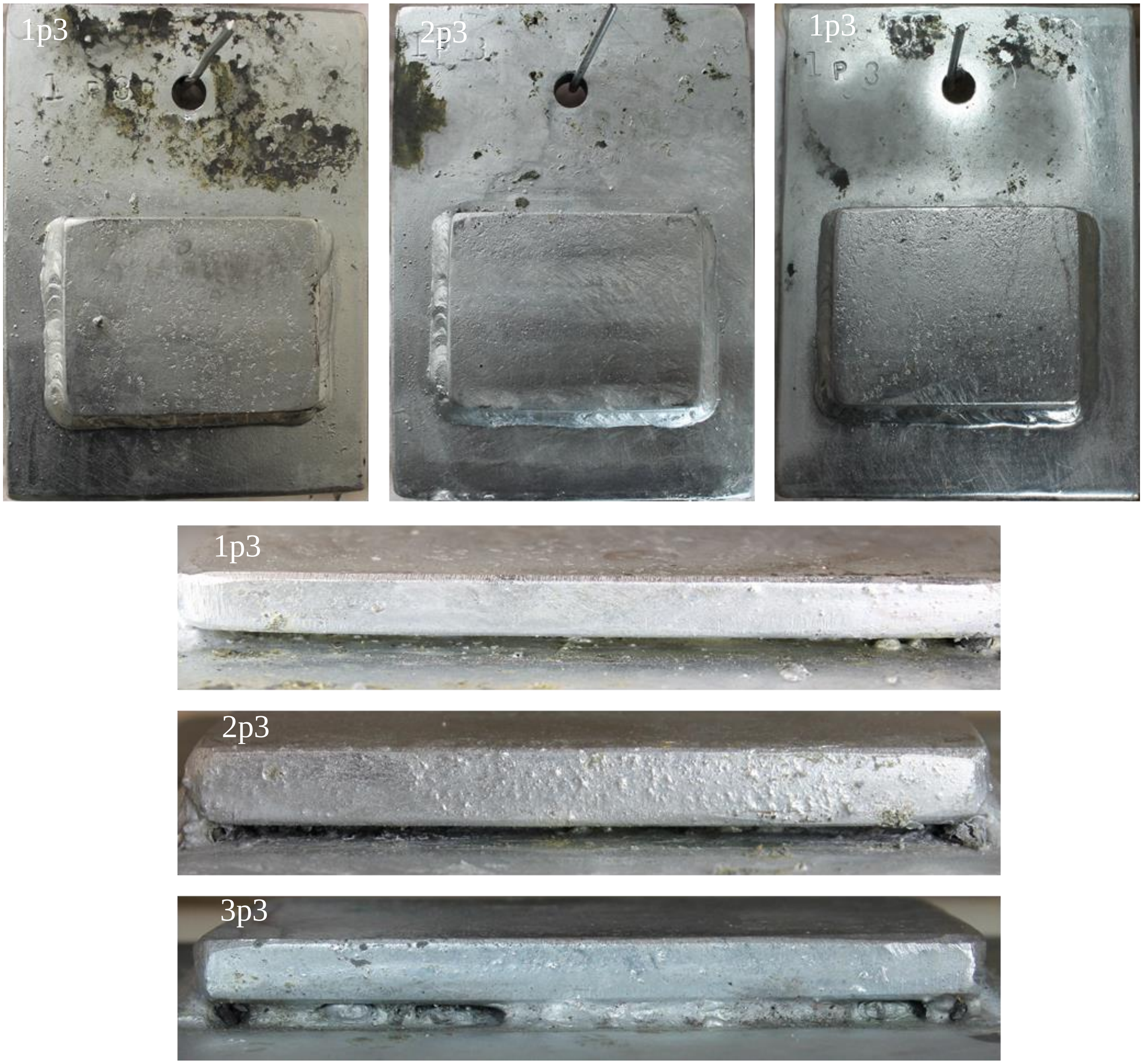


Figure 57: Configuration 3 After Galvanizing

Configuration 4

Except for the control configuration, Configuration 4 has yielded the best results in comparison with the other configurations, as shown in Figure 58. This configuration experienced uniform coating, meaning the surface of the specimens was smooth. Additionally, despite some minor bare spots, the surface of the specimens was free from any galvanizing defects such as drainage spikes and dots which were found in the other configurations. Nonetheless, some fluid leaching was observed along the weld edges as indicated by the white arrows from the same figure, these were likely due to the cleaning solutions not being able to clean the weld edges such as slags and spatters. The tasks implanted for this research, detailed in the next sections, gave more insight into these leaching.

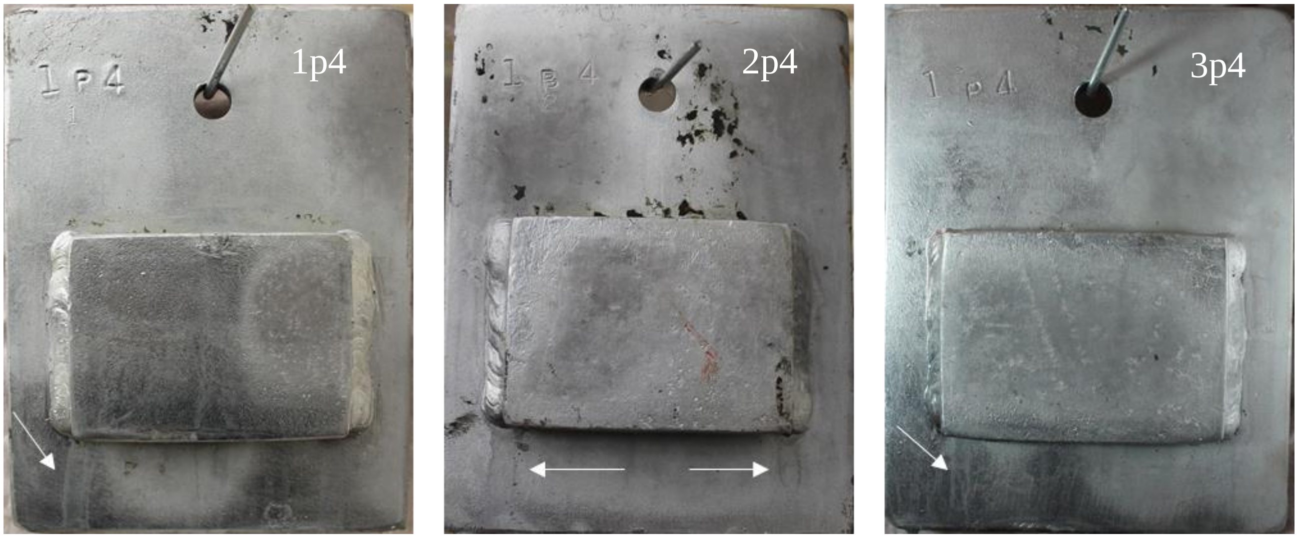


Figure 58: Configuration 4 After Galvanizing

The top gaps in this configuration for the three specimens experienced some minor damage while the bottom gaps were uniformly coated, regardless of which gap was larger. Figure 59 shows two gaps of the 2p4 specimen. For this specimen, the difference in behavior between the two gaps can be explained by the width of the gaps. The average gap width was 0.108 in. for the top view, and the average gap width for the bottom gap was 0.184 in.. However, for 1p4, the top gap was considerably larger than the bottom gap when measured. Also, for specimen 3p4, the top and bottom gap measurements were very close to one another. A conclusion can be made that even if the top gap was larger than the back gap, bare spot areas were always present in the top gap.

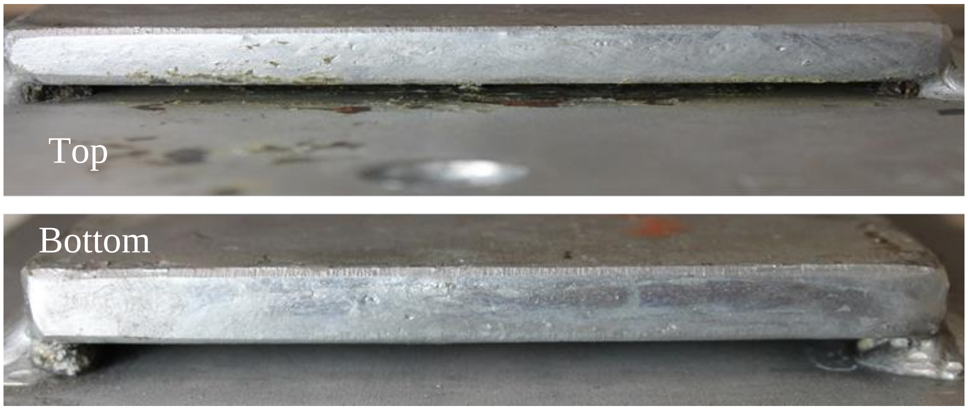


Figure 59: Gap View (top and bottom) of Specimen 2p4 of Configuration 4

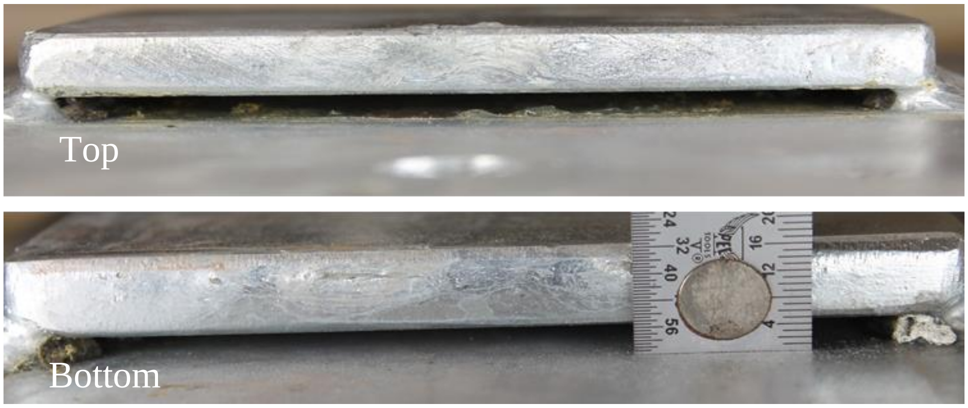


Figure 60: Gap View (top and bottom) of Specimen 1p4 of Configuration 4

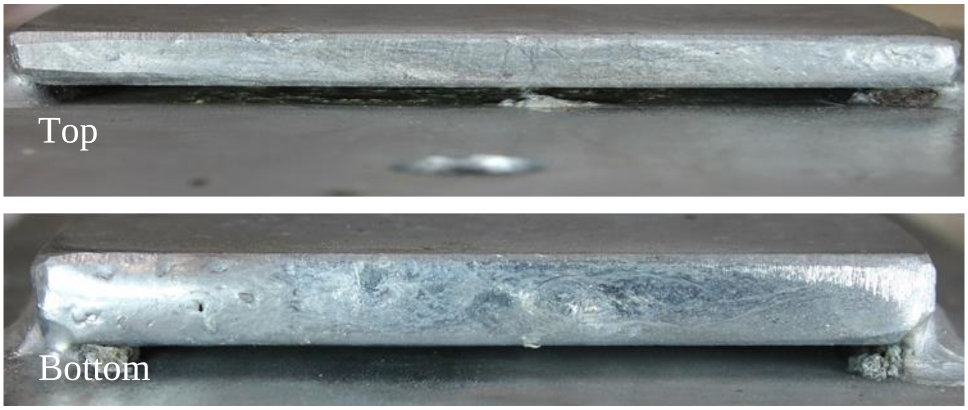


Figure 61: Gap view (top and bottom) of Specimen 3p4 of Configuration 4

Configuration 6

The overall coating results for this configuration were not satisfying although it provided better outcomes than Configuration 5, as shown in Figure 62. Two features were observed for this configuration. The first one was the yellow-green deposits near the gaps. These were probably flux deposits. Flux deposits are non-metallic chlorides or oxides deposits that occur when the flux from the HDG process did not release or flow freely from the metal surface (Maass & Peißker, 2011). The second observation was the existence of spikes near the gaps and at the bottom of the specimens. Both observations, zinc being able to solidify to spikes and flux not being able to release, all indicate the surface tension property influence for this geometrical configuration near the gaps since they were oriented on the bottom. Comparing Configuration 6 to Configuration 3, it can be concluded that Configuration 3 yielded better outcomes near the gaps while Configuration 6 had a better overall coating elsewhere.

Figure 62: Configuration 6 Specimens (1p6, 2p6 and 3p6 respectively)

4.2 Corrosion Study

Overview

After 40 cycles, it was found that the corrosion behavior for Configuration 1 and 4 was better than the other configurations. Configurations 3 and 6 had noticeable concentrated corrosion products and red stains near the gaps. Also, Configurations 5 and 2 had white corrosion products distributed along the open edges. Comparing the open edge configurations (2 and 5) with the wide gap configurations (3 and 6), the open edges had less severity along the edges/gaps. To the left, since Configuration 1 was seal-welded, and Configuration 4 had two gaps, these details prevented moisture and corrosion product concentrations and thus contributed to a finer behavior.

Some general observations are described below. The first observation is related to the orientation of the specimens inside the chamber. Because the specimens were hung vertically in the plastic PVC pipes through the 1/2 in. hole on top of the plates, it was noted that this set up allowed accumulation of moisture and salts, from the immersion stage and the chamber humidity during the cycles, on top of the smaller plate due to the presence of the overlapping surface. In return, this accumulation caused non-uniform corrosion over the surface of the specimen. The second observation is that the most severe corrosion damage occurred near the gaps. In other words, the corrosion products were concentrated near the gaps, that is for configurations 3 and 6. This was due to the existence of the gap collecting moisture and salts and the relatively slow air circulation in these regions, compared to the other parts within the specimens, affecting the drying process and thus increasing the corrosion rates and products (Thierry & LeBozec, 2009). Lastly, the corrosion rate of all the specimens showed something in common—during the first 10 cycles, the specimens were experiencing a relatively uniform white corrosion product. Then, for cycles 20, 30 and 40, the white corrosion product was relatively reduced and a red to a yellow color of corrosion started to form. The white product was believed to be zinc oxide, ZnO (Thierry & LeBozec, 2009). The red to yellow corrosion products were believed to be due to the consumption of the zinc coating. In conclusion, the first observation should not be mixed with the result as it originated from the test set up, the second and third observations, however, were outcomes from this task of this investigation.

The fact that the white products were consumed to a red corrosion is a healthy corrosion process of zinc coated steel. Interestingly though, near the open edges of Configurations 2 and 5, some of the white products were accumulated near the gaps that were not fully consumed. This can be explained by the electrochemical process of the corrosion. Sometimes when the presence of the accumulation of the white corrosion products, such as zinc oxides or zinc chloride, is abundant in certain locations such as gaps or crevices, this prevents the functionality of the zinc coating and initiates the corrosion of the steel substrate (El-Mahdy, Nishikata, & Tsuru, 2000). Furthermore, this was also due to the drying process. For example, the specimens in the first cycles experienced a fast-drying rate, then for later cycles, they experienced a slow-drying rate due to the accumulation of corrosion products that impeded the drying process. Thus, zinc oxides or zinc hydroxides could not further get carbonated, and therefore, did not protect the steel (Bottcher et al., 2011).

Configuration 1

This configuration experienced a good coating behavior over testing, as shown in Figure 63. Except for the top of the overlapped surface where the yellow to red corrosion started to form. This, as mentioned previously, was due to the test set up and not results from the task outcome for this configuration. At cycle 10 as seen from the figure, the white corrosion products were dominated and clear to see. At cycle 40, the white corrosion products were likely carbonated and consumed and thus disappeared. This, again, indicates a healthy corrosion behavior of this configuration.

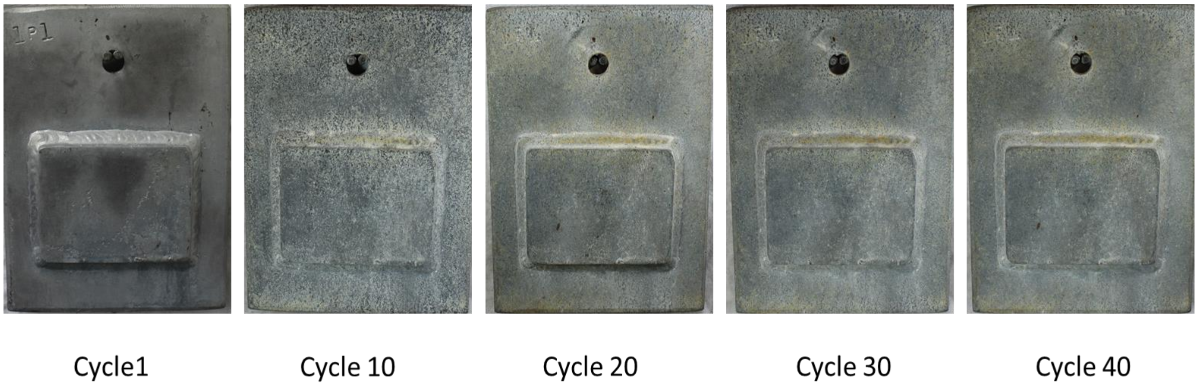


Figure 63: Cyclic Corrosion of Configuration 1

Configurations 2 and 5

Despite the bad coating in the surface of Configuration 2, all of the specimens for both configurations experienced a relatively uniform corrosion except the white rust accumulation along the open edges, which was insignificant compared to the wide gap non-uniformity in configurations 3 and 6 as shown in the next section. Figure 64 shows Configuration 2 (upper row) and Configuration 5 (bottom row) after 40 cycles. The first two specimens for both rows from the left were not sealed, the second two were GE Silicone sealed, and the last two were DAP sealed.

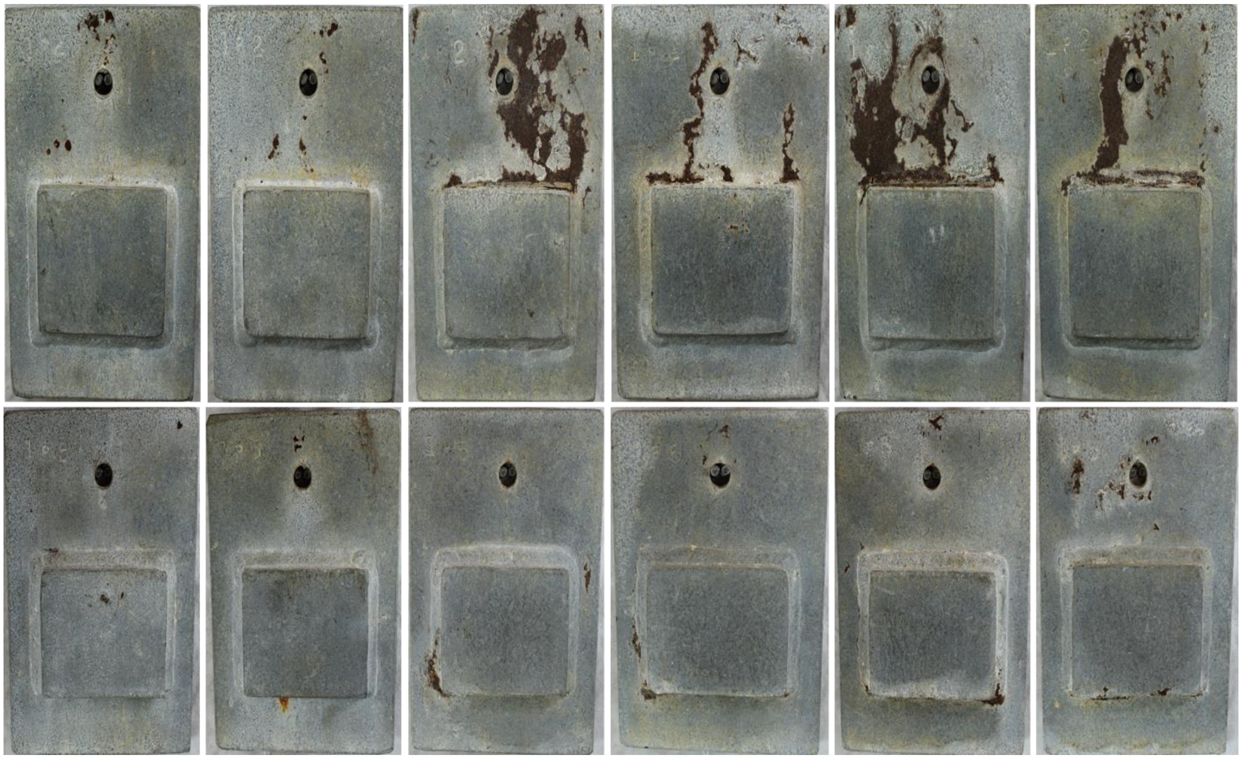


Figure 64: Configuration 2 (upper row) and Configuration 5 (bottom row) After 40 Cycles

Note the formation of a rust bleeding (iron oxide) in one of the specimens of Configuration 5 as shown in Figure 65, this specimen was not sealed with sealants. Although there was another specimen that was not sealed with sealants for the same configuration, this was the only specimen that experienced rust bleeding. The reason can be explained by the gap width. The gap was measured to be .019 in. on the red bleeding specimen, whereas the gap on the other specimen could not be measured by the feeler gauge, meaning it was less than .0015 in.. Another set of two specimens from Configuration 2 were not sealed with GE Silicone and yet did not experience rust bleeding, this was due to the fact that the orientation of hanging plates through the 1/2 in. gap allowed the open edge to be on top, which was the opposite of the gravitational force. Hence, had the specimens experienced rust stains inside the overlapping surface, it could not leach out or be visualized.

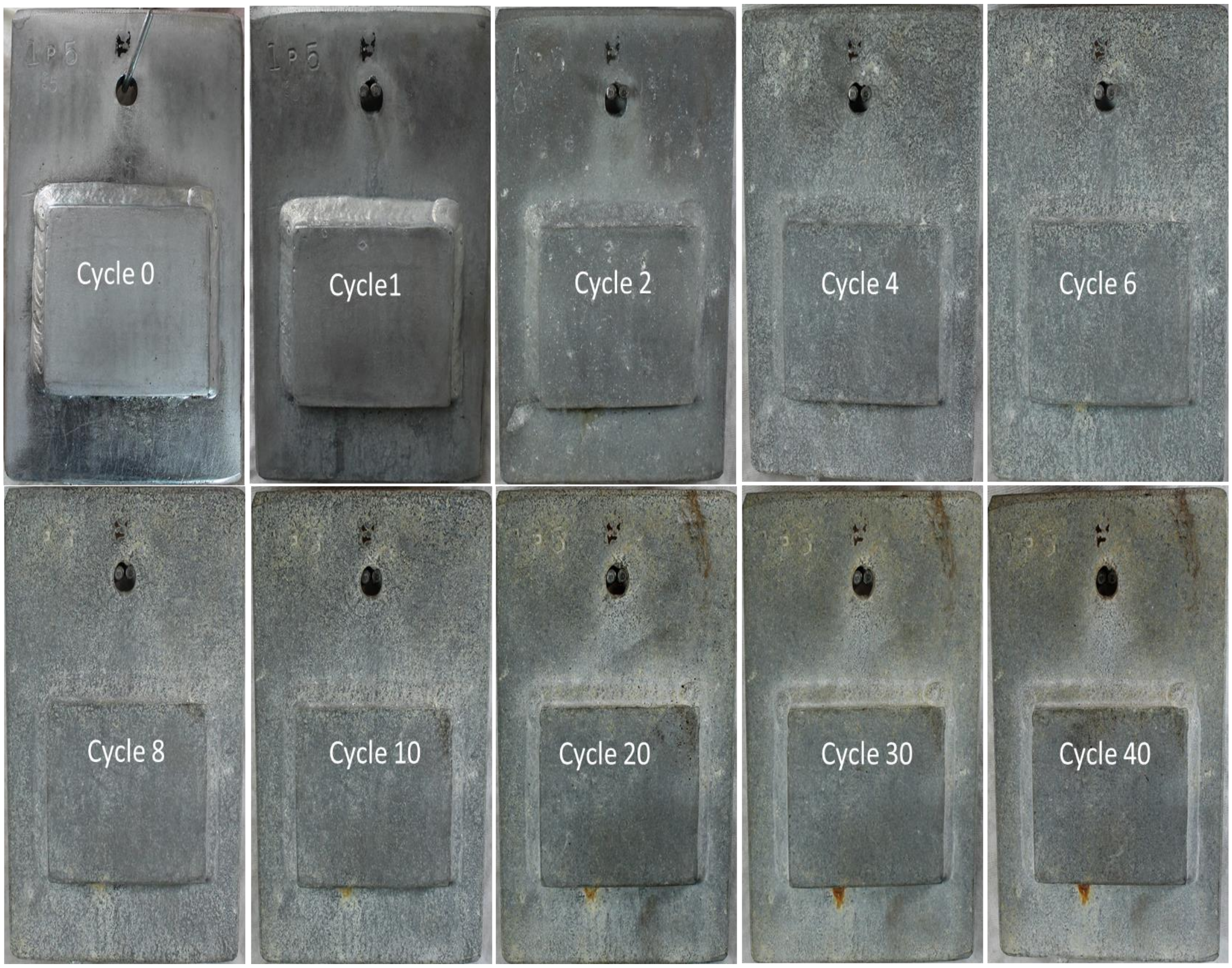


Figure 65: Configuration 5 Specimen 5p5 (not sealed) from 0 to 40 Cycles

The rust bleeding was believed to be a corrosion product of the steel substrate, due to a defect that occurred between the overlapping surface, that traveled along the surface of the coated steel. It was not, however, a corrosion or consumption of the zinc coated over the traveled path surface. The reason behind this explanation is that it was observed that the red corrosion was initiated at early stages of the cycles in this specimen (around 4th cycle), as shown in Figure 66, unlike the other specimens where the red corrosion appeared around the 20 cycles. It can be concluded that, first, the overlapped surface was not cleaned or galvanized properly. Second, as mentioned previously, the coatings along the open edges were probably inhibited due to the white products presence and thus did not function very well as the steel substrate started to corrode and leach out.

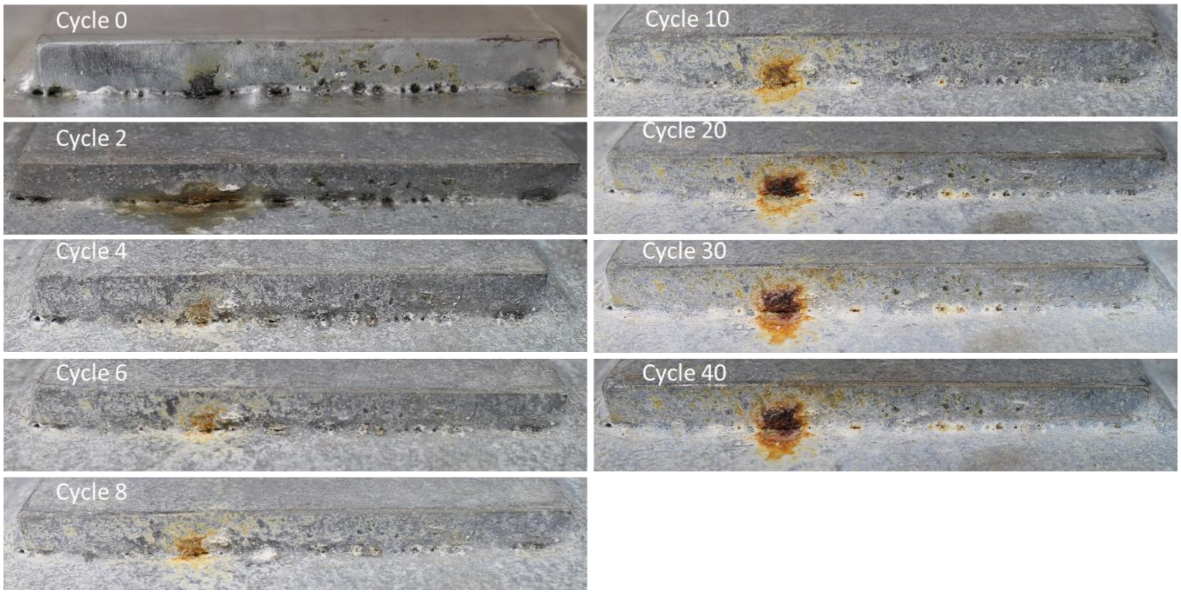


Figure 66: Configuration 5 Specimen 5p5 (not sealed) from 0 to 40 Cycles (gap view)

Configuration 3

There were two specimens of this configuration, namely 2p3 and 3p3. Specimen 3p3 had a considerably larger gap than 2p3. Hence, this led to the visible zinc coating through the gap in specimen 3p3 but not in specimen 2p3 as was seen in Figure 57. As seen in Figure 67, 2p3 had more severe damage than 3p3 even though 2p3 was smaller, especially near the gap where the red rust is clearly visualized in 2p3, meaning the white corrosion products and the zinc were consumed. This can be explained by the difference in the gap. Since 3p3 was filled with zinc, this made the gap shallower into the overlapping surface, allowing only limited air circulation. This limitation slowed down the drying process of the moisture and zinc thus contributed to white rust accumulations. To the left, 2p3 had more damage which indicates a faster drying and corrosion rate, compared to 3p3, due to the wide deep gap.

Figure 67: Configuration 3 After 40 Cycles

Comparing Configuration 3 with 2, Configuration 3 had more red stains and faster corrosion rate than Configuration 2. This again goes to the existence of the gap. A clear comparison can be seen in Figure 68. The right column shows unsealed specimens from Configuration 2 with Configuration 3 in the left column. Although specimen 3p3 behaved similar to Configuration 2 specimens in terms of the white corrosion products, specimen 2p3 appeared to be worse than Configuration 2. Nonetheless, the red stains and corrosions in 2p3, again, indicate a healthy corrosion process. For Configuration 2, the white products along the edges indicate a poor diffusion of oxygen and slower drying rate since the gaps were too small, which could probably lead to the risk of unforeseen corrosion of the steel substrate. To sum, although Configuration 2 had less severity than Configuration 3, both of them behaved poorly compared to the other configurations.

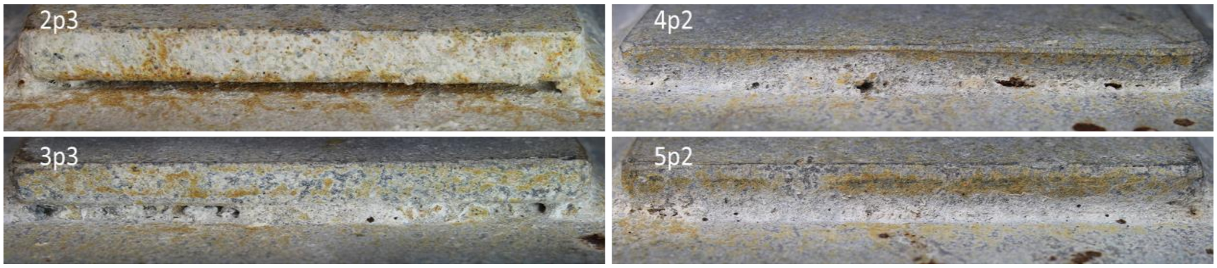


Figure 68: Configuration 3 (left) and Configuration 2 (right) After 40 Cycles

One interesting observation was noticed for this task, in Configuration 3 specifically, was the disappearance or the reduction of some of the bare spots as the cycles progress. This is shown in the three circles indicated in Figure 69. The basic premise of this occurrence is that the zinc adjacent to bare spots, steel substrates that did not get galvanized, migrated or sacrificed to them due to the difference of the electro-potential between the two elements. This is one of the powerful benefits of using HDG as a preventative mean for steel against corrosion. More investigations should be done for this phenomenon.

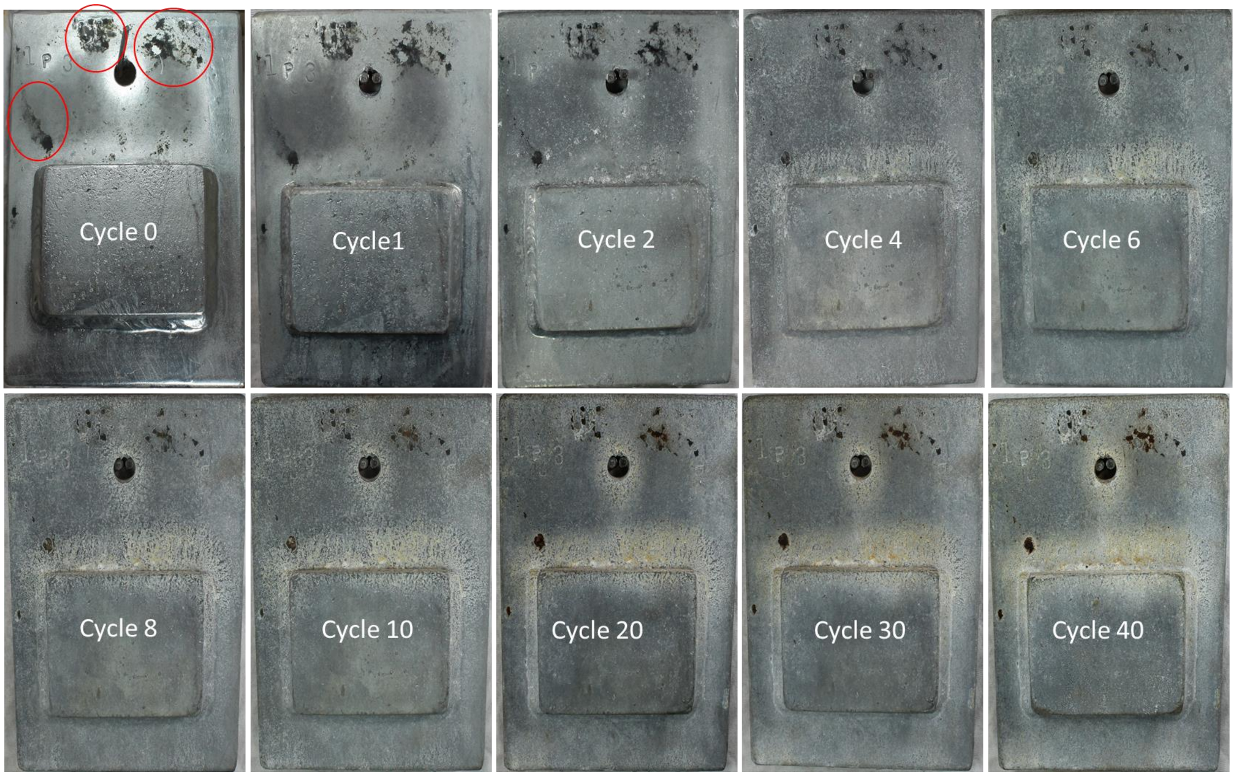


Figure 69: Configuration 3 Specimen for 40 Cycles

Configuration 6

As can be seen in Figure 70 and Figure 71, the corrosion products were slightly different between the two specimens. White products were dominant in specimen 2p6 whereas 3p6 had more reddish corrosion products. In other words, the white corrosion products in specimen 3p6 had been consumed more than that in 2p6. This can be explained by the gap measurement. Specimen 2p6 has a relatively smaller gap then 3p6. It can be concluded that red corrosions grow and dominant the area adjacent to the gap as the gap width increases, which can be explained by the fast-drying process in larger gaps.

Figure 70: Configuration 6 After 40 Cycles

Figure 71: Configuration 6 After 40 Cycles (gap view)

Similar to the comparison between Configurations 2 and 3, Configurations 5 and 6 experienced the same issue, that is, the localized corrosion adjacent to the gaps was much more severe in Configuration 6 than in Configuration 5 as shown in Figure 72. However, note that Configuration 6 did not experience or show any symptoms of rust bleeding. This formed two theories: The first one could be that part of the overlapped surface between the two plates had been properly galvanized in Configuration 6 due to the existence of the gap. Thus, more testing cycles could corrode the specimen and thus form rust bleeding. The second theory is that zinc migrated, as was proved in Configuration 3, between the overlapped surfaces towards the bare spots, thus eliminating bare spots and rust bleeding. However, the second theory contradicts 5p5 specimen from Configuration 5 where rust bleeding was observed. Nonetheless, as discussed at the beginning of the results of this task, accumulation of white corrosion products, as was the case for Configurations 2 and 5 near the open edges, probably stopped the functionality of the zinc coating, as a result, allowing steel substrates or bare spots to further corrode. It can be concluded that the exitance of the minimum 3/32 in. gap eliminated the rust bleeding phenomenon as in Configuration 6, yet, had a faster corrosion rate and more growing red rust than the open edge/small gap specimens.

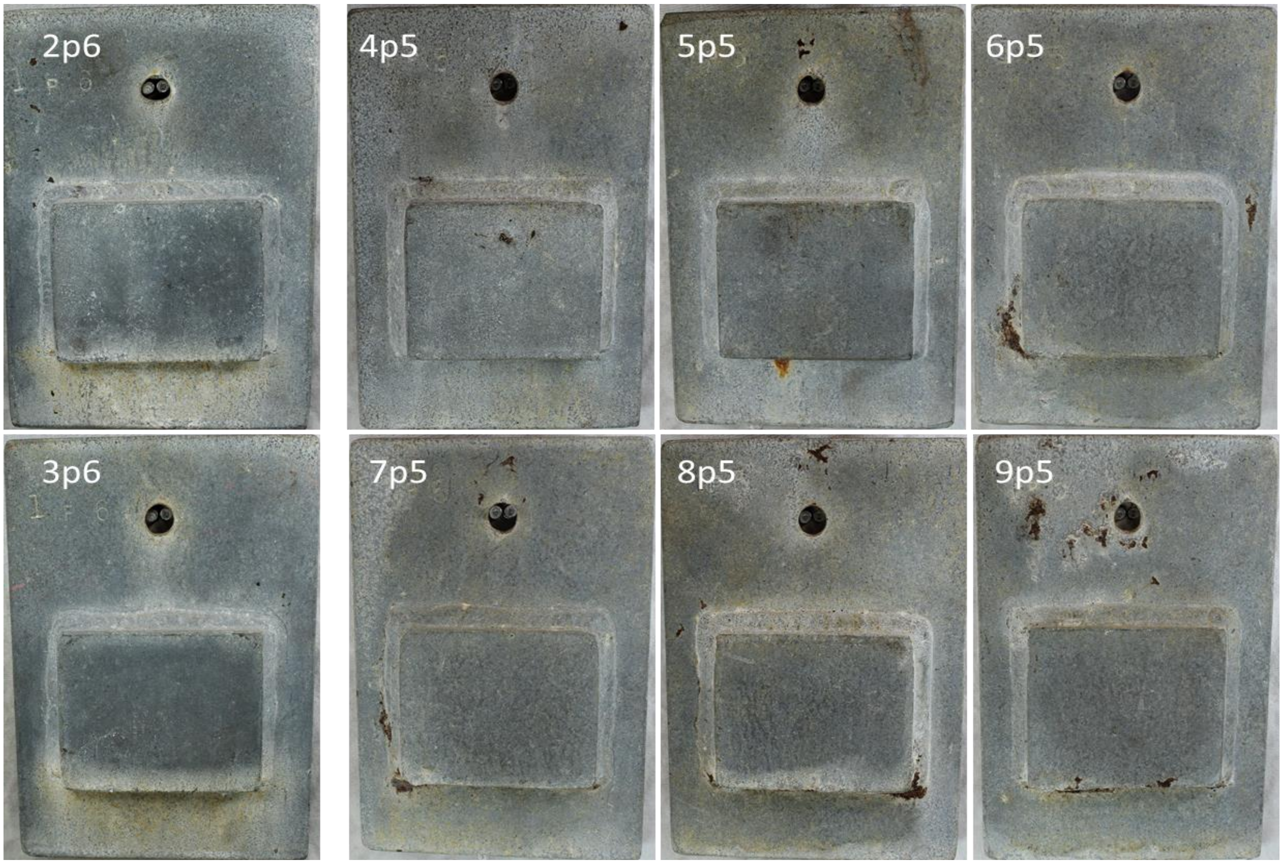


Figure 72: Configuration 6 (left column) and Configuration 5 After 40 Cycles

Configuration 4

Configuration 4 had the highest quality corrosion behavior from the accelerated corrosion test when compared with the other configurations, except for the control specimens. This configuration experienced a relatively uniform corrosion. As seen in Figure 73, there was no localized corrosion near the gaps as opposed to what was found in the other configurations. This was due to the open gaps in both edges that allowed air circulation and thus a fast-drying process after the immersion in the salt solution or from the moisture of the chamber. However, in agreement with what was observed in 4.2.2 regarding the leaching along the edges, it can be noted that the damages were slightly distributed or oriented along the edges where leaching occurred as shown in the white arrows of Figure 73. This was believed to be due to improper edge cleaning due to the welds. In addition to the improper cleaning, the salt solution and moisture from the tests were contributing factors to have corrosion products along the edges as they were likely traveled along the edges due to the surface tension property. A comparison between Configurations 3, 4 and 6 is shown below in Figure 74. Configuration 4 corrosion behavior was relatively uniform even near the gaps in contrast to the wide gap configurations where the corrosion products were localized near the gaps, this what favors this configuration to the other configurations.

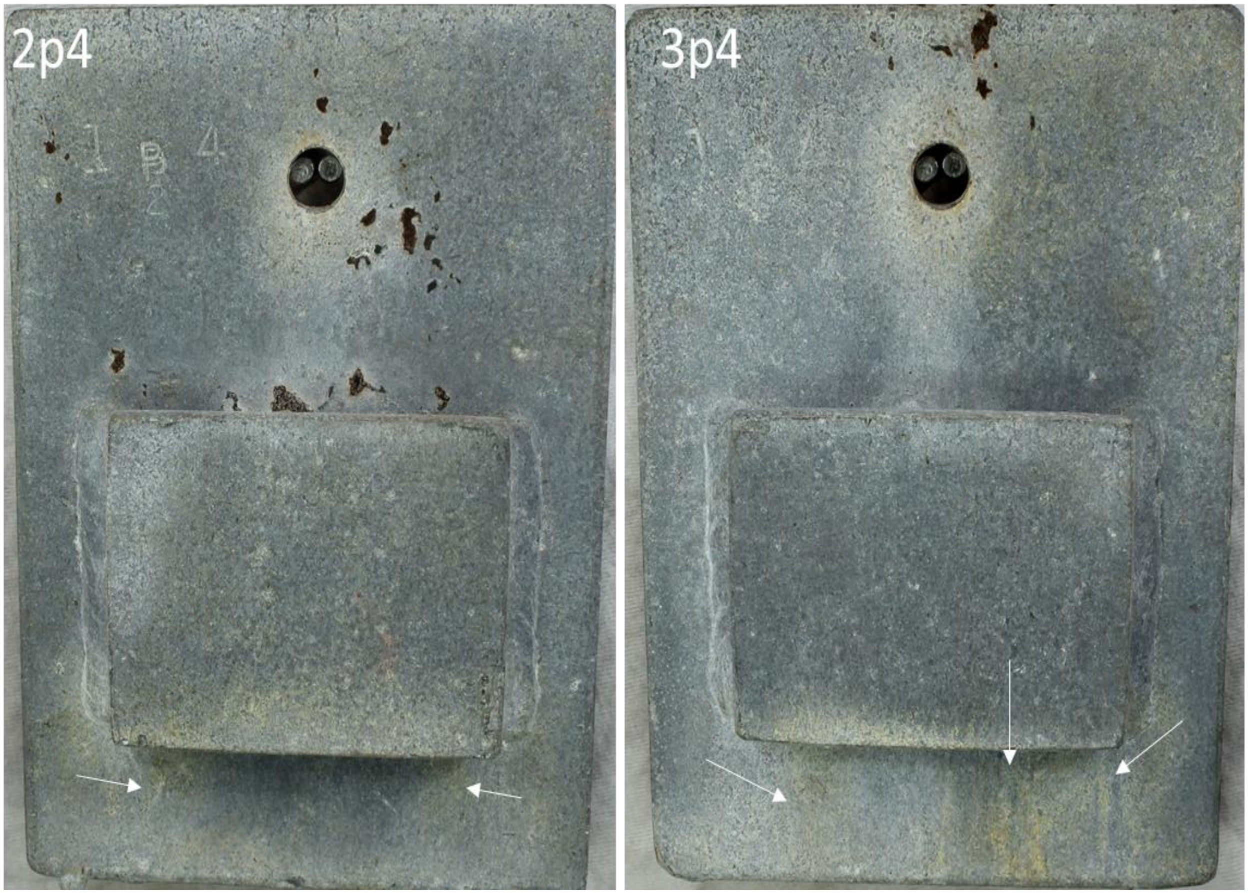


Figure 73: Configuration 4 After 40 Cycles

Figure 74: Configuration 3 (left column), Configuration 6 (middle column) and Configuration 4 (right column) After 40 Cycles

4.3 Material Cross-section Investigation

This section investigated the two cuts that were described in 3.5 section. One modification was done in Configuration three. The smaller plate was not removed, as was the intent to investigate the overlapping surface, this is because the gap was filled with zinc. Removing the overlapping surface would not be sufficient in this case.

Configurations 1, 2 and 5

For these configurations, the weld cross section was not affected by the galvanizing process as shown in Figure 75 and Figure 76. This was expected as the seal-weld prevented the fluids from the cleaning solution and zinc from penetrating for Configuration 1. Similarly, for Configurations 2 and 5, the weld sections were not affected by the galvanizing process, further investigations were done (1p2 unsealed) via microscope, as shown in Figure 77, which is a zoom-in from the upper left specimen of Figure 76, neither the galvanizing zinc nor the cleaning solutions penetrated inside the open edges. It should be noted that the red corrosion appearing in this piece specimen does not correlate with the configuration/type. The red corrosion started to appear after cutting the specimens for a period of time and was due to the atmosphere surrounding the specimen. In addition to the weld section, the open edge sections (for Configurations 2 and 5 only since Configuration 1 the top and the bottom were the same), whether with sealants or not, did not yield satisfactory results in the top interface, as shown in Figure 78 and Figure 79.

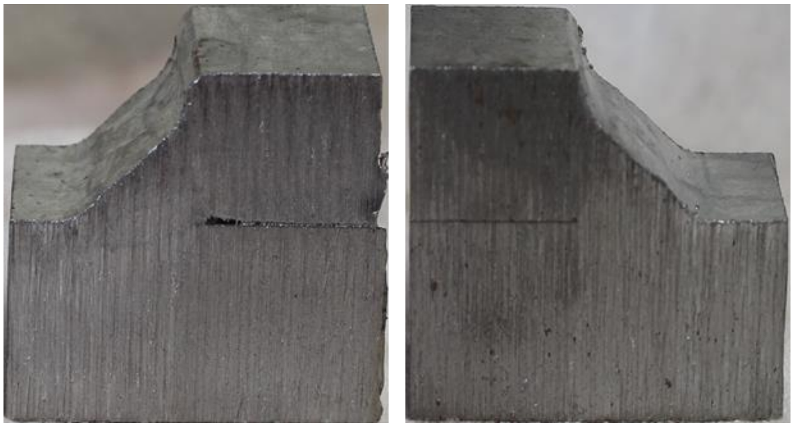


Figure 75: Weld Cross Section Configuration 1

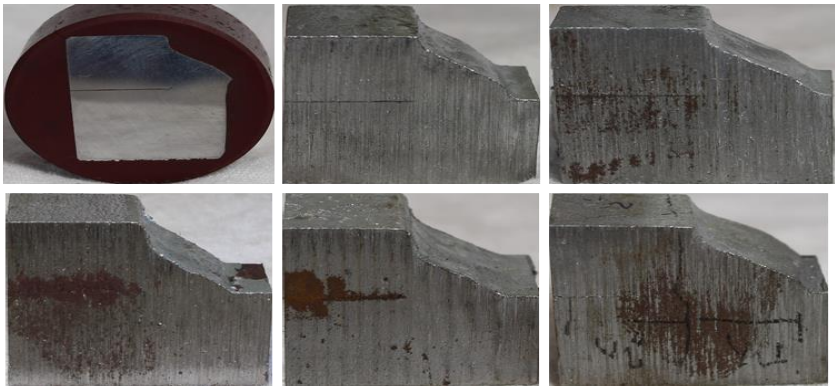


Figure 76: Weld Section for Configuration 2 (upper row) and Configuration 5 (bottom row)

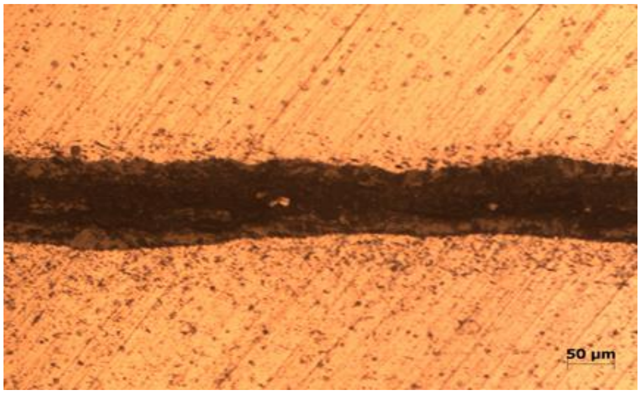


Figure 77: Corrosion of the Contacting Surface of Specimen 1p2

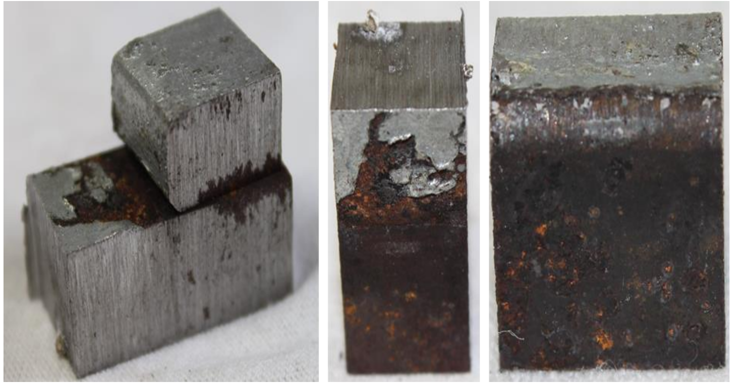


Figure 78: Top Interface of 2p2 (GE Silicone specimen)

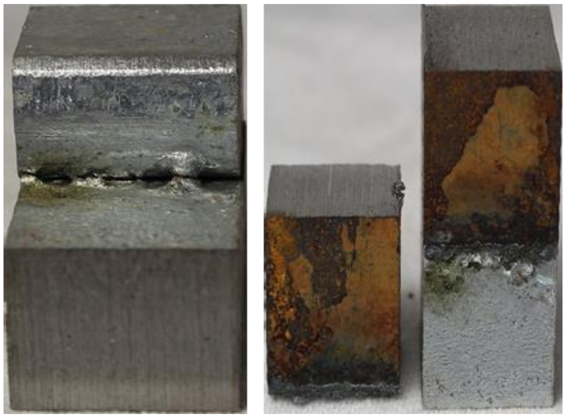


Figure 79: Top Interface of 5p1 (no sealant)

Configuration 3

Figure 80 shows the cross-section of configuration 3 when cutting in half. As can be seen, the gap was filled with zinc, which is the light gray layer between the two plates. Notice the blue and red circles, these were defects of the zinc thick layer. The blue circles show the existence of voids in the coating zinc. These voids could be problematic if located near the steel substrate as they could affect the metallurgical layer between the zinc and the steel. A cut was made in the right blue circle, as was indicated in section 3.3, to further investigate the coatings. Figure 81 shows the cut where the steel interfaces with the zinc in a microscope zoomed view. Clearly, there were plenty of voids in the zinc layer. A zoomed in picture is shown in Figure 82 (left), compared to a typical cracked coating section in the middle (right). Fortunately, the interface between the steel and zinc was uniform along the length of the interface and was not cracked. The second cut, which was located in the bottom of the specimen, is shown in Figure 83. As it can be seen, the zinc layer did not go all the way to the weld. The black material inside the red circle was believed to be a weld slag, and it was the cause of preventing the corner from being coated. It can be concluded that weld slags cannot be removed by the cleaning solutions from the HDG process, thus, it should be removed by alternative methods.

Figure 80: Cross Section of Configuration 3

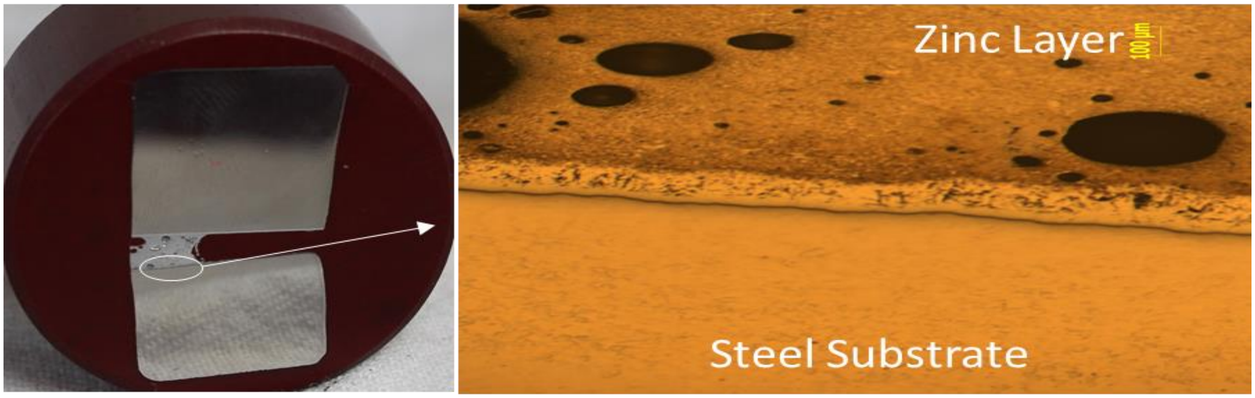


Figure 81: Interface Between the Zinc and the Steel Plates

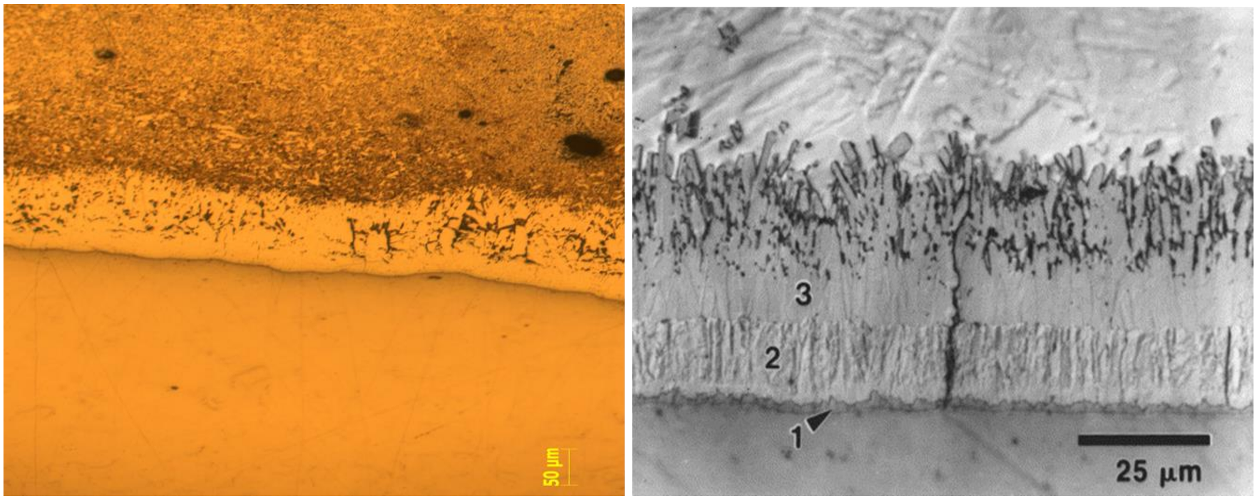


Figure 82: Coating Layer from Configuration 3 (left) and a Cracked Coating Layer (right) (Marder, 2000)

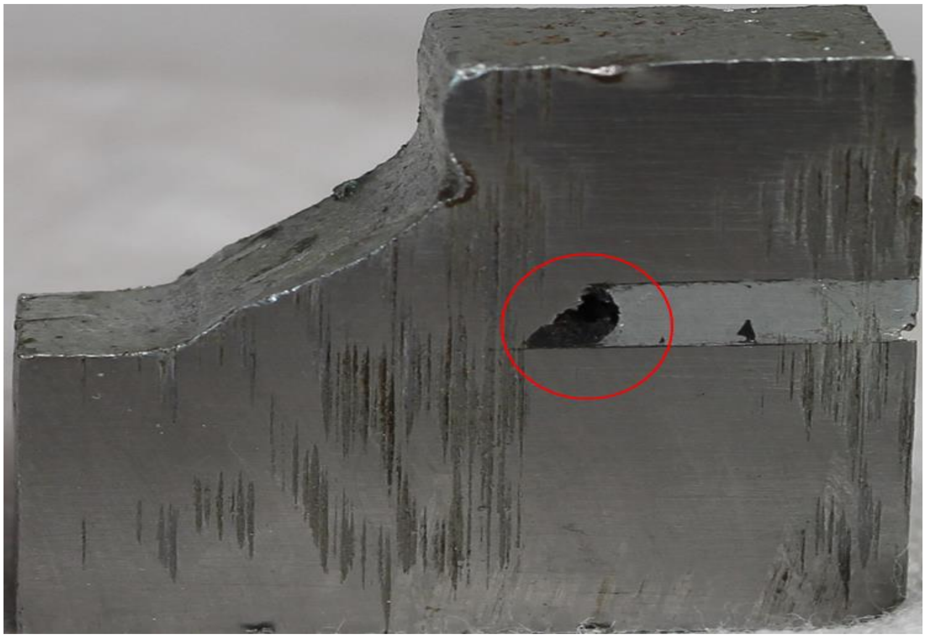


Figure 83: Zinc Coating in the Bottom Interface of the Specimen.

Configuration 4

The cut of configuration 4 resulted in a relatively good coating in the bottom gap, while experienced unexpected poor galvanizing in the upper part, in spite of the fact that the top gap was wider than the bottom gap for this specimen in particular. Figure 84 shows the specimen after removing the overlapped plate. As can be seen, bare spots were concentrated near the top edge. They were probably an indication of insufficient cleaning of the specimen or poor drainage of the zinc. Also, note the green defect spots, these, as mentioned earlier, were probably flux deposits.

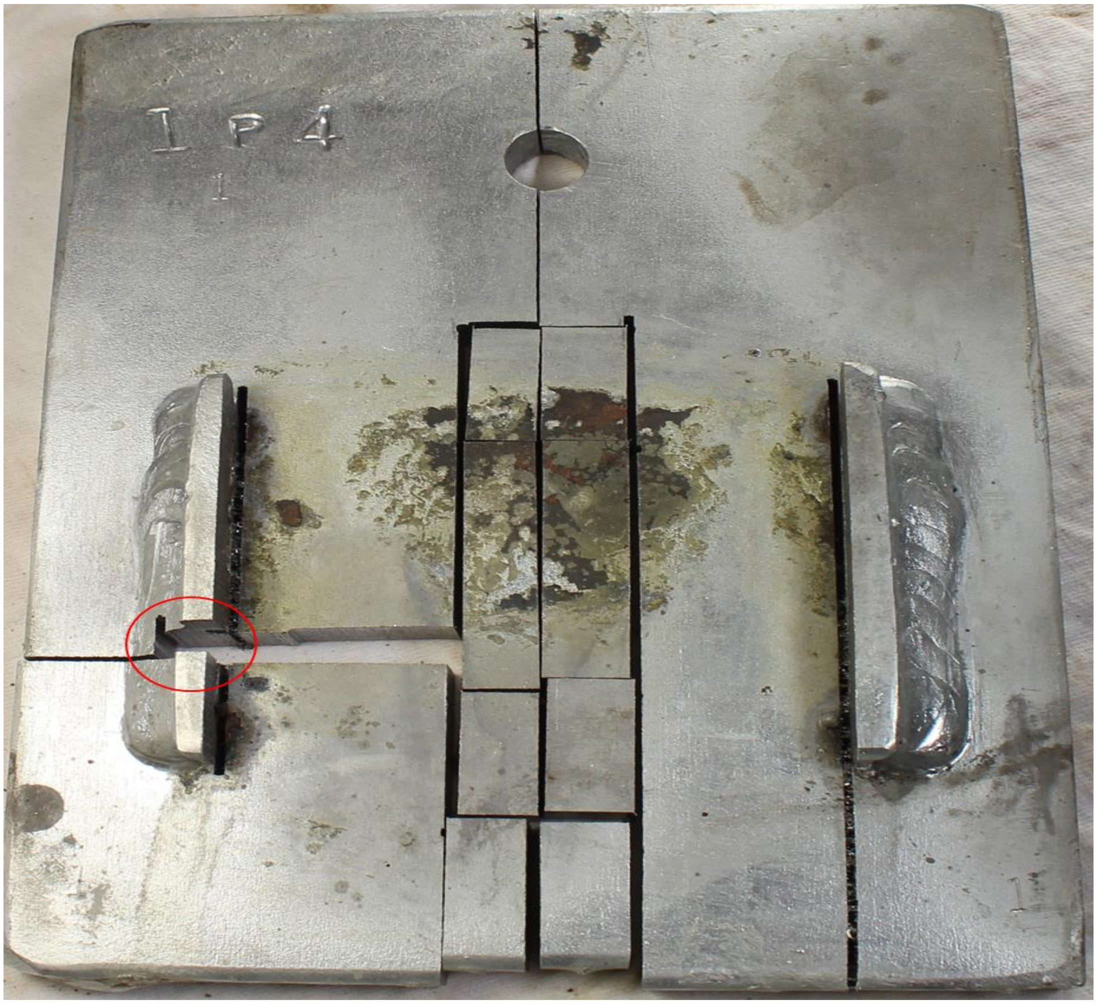


Figure 84: Configuration 4 After Cutting and Removing the Smaller Plate

In addition to the bad quality in the upper part of the overlapping surface, the edges did not experience good coating as well. In an agreement with Configuration 3, weld slags were dominant in these spots. A further investigation was done via microscope in the weld section from this configuration to assess the weld/slag coating interfaces. The red circle from Figure 84 is the weld cut section shown in Figure 85. Two spots were observed where the coating stopped adhering to the steel surface as indicated by the white arrows. This means the upper and the bottom surfaces of the slag were galvanized to a certain extent, then stopped. This forms a new theory, in addition to the slags impeding the corners being galvanized, they did not get galvanized because of the narrow-angle of the weld detail that probably prevented the thick zinc from reaching the corners. The bottom right picture represents the coating layer when zoomed, which seemed to be a good bond coating. In brief, even though Configuration 4 performed well from the corrosion behavior task, this task showed that the overlapping surface had inferior coating quality.

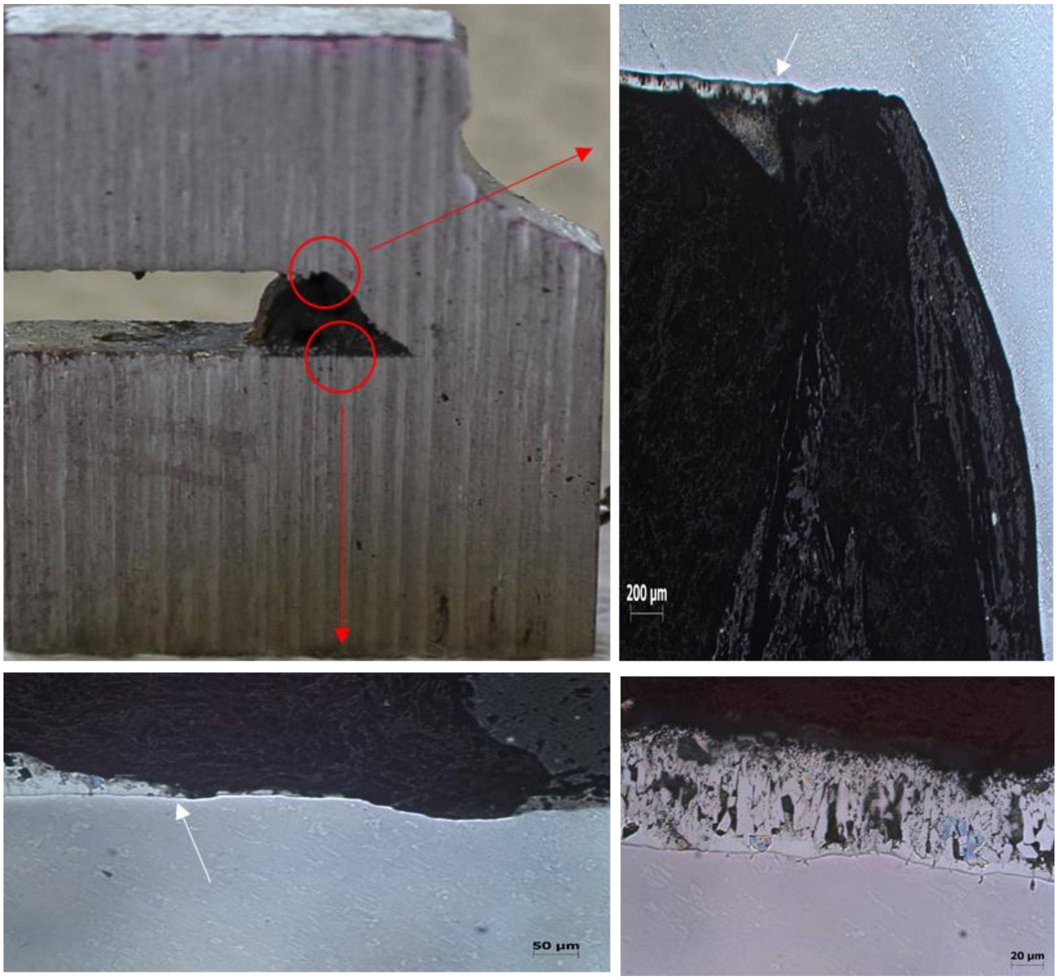


Figure 85: Microscope Analysis in the Weld Section of Configuration 4

Configuration 6

Configuration 6 did not yield satisfactory results in the overlapping surface. Figure 86 shows the removal of the overlapping surface. As seen, the profile of zinc coating over the overlapping surface was undesirable. Bare areas were dominant in the upper part, then reddish/brown rust, and then bad rough coating at the bottom edges. Clearly, the gap in the overlapping surface did not experience proper cleaning and galvanizing. Although it was concluded in task 2 for this configuration that the gap contributed to preventing the rust bleeding occurrence due to the overlapping surface being galvanized, the results shown in this figure contradicts the findings from task 2. This could indicate that the zinc migrated to the bare spots and thus stopped rust leaching out from the overlapping surface for task 2. To prove which outcome is right, more cycles should be done for this configuration.

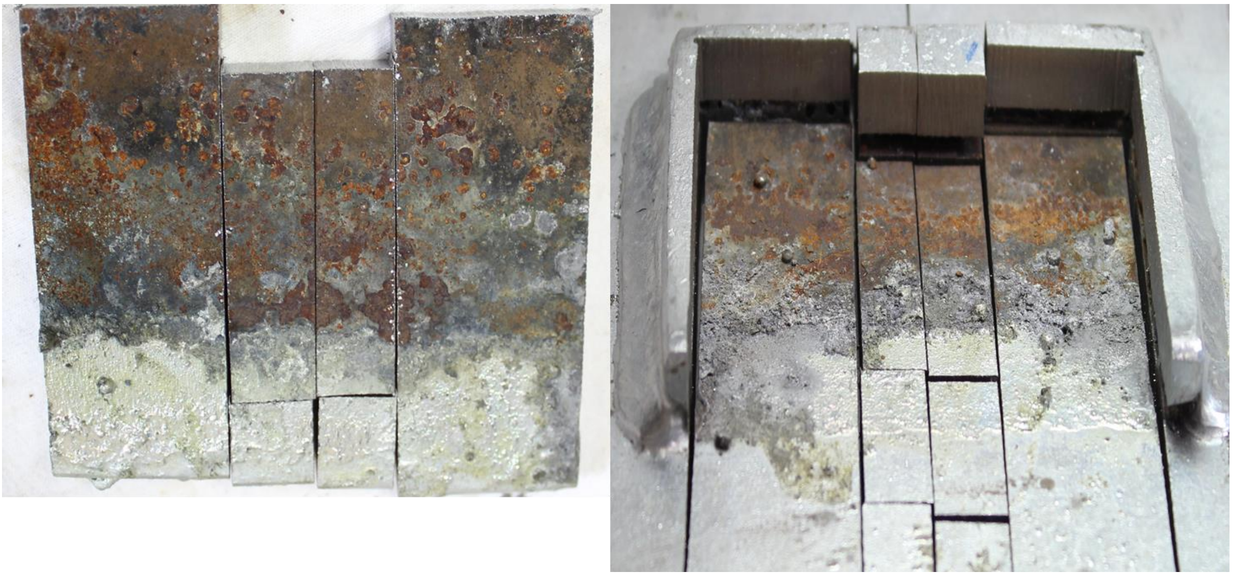


Figure 86: Removal of the Overlapping Small Plate (left) From the Bigger Plate (right) in Configuration 6

Chapter 5: Conclusions

After implementing the tasks, general observations and future recommendations are described below.

Observations

- The results of the test were inconclusive due to the galvanization process. Several surfaces did not have good adhesion with the molten zinc, which made it challenging to determine whether the poor bond was a result of the process (and any impurities on the surface of the steel), or because of the specific details investigated.
- Overall, the seal-welded specimens performed the best.
- The silicone sealants proved to prevent the cleaning solutions from penetrating. However, they did not result in obtaining good galvanized surface and were therefore not desirable.
- Dipping orientation was found to have a significant effect on galvanization quality for specimens which were not fully seal-welded. For example, Configurations 2 and 3, which had gaps facing up, had relatively better finished galvanized surfaces than Configurations 5 and 6, which had gaps facing down. However, both orientations did not result in desirable results.
- A wider gap resulted in a better finished surface than a narrow gap. Configurations 3 and 6, both of which had gaps of 3/32 in., had relatively better surfaces than Configurations 2 and 5.
- The detail which allowed flow-through of the zinc, Configuration 4, resulted in a much better (although still not desirable) galvanized surface than other options. However, upon cutting open the detail, weld slag and other imperfections were found to have prevented good bond with the zinc and were therefore suspect for future corrosion issues.
- Corrosion resistance was best for Configuration 1 with no gaps.
- Configuration 4 had the best corrosion resistance for all specimens with gaps. This was a result of the flow-through of the zinc. After the 40 cycles, the corrosion was relatively uniformly distributed over the surface of the specimen, except for near the edges where leaching from the weld slag was observed.

- Narrow gapped specimens, Configurations 2 and 5, had white rust accumulation at the gaps (open edge). This was believed to be corrosion products that was not consumed due to the slow drying process of moisture and salts.
- Wide gapped specimens, Configurations 3 and 6, had clearly visible white and red concentrated corrosion products near the gaps. This was also due to the relatively slow drying process of moisture and salt adjacent to the gaps compared to the other locations of the specimens.
- None of the specimens with gaps had acceptable galvanized surfaces. Several bare spots were observed inside the overlapping surfaces of Configurations 4 and 6. Configuration 3, which was wide and oriented upwards, had filled with zinc with some voids between the overlapping surface. The three wide gap configurations (3, 4 and 6) had weld slags and impurities at the weld cross-section that did not get cleaned well and thus did not get coated at the corners. For the narrow-gapped configurations (2 and 5), the interface between the two plates was severely damaged, whether sealed or unsealed.
- During the accelerated corrosion test, only one unsealed specimen from Configuration 5 resulted in rust bleeding. The gap, where the rust bleeding occurred, was 0.019 in. Configuration 6, however, did not show any symptoms of rust bleeding even though the overlapped surfaces were not fully galvanized.

Future Research

The following items are suggested to further investigate improved details for galvanization of overlapped steel specimens:

- Since the galvanization process was not successful, weld slag removal and potentially blast cleaning are recommended as they would likely improve the performance of the cleaning solutions before entering the hot-dip galvanizing, especially for Configuration 4. Or, a use of a different welding method to prevent the formation of slags.
- Given that Configuration 4 performed relatively better than the other wide gap configurations for this investigation, more investigations are recommended to be done for

this configuration. These could be constructing larger gap width on top or bottom, different dipping/withdrawing orientation and different welding methods.

- Choosing other types of sealants or masking materials to prevent the penetration of the cleaning solutions may also be of benefit. Since the sealants did not melt off during the cleaning process of HDG even though the melting temperatures were less than the molten zinc temperature bath, more investigations should be done on the sealants. These investigations should be focused on melting temperatures and whether the chemistry of the sealants was affected by the cleaning baths or the zinc bath.
- More space should be used between each of the specimens during the HDG process. This would prevent any bad coating that could occur due to blow out or splash from adjacent specimens.
- More investigations on "zinc migration" from an area of base metal with a good galvanized surface to one without. This should include the migration mechanism, the rate of zinc migration to bare spots, whether there is a difference in the performance or mechanism between open coated steel surfaces versus overlapped, confined, or gap surfaces.
- The use different immersion times in the zinc bath for the same configuration detail, this will maximize the chances of having an optimum result for overlapping surfaces.
- More accelerated corrosion cycles are recommended to be performed, especially for Configurations 5 and 6, to better assess the potential for rust bleeding through the gaps.

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Appendix A: Tables

Table 7: Guidance of the Different Types of Specimens with their Indicated Mark

Configuration	Description	Quantity	Mark	Tasks
1	Control Specimen - Welded in each side	2	1p1	Cut Open
			2p1	Corrosion Ctudy
2	Welded on three sides - with an open edge on top	17	1p2	Cut Open
			2p2	Cut Open - Silicone
			3p2	Cut Open - DAP
			4p2	Corrosion Study
			5p2	Corrosion Study
			6p2	Corrosion Study - Silicone
			7p2	Corrosion Study - Silicone
			8p2	Corrosion Study - DAP
			9p2	Corrosion Study - DAP
			10p2	Nothing - Silicone
			11p2	Degreased & Rinsed - Silicone
			12p2	Degreased, Rinsed, Pickled and Rinsed - Silicone
			13p2	Degreased, Rinsed, Pickled, Rinsed, Fluxed - Silicone
			14p2	Nothing - DAP
			15p2	Degreased & Rinsed - DAP
			16p2	Degreased, Rinsed, Pickled and Rinsed - DAP
			17p2	Degreased, Rinsed, Pickled, Rinsed, Fluxed - DAP
3	Welded on three sides with a specified min. gap of 3/32" on top	3	1p3	Cut Open
			2p3	Corrosion Study
			3p3	Corrosion Study
4	Welded on two sides with a specified min. gap of 3/32"	3	1p4	Cut Open
			2p4	Corrosion Study
			3p4	Corrosion Study
5	Welded on three sides - with an open edge on bottom	17	1p5	Cut Open
			2p5	Cut Open - Silicone
			3p5	Cut Open - DAP
			4p5	Corrosion Study
			5p5	Corrosion Study
			6p5	Corrosion Study - Silicone
			7p5	Corrosion Study - Silicone
			8p5	Corrosion Study - DAP
			9p5	Corrosion Study - DAP
			10p5	Nothing - Silicone
			11p5	Degreased & Rinsed - Silicone
			12p5	Degreased, Rinsed, Pickled and Rinsed - Silicone
			13p5	Degreased, Rinsed, Pickled, Rinsed, Fluxed - Silicone
			14p5	Nothing - DAP
			15p5	Degreased & Rinsed - DAP
			16p5	Degreased, Rinsed, Pickled and Rinsed - DAP
			17p5	Degreased, Rinsed, Pickled, Rinsed, Fluxed - DAP
6	Welded on three sides with a specified min. gap of 3/32" on bottom	3	1p6	Cut Open
			2p6	Corrosion Study
			3p6	Corrosion Study
	Total	45		

*** In the mark section, the first number refers to the number of the specimen, the second number refers to the configuration type. For example, 3p5 means specimen three of configuration 5**

Table 8: Gap Measurement Before Galvanizing

		Edge 1 (left)	Middle	Edge 2 (right)
Configuration	Mark	in.		
2	1p2	<0.0015	<0.0015	0.0015
	2p2	0.007*	<0.0015	<0.0015
	3p2	<0.0015	<0.0015	<0.0015
	4p2	<0.0015	<0.0015	<0.0015
	5p2	<0.0015	<0.0015	<0.0015
	6p2	<0.0015	<0.0015	<0.0015
	7p2	<0.0015	<0.0015	<0.0015
	8p2	<0.0015	<0.0015	<0.0015
	9p2	<0.0015	<0.0015	<0.0015
	10p2	<0.0015	<0.0015	<0.0015
	11p2	<0.0015	<0.0015	<0.0015
	12p2	<0.0015	<0.0015	<0.0015
	13p2	<0.0015	<0.0015	<0.0015
	14p2	<0.0015	<0.0015	<0.0015
	15p2	<0.0015	<0.0015	<0.0015
	16p2	<0.0015	<0.0015	<0.0015
	17p2	<0.0015	<0.0015	<0.0015
3	1p3	0.1350	0.1230	0.1190
	2p3	0.0930	0.0930	0.0990
	3p3	0.1300	0.1270	0.1340
4*	1p4 (bottom)	0.1270	0.1260	0.1260
	1p4 (top)	0.1480	0.1430	0.1430
	2p4 (bottom)	0.1860	0.1820	0.1830
	2p4 (top)	0.1100	0.1070	0.1070
	3p4 (bottom)	0.1320	0.1360	0.1450
	3p4 (top)	0.1380	0.1310	0.1310
5	1p5	<0.0015	<0.0015	<0.0015
	2p5	<0.0015	<0.0015	<0.0015
	3p5	0.0660	0.0740	0.0740
	4p5	<0.0015	<0.0015	<0.0015
	5p5	0.0190	<0.0015	<0.0015
	6p5	<0.0015	<0.0015	<0.0015
	7p5	<0.0015	<0.0015	<0.0015
	8p5	<0.0015	<0.0015	<0.0015
	9p5	<0.0015	<0.0015	<0.0015
	10p5	<0.0015	<0.0015	<0.0015
	11p5	<0.0015	<0.0015	<0.0015
	12p5	<0.0015	<0.0015	<0.0015
	13p5	<0.0015	<0.0015	<0.0015
	14p5	<0.0015	<0.0015	<0.0015
	15p5	<0.0015	<0.0015	<0.0015
	16p5	<0.0015	<0.0015	<0.0015
	17p5	<0.0015	<0.0015	<0.0015
6	1p6	0.1470	0.1460	0.1470
	2p6	0.1370	0.1370	0.1390
	3p6	0.1510	0.1470	0.1470

***Since configuration 4 has two open gaps, bottom and top correspond to the gap location, where the top is the edge gap near the ½ in. hole, the bottom edge is the far side**

Appendix B: Environmental Chamber

The alternating wetting and drying of the chamber are described briefly below. All the information is obtained from the Installation Operation Maintenance Manual ZP-Series as well as from a colleague who has worked on the chamber previously.

B.1. Chamber Operation

Humidity Stage:

Air and water moisturize the chamber. This is done by a boiler heating water to generate steam. Water is pumped from a recirculating water reservoir, which is a filled water reservoir. After providing the necessary humidity, the condensed water from the steam is ultimately recirculated back to the reservoir. Through this journey, the water must be filtered first by a demineralizer filter as it removes impurities from the corrosion products of the specimens as they might corrode the components of the chamber if the water is not cleaned. It was found that cleaning the interior of the chamber daily, where moisture and corrosion products from the specimens are collected, increase the serviceability life of the filters since these are recirculated back to the reservoir (Groshek, 2017). In addition to cleaning the chamber, filling the reservoir with a de-ionized water maximize the life of the demineralization filters. Figure 87 shows the chamber and some components.

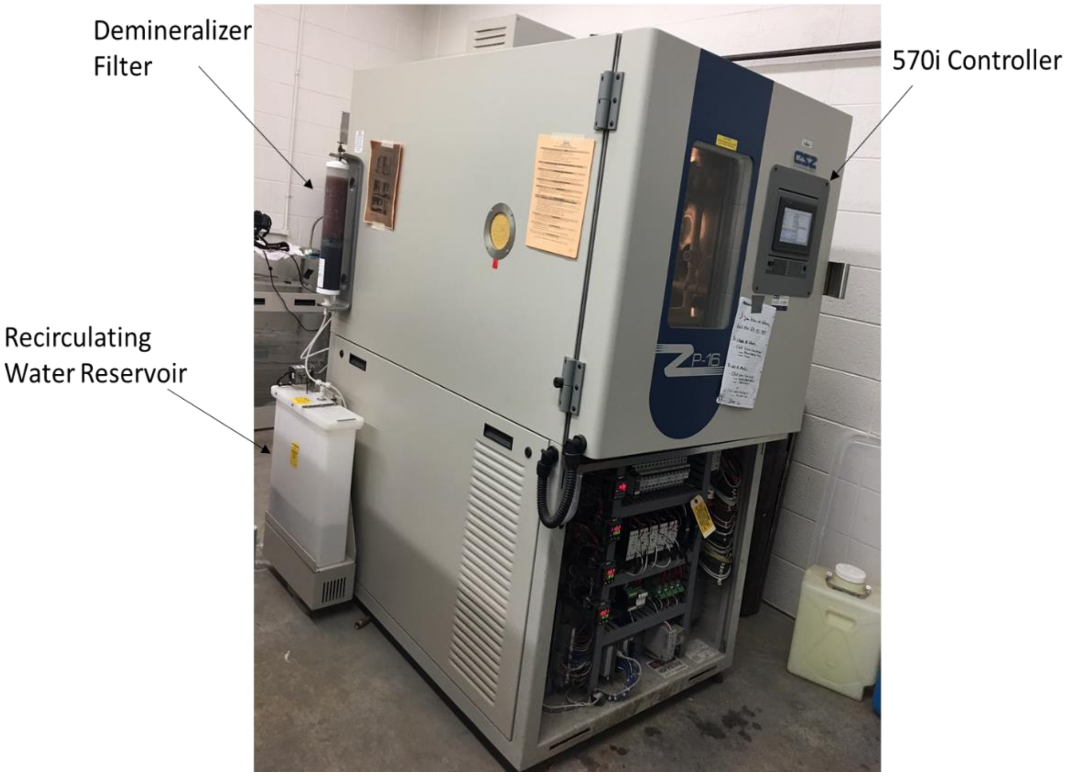

Figure 87: ZP-16 Chamber with Various Components

Dry Stage

There are no components, maintenance, or manual insertion, except from the controller, needed for the drying stage as the chamber is able to produce a temperature ranging from -30°F to +375°F.

B.2. Chamber Screen Controller

The screen controller, EZT-570i, indicated by the previous figure, controls the humidity and temperature. This can be done either manually or automatically. The automation was used to operate cycles. A cycle is 24 hours of operation, where 15 minutes of the 24 hours are external operation of immersing the specimens into the salt solutions and the rest are automated in the chamber.

The screen controller has many important features. One of them is providing a graph representing the temperature and humidity over time. This clarifies the alternating wetting and drying visually. Figure 88 and Figure 89 provide actual readings of temperature and relative humidity of two cycles during the testing, it should be noted that the graphs are not to scale. Before detailing them, some programming chamber concepts must be introduced. For this study, all the events were done automatically, using a term called “profile”. A profile consists of multiple steps that provide the events needed (temperature or humidity) to achieve a cycle. Each step is either called a ramp step or a soak step. A ramp step is used when the event is shifting from one stage to another. A soak step is when the event is constant. Also, the screen provides actual readings using sensors, which are called process variables “PV”, and provides the set values which the PV are projected to, which are called set-points or “SP”. In other words, SP is the value that the user inserts, whereas PV is the actual adjusting value to achieve the user’s input.

Back to the graphs, as can be seen, stage 1 represents the humidity stage (RH is 50% with a temperature of 50°C for 6 hours), which is a soak step since the temperature and RH are constant for the 6 hours. Then, a shift from stage 1 to stage 2, which is a shift from the humidity stage to the drying stage (60°C with 100% for 17 hours and 45 minutes), must occur. Since the chamber is incapable of shifting between two points at once, a ramp step is used to gradually transition between two events (Groshek, 2017). The arbitrary movement of the PV of the temperature and the humidity between the two stages as shown in both figures is due to the salt application. Since the specimens were taken manually from the chamber to apply the salt stage, opening the chamber’s interior to the atmosphere decreases the temperature and the humidity of the chamber significantly. Lastly to complete a cycle, after the drying stage, the chamber shifts back to the humidity stage. Because there is no salt application between the drying and the humidity shift, notice the gradual shift in both the PV and SP without abrupt changes.

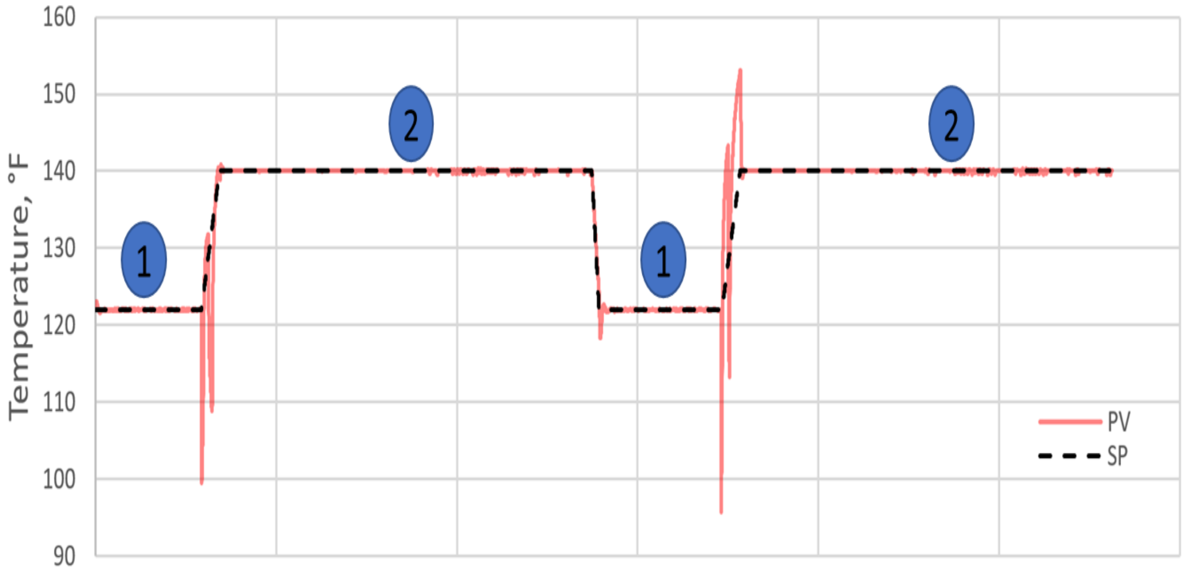

Figure 88: Altering Events of Chamber Temperature

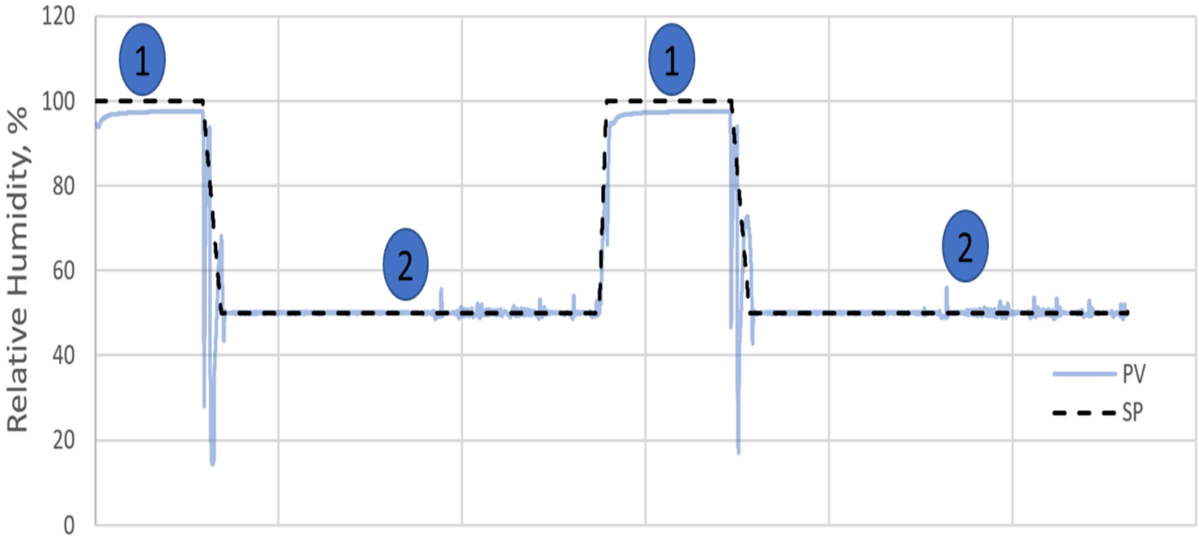

Figure 89: Altering Events of Chamber Humidity

Appendix C: Salt Solution Preparation

Reagent Water

The initial step of preparing the salt solution is to have a reagent purified water. The SAE J2334 requires using type IV of ASTM D1193 water. This entails having a resistivity of water at least .2 $M\Omega.cm$ with a maximum conductivity of 5 $\mu s/cm$, and a pH level between 5.0 and 8.0. To meet this specification, water was obtained from Barnstead filters. The filters provide direct resistivity readings on the screen, as shown in Figure 90. To verify the readings from the filters, a conductivity meter was used as well. Likewise, a pH meter was used to record the measurements.

Table 9 shows the records during the testing. The fluctuation of the resistivity values indicates the consumption of the deionizing filters and that a replacement is needed.

Figure 90: Barnstead Filters

Table 9: Records of pH and Resistivity of the Regent Water

Cycles	pH	Resistivity ($M\Omega$-cm) (Average)
10	7.8	10
19	7.75	5
27	7.72	0.4
34	7.88	1.84
38	7.72	17
40	7.7	16.3

Salt Solution

After creating the reagent water in a soaking container, chemicals were added creating the salt solution. A total of 60 liters of regent water used to achieve the required mass concentrations of the accelerated test indicated in Table 4, referenced in Chapter 3. The process simply includes measuring the mass of the chemicals, pouring them in the soaking container, and stirring them firmly. To insure a complete dissolving of the chemical particles in the water, 59 liters were first created and mixed with sodium chloride and calcium chloride, to the left, 1 liter of water with sodium bicarbonate was created separately on a small container and then added to the 59 liters. This separation is recommended by the SAE J2334 in order to eliminate any formation of insoluble material.

The salt solution requires certain specifications and measurements after adding the chemicals. The pH levels should maintain the same range, per ASTM D1193. However, the conductivity now changed to be between $10 - 12\ \mu s/cm$ per SAE J2334. Since this research used 5.0% concentration sodium chloride as opposed to the .5% per SAE J2334, the conductivity values obtained for the solution far exceeded this range. Given the 10x factor modification, the projected acceptable limit is assumed to be around 100 $\mu s/cm$. Table 10 shows the measurements taken throughout the testing.

Table 10: Records of pH and Conductivity of the Salt Solution

Cycles	pH	Conductivity (µS/cm)
10	7.4	110.8
19	7.5	112.8
27	7.42	108.6
34	7.24	106.8
38	7.22	103.6
40	7.3	90

The records were taken in each iteration of creating the solution. Although the salt solution is recommended to be replaced on a weekly basis depending on the contaminants, sometimes it takes longer or shorter than this period, as indicated by the cycles in the tables. This is explained by the amount of contaminants observed, as well as the readings done in the middle of testing to insure the values were under the acceptable limit.

Appendix D: Polishing and Grinding

Polishing and grinding were done with the help from the Material Science and Engineering (MSE) department. A colleague from the MSE department demonstrated the process and gave insightful knowledge regarding the equipment. There are three major steps to polish and grind the specimens: mounting the press, grinding, and polishing.

The first step involves mounting the sample with the aid of the hot press. The goal of this step is to facilitate the handling of the specimen for the following grinding and polishing steps by pressing a powder by applying heat and pressure to form a solid-state disc to carry the specimen. Figure 91 shows a picture of the machine and a zoomed picture showing the place where the specimen is placed. It is an automated machine and goes through three basic stages.

Figure 91: Mounting Press Machine

Before describing the stages, it should be noted the machine limits the size of the specimen. As seen in the same Figure 91, this specimen must fit the chamber's circular piston. Also, the face of the area that is investigated through the microscopic must face down toward the machine. Figure 92 shows the powder and how it is poured on top of the specimen, that is, after pressing the specimen inside the machine. The amount of powder poured is a function of the specimens' thickness.

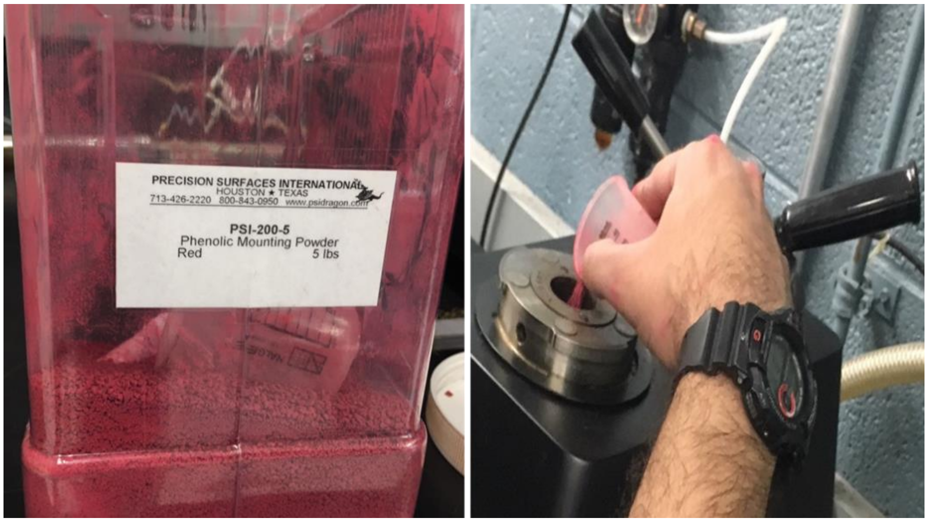

Figure 92: Phenolic Mounting Powder (left) Poured Inside the Machine on Top of the Specimen (right)

Back to the stages, the goal of this process is to press the powder to make it in a solid state. This is done by first preheating the chamber to around 100°C, which takes about 4 minutes. The purpose of this step is to make the powder softer and to facilitate the chemical reaction and sintering. Next, the temperature is increased to around 160°C and pressure is applied to around 3700 psi. This step takes between 5–7 minutes. Lastly, a cool down process is done for around 6 minutes. The result is shown in Figure 93.

Figure 93: Specimen in a Solid Disc After Heating the Powder

Because the mounting press enforces pressure and heat, specimens that contain sharp edges, where stress is concentrated, might cause cracks to the pressed powder polymer. Thus, a preventative measure is sometimes done before the mounting press is utilized, which involves rounding up the edges. This is done by holding the specimen against a fast-moving belt machine, as shown in Figure 94. This step takes about 2 minutes. Also, sometimes water rinsing is used to smoothen the contact between the moving belt and the specimen.

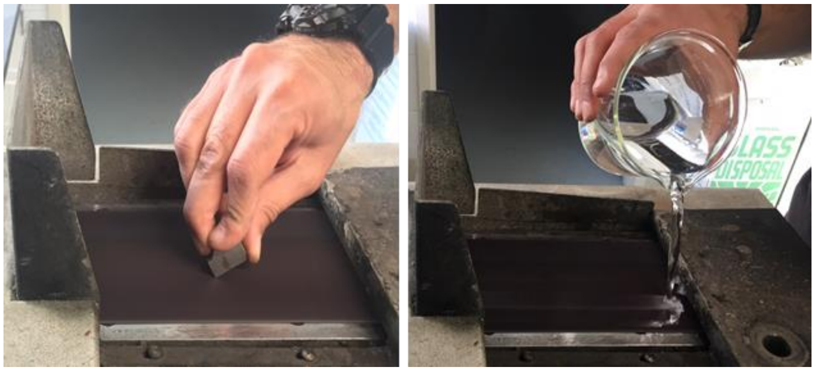

Figure 94: Grinding Belt

The second step is the grinding step. This is done by using a roll grinder as shown in Figure 95 . These grinders consist of different size of grits (sand paper). As the number of the grit size increases, the finer the abrasive grain used. The process of grinding is done manually by simply applying enough force to move the specimen by hand back and forth for around 50 rounds in each grit, starting from the lowest number grit to the highest. This is done to insure a smooth removal of the material. The MSE lab has four grit sizes: 240, 320, 400, and 600. When moving the mounted specimen from one grit to another, it is rotated 90° degrees each time. This is to insure having a finished flat surface, which is an important characteristic to have when looking at the specimen through microscope. Also, during grinding, water is applied to the grits to insure a smooth contact between the specimen and the grit.

Figure 95: Roll Grinder Machine

The last stage before looking through the microscope is the grinder polisher. The premise of this machine is applying force and rotation to the specimen to rub the face of it against a polishing cloth covered with a chemical suspension to remove scratches. The force and rotation is exerted by a rod attached to an unseen spring from in the machine. The polishing cloth to which the specimen is rubbed against is cut to a circular shape to fit in a circular plastic container. Figure 96 shows the rod on top of the paige color polishing cloth and there is a circular glass underneath the polishing cloth to resist the force exerted on it.

Figure 96: Grinder Roller (left) and Container with Polishing Cloth (right)

Unlike the other machines, this machine requires experience and knowledge to obtain satisfactory results via the microscope. This is due to the fact that the machine has variables that depend on the type of specimen used. These variables can be divided into machine variables and external variables. The machine variables are the force, speed, and time applied to the specimen, and can be controlled through the machine. These factors depend on the specimen being used. For example, polishing steel requires different force applied than polishing a titanium sample; having too much force may result in poor visualization via the microscope. To the left, the external factors are the use of a polishing cloth and the type of chemical polishing suspension used. Different polishing cloths have different microns and surfaces, thus they affect the scratches on the surface. Fortunately, the colleague who helped with this task provided significant tips and techniques to obtain fine results.

Three steps were performed for polishing in this project, as shown in Table 11. Time and polishing suspensions were the only variables changing. Since only steel specimens were used, the only variable changed within the machine is time. Regarding the polishing suspension, a high number of micron suspension should be used first and then descending to a small number of microns. This is to insure the removal of the scratches on the surface from the coarse to fine grains. The amount of the polishing suspension poured should be enough to cover the surface of the polishing cloth. And, whenever the liquid is dried, and the polishing cloth color can be seen, adding more polishing suspension is necessary. Note that each step requires a different polishing cloth. In other words, three polishing cloths were used for polishing a sample. Figure 97 shows one of the suspension liquids used along with a sample in the machine. Note that to attach the rod to the resin, a hole must be drilled in the center of it.

Table 11: Summarized Steps for Polishing

Steps	Force (lb.)	Speed (rpm)	Time (minutes)	Polishing Suspension
1	5	40	5	9.5-micron aluminum oxide
2	5	40	3	3.0-micron aluminum oxide
3	5	40	5	.04-colloidal silica

Figure 97: Aluminum Suspension (left) and a Sample in Process (right)

To remove any excessive polishing suspension between each step, as this may distribute the uniformity of the surface, ultrasonic cleaning is used between the steps. As shown in Figure 98, the device vibrates the water in a small container to clean the surface from the polishing suspension and prepare it for the next step. Also, for the last step, the .04-colloidal silica polisher, ethanol was added with water in the device to neutralize any chemical reaction from the surface.

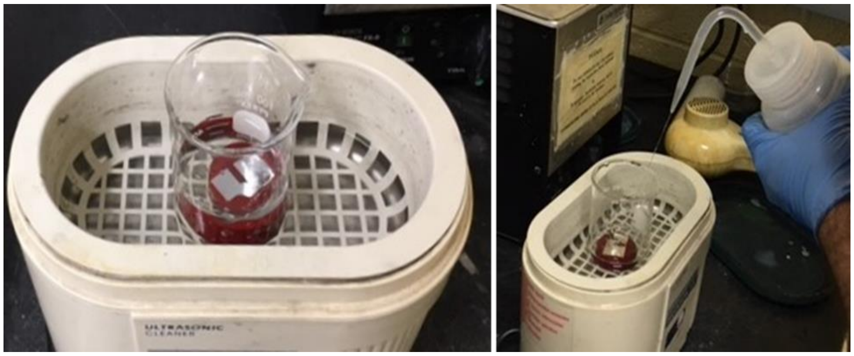

Figure 98: Ultrasonic Cleaner

Appendix E: Cost Estimate

E.1. Contacting Surface Lengths

$$l_4 = \sqrt{5^2 + 5^2} = 7.07\ in$$

$$l_4 = l_2 = 7.07\ in$$

$$l_3 = l_2 - 5\ in = 2.07\ in$$

E.2. Deposit Material and Time Calculations

Welding Rate → 1 ft = 99 s → $0.049\,\frac{in^3}{in}$

➔ $\frac{1\,ft}{99\,s} = 0.0101\,\frac{ft}{s}$

Time required for one single overlapping surface

4 edges → $\dfrac{(5 + 7.07 + 7.07 + 2.07)in\,(\frac{1\,ft}{12\,in})}{0.0101\frac{ft}{s}} = 175\text{ s}$

3 edges → $\dfrac{(5 + 7.07 + 2.07)in\,(\frac{1\,ft}{12\,in})}{0.0101\frac{ft}{s}} = 116.65\text{ s}$

2 edges → $\dfrac{(7.07 + 2.07)in\,(\frac{1\,ft}{12\,in})}{0.0101\frac{ft}{s}} = 75.4\text{ s}$

Deposited material for one single overlapping surface

4 edges → $0.049\,\frac{in^3}{in}(21.21\ in) = 1.039\ in^3$

3 edges → $0.049\,\frac{in^3}{in}(14.14\ in) = 0.693\ in^3$

2 edges → $0.049\,\frac{in^3}{in}(9.14\ in) = 0.447\ in^3$

Total time and deposited material for 164 K-frames with four contacting surfaces in each frame

Total time:

4 edges → (164)(4)(175 s) = 114,800 s

3 edges → (164)(4)(116.65 s) = 76,522.4 s

2 edges → (164)(4)(75.4 s) = 49,462.4 s

Total deposited material:

4 edges → (164)(4)(1.039 in^3) = 681.584 in^3

3 edges → (164)(4) (0.693 in^3) = 454.608 in^3

2 edges → (164)(4) (0.447 in^3) = 293.232 in^3

Conversions

1 minute = 60 seconds

1 hour = 60 minutes

1 ft = 12 in.