

Corrosion Test of the Steel Plate in a WJ-8 Fastener for High Speed Rail

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Abstract

It was found that the steel plate in the composite plate in the WJ-8 fastener used in high speed rail is rusty. The objective of this study is to test the zinc coating of the steel plate. A literature review was conducted to identify the zinc coating techniques, and the companies that can provide different coating service was identified. A salt fog chamber was built that was in compliance with the ANSI B117 code, and the steel plates that were coated by the identified companies were tested using the salt fog chamber. The results indicated that the coating technique that had the best performance in preventing corrosion was the Greenkote plates with passivation. The galvanized option had the roughest coating layer, and it was the most reactive in the salt water solution. This makes it non-ideal for the dynamic rail environment because the increased friction of the plate could damage the supports, especially during extreme temperatures that would cause the rail to expand or contract. Greenkote with Phosphate and ArmorGalv also provided increased corrosion prevention with a smooth, strong finish, but it had more rust on the surface area than the Greenkote with ELU passivation. The ArmorGalv sample had more rust on the surface area than the Greenkote samples. This may not be a weakness in the ArmorGalv process; rather, it likely was the result of this particular sample not having the added protection of a colored coating.

Keywords

Steel Plate for High Speed Rail Fastening, Steel Corrosion, Zinc Coating, Salt-Fog Chamber

1. Introduction

In railroad tracks, fasteners are important equipment because they hold the rail

upright to the tie, which allows the wheel to roll over it safely. The interaction between the fasteners and the track structure on the bridge is different from that for track on the ground because the bridge structure expands and contracts with weather while the ground does not. The fasteners on the bridge should be able to move with the bridge as it moves, leaving the rail (usually continuous welded rail) on the bridge unstrained. If the rail is strained longitudinally from the fasteners due to the movement of bridge, the rail would be broken or buckled, and this is a major safety issue for the railroad.

Figure 1 shows a WJ-8 fastener used in China that can be used in track on ground where the pink rubber plate under the rail absorbs most of the vibration. On bridges that are used for high speed rail, a steel plate is embedded into the rubber plate (see **Figure 2**), and it is called the composite tie plate. This steel plate has a small resistance that allows the fastener, tie, and track structure to move with the bridge structure. Thus, this fastener is known as the small resistance fastener.

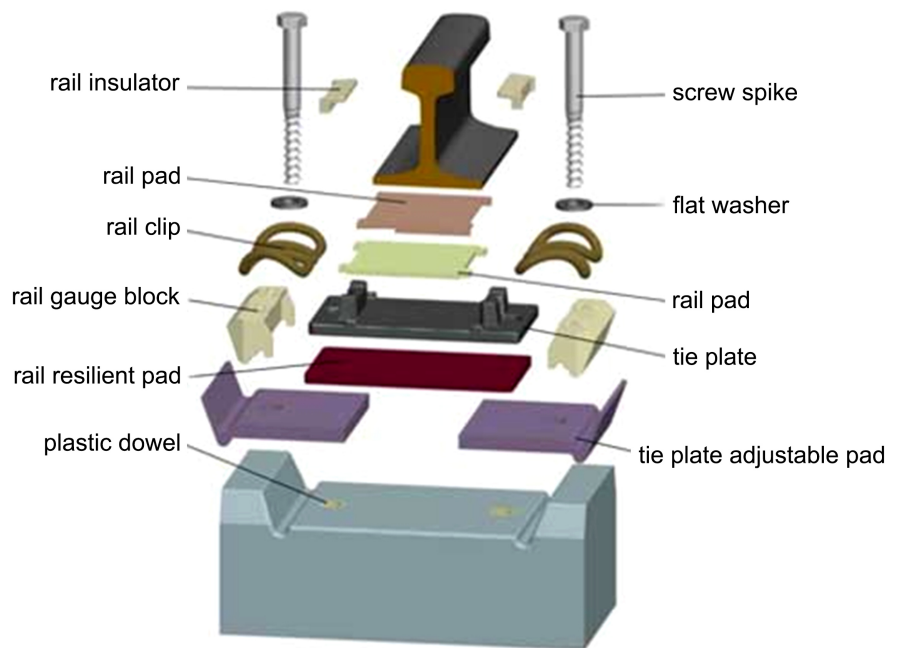


Figure 1. WJ-8 fastener used in China.

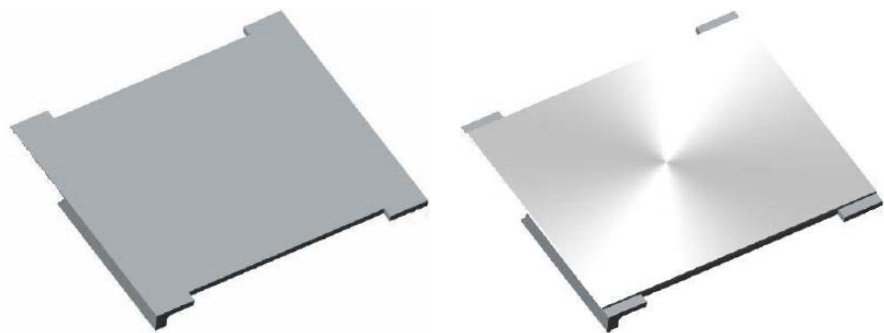


Figure 2. Rubber plate without a steel plate (left) and with a steel plate (right).

The steel plate in the composite plate is rusty because there is direct contact between the steel plate and the rail (see **Figure 3**). The rust is caused by the two materials that have different chemical properties. Zhang *et al.* [1] proposed three solutions for this issue, *i.e.*, 1) separating the two materials, 2) providing a material that can absorb the chemical interaction, or 3) developing a plate with composite materials [2]. In our study, we propose to use a zinc coating that can reduce the chemical interaction and increase the durability of the composite plate.

In the exterior environment, ferrous metals spontaneously become corroded. This oxidation is a thermodynamic process in which the metal attains a lower energy state by reacting with oxygen. Ferrous metals are found in nature as oxides inside ores. Their natural energy state is to be bonded with oxygen, and manufacturing processes are used to smelt ferrous metals and refine them to enhance their purity. This journey from oxide to metal requires that energy be introduced to the material, leaving the pure metal at a higher energy state than it was when it was part of an oxide. When this higher energy state metal interacts with air that contains moisture, oxidation will occur. The aim of most corrosion protection techniques is to slow the rate of corrosion with the ideal case being to stop it altogether.

Corrosion is an electrochemical process that takes place when a full circuit is completed with the connection of an anode and cathode. The anode is the site of the corrosion process where the metal is weakened by the oxidation reaction that occurs. The reduction reaction occurs at the cathode. This process is sped up by the number of electrical connections between the cathode and the anode and the presence of electrolytes. The different kinds of electrolytes in the railway environment are soil, water, and salts. Electrolytes speed up the process by promoting oxygen to react with the metal. In snowy areas, this is even worse because salt is used to melt the snow, and this adds to the presence of electrolytes, which increases the amount of hydroxide ions in the system.



Figure 3. Steel plate without rust and with rust.

The idea of using zinc to protect the substrate is based on the fact that zinc will react with oxygen more readily than iron does. This is because zinc has a higher electronegativity than iron does. Although there are other metals that are higher on the reactivity scale than zinc, zinc provides long standing service in its ability to protect metals from corrosion. Aluminum also is present in some coating technologies. In some applications, the zinc oxide layer doubles as a physical barrier that blocks the interaction between the deeper layers of the coating and the substrate.

The impact of developing an anti-corrosion steel plate is very significant. With an improved steel plate, the maintenance work on the track would be reduced, and the resulting costs in maintaining the track would be saved. It is noted that the corroded steel plates influence the function of other track elements. By improving the steel plate, the cost of maintaining other track elements can be reduced as well.

The objective of this study is to test the zinc coating of the steel plate in the WJ-8 fastener in the high speed rail system. A literature review was conducted to identify the zinc coating techniques, and contacts were made with companies to get the steel plates coated with zinc with different coating techniques. In compliance with the ANSI B117 code, these coated steel plates are tested using a salt fog chamber. The results of the tests are analyzed, and conclusions and recommendations are made.

2. Literature Review: Zinc Coating Techniques

There are several coating techniques available, for example Hot Dip Galvanization and Thermally Diffused Coatings including Greenkote and ArmorGalv. In the Hot Dip Galvanizing process, metal samples are submerged in a molten zinc bath. While in the bath, zinc will bond to the steel substrate to form an alloyed layer followed by an outer layer of pure zinc. The surface hardness of galvanized products is lower than that of the steel substrate because the outer layer is composed of pure zinc. But, having the substrate entirely covered may be beneficial in efforts to protect the substrate from the environment.

Thermally Diffused Coatings refer to a category of coatings that find their inspiration from the Sherardizing process that was first developed around the year 1900. This process involves placing samples inside a rotating drum with micron-scale zinc granules. The drum is heated and rotated for a period of time allowing the zinc powder to alloy into the steel. Ideally, the zinc powders will not melt during this process, which would cause the powders to coalesce and diminish the quality of the alloy. Since the process requires temperatures close to the melting point of zinc, inert filler usually is added to attempt to keep the granules apart. A Soviet patent (SU 1534091) describes a treatment that provides a surface layer on the granules that also prevents the granules from coalescing. Thermal Diffusion Coating typically is applicable for the smaller parts, but, ultimately, the part sizes are limited by the size of the rotating drum. Typically, thermally dif-

fused coatings techniques are patented as Greenkote and ArmorGalv.

The Greenkote technology includes the addition of aluminum powder into the mixture. The addition of aluminum may help the coating due to its self-passivating nature. There are three phases of the coating. The first two phases are primarily composed of zinc and iron alloying. The outer phase has the highest composition of aluminum. The aluminum serves as an additional protection to the coating. Aluminum will quickly form an oxide layer, and the benefit of aluminum oxide is that it may form a watertight layer. Since there isn't a continuous covering of aluminum (or aluminum oxide) and the oxide does not always form a watertight cover, the utility of aluminum may be further separation between the environment and the substrate, and these results in extending the service life of the component. Two samples were coated from Greenkote. One sample has a top coat of zinc phosphate, after which it is sealed with sodium silicate. The second sample is chemically passivized, and it also is sealed with sodium silicate.

The ArmorGalv technology focuses on the appearance of the coating, *i.e.*, the ability to color the coating to achieve better aesthetics. Different coating colors are created by the addition of transitional metal oxide powders (titanium dioxide, cobalt oxide, chromium oxide, and others). It has been claimed that the addition of these oxides that contribute to the coloration also contribute to increased corrosion resistance, *i.e.*, by as much as 50% - 100% above the resistance of uncolored coatings (most likely uncolored coatings of the same process). In this study, the coating received from the ArmorGalv distributor, Agritek, was coated uncolored. **Table 1** below shows comparisons between the coating techniques.

Note that the modern coatings mentioned fall under a broad category labeled "Thermally Diffused Coatings", and they are achieved largely by alloying zinc into the metal substrate. This alloying process is claimed to provide a much higher performance coating compared to conventional coatings. Conventional coatings refer to old techniques in which most of the coating is composed of a pure zinc layer on the exterior of the substrate, and there may or may not be a very thin layer of zinc alloying into the substrate, such as galvanizing, electropainting, zinc paint, etc. [3]-[9].

Table 1. Costing properties.

	Stainless Steel	Hot Dip Galvanize	Thermal Diffusion Coating	
			Greenkote	ArmorGalv
Surface hardness (DPN)	200 - 300	70	400 - 550	316
Coating Thickness (microns)	n/a	75 - 100	5 - 100	15 - 120
Zn Zine (micro)	n/a	n/a	75	20 - 60
Coating Temp (°C)	n/a	>420	370 - 450	380 - 420
Advertised Salt Spray (B117) Times (hrs)	n/a	<150	700	800 - 3000

3. Methodology

In this study, the investigation of the impact of zinc coating on steel plate corrosion started with purchasing the steel plate of WJ-8 Fastener that are popular in China. The companies in the U.S. that can coat the steel plate using different coating techniques were identified. After the identification, the purchased steel plates were shipped to these companies and they shipped the coated steel plate to UNLV for the testing. At the same time, a salt-fog chamber was built that can satisfy the need of testing multiple steel plates together. With the coated steel plates and the salt-fog chamber built, multiple steel plates were placed in the salt-fog chamber by following ASTM procedure. After the test, the steel plates were taken out of the chamber and their rusty conditions were reviewed for evaluation. The rusty conditions were analyzed based on measuring the size of rusty on the steel plates. This methodology is presented in **Figure 4**.

4. Salt-Fog Chamber

A salt-fog chamber was built in compliance with the standards defined in ASTM B117. The salt-fog chamber that was constructed is to provide an enclosure allowing for environmental isolation of tested samples which are to be exposed to 5% by weight salt-water solution at 100°F under continuous loading with down time and exposure of the tested samples to the outside environment without solution to be limited to one 1 hour per day. In addition, within the enclosure, the tested samples are to be oriented at 30° from the vertical position to allow the samples to be exposed to the corrosion solution without allowing the solution to settle and pool on the samples. From the defined constraints within the scope of senior design with cost analysis, the salt-fog chamber was designed, constructed,

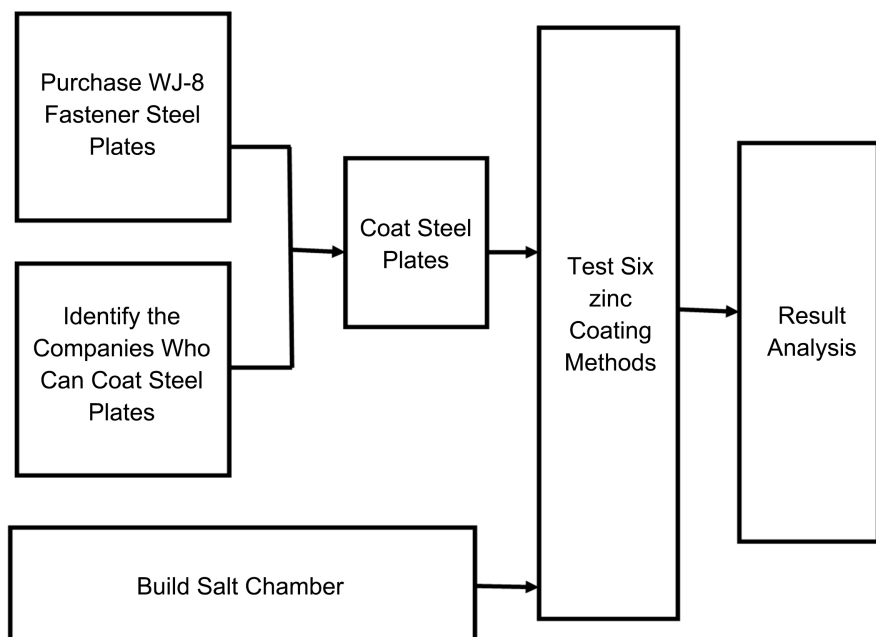


Figure 4. Methodology flow chart.

and operated for a period of 915 hours to maximize the exposure time of the samples to the allowed time period of senior design. The resulting final constructed design is shown in **Figure 5**. The salt-fog chamber is composed of two systems, *i.e.*, a salt-water solution system and an air system. Both systems are housed on an industrial strength 4' × 5' shelving structure table.

The shelving structure provides support to hold all equipment along with external weather environments. The size of the structure allows space for the reservoir on the pedestal, which contains all small equipment and air controls, the heat source, and the environment chamber, the size of which is 3' × 4' to allow space for the sample support structures. The only exception is the air compressor, which is housed in an external rack system such that, in the case of failure during continuous operation, the rest of the system is isolated and not affected.

The solution system was constructed such that solutions flow by means of gravitation and head pressure from a high point to a low point. This allows the flow to be maintained without the use of a pump that would be corroded by the salt-water solution. The solution system is composed of a 16-gallon reservoir on an 18" high pedestal box as the high point that holds the premade 5% by weight salt-water solution. The solution flows from the reservoir and goes through an isolation ball valve at the base of the reservoir to an intermediary container. The container sits on a heat plate where the solution is heated to 100°F. The heat plate is placed on 4-inch cement tiles to isolate the heat from the rest of the support structure and to provide additional height to promote flow.

The heat plate is controlled with a temperature probe in the hot water flow pipe with the temperature controller housed in the pedestal box. The temperature controller applies an on/off signal to the heat plate to operate around the setpoint of 100°F. From the intermediary container, the solution flows to the reservoir of the spray apparatus with an isolation ball valve located at the center of the environmental chamber. The reservoir of the spray apparatus is composed of a 4" × 4" plexiglass box sealed water tight with a cap for access on each of the Cardinal faces; one face has the supply with isolation valve, the next has the



Figure 5. The salt-fog chamber.

spray nozzle, an extra for an additional spray nozzle, and the last to allow for access to the inside the box and a means to vent air from the box. Then, the solution is pulled from the spray apparatus reservoir by a venturi effect nozzle which creates a mist with compressed air that fills the environment chamber. The mist in the environment settles on the samples that are being tested, and these samples are oriented at 30° from vertical which allows the solution to interact and allows the samples run off. The samples are individually supported with tie wraps that are resistant to the solution secured to the PVC stands. The solution that interacts with the samples runs off and settles in a drain pad that makes up the bottom of the environment chamber; additional misted solution that does not interact with the samples collects into the drain pan. **Figure 6** shows the internal environment system, including the spray tower with the spray valve, samples and support structures, and drain pan with drain ports.

The solution that collects in the drain pan goes to waste through a primary or secondary drain in the pan. The primary drain is located at one corner of the pan, and the secondary drain is located near the spray tower opposite the corner of the primary drain. Both drains connect to a main drain pipe constructed of 1/4" Chlorinated Polyvinyl Chloride (CPVC) that runs to a waste bin which is emptied manually to an appropriate drain receptacle. The air system is composed of an air compressor which supplies air through a ball valve to the system at 21 psi. From the air compressor, the air runs through an air filter into a pipe header within the support pedestal. Each branch line from the header is controlled with an independent pressure regulator to ensure flow and pressure are only as required and controlled. The primary branch from the header runs through a pressure regulator within the support pedestal set at 20 psi to a spray valve mounted on the spray apparatus reservoir. The spray valve utilizes air pressure to apply a venturi effect across a nozzle pulling solution from the chamber and creates a mist. The rest of the compressed air in the header runs through a pressure regulator within the support pedestal operating at 1 psi to the solution reservoir where the compressed air runs through a pipe with puncture points allowing compressed air to bubble and provide mixing to the reservoir to ensure the salt in the solution does not separate without mechanical components which would be at risk of corrosion and contamination of the reservoir. A check



Figure 6. Salt-fog chamber.

valve in the top of the reservoir provides pressure release from the container such that the system can run continuously without being over pressurized and being sealed from outside exposure.

5. Testing Procedure

The test began on October 26, 2018 at 10:15 AM, and it ended on December 03, 2018 at 1:30 pm. The total time of the test run was 915.25 hrs. All five samples were tested during this time to ensure equivalent conditions for all samples. It is standard operating procedure that the salt fog testing is conducted until a failure condition of 2% - 5% surface area rust appears on the sample. After the failure condition is achieved, the time of the test is logged and reported in hours. Due to time constraints, the time of the salt fog is held constant, and the surface areas of rust on the samples are compared. Maintenance was carried out during testing, some changes were made, and details about the apparatus were noted.

In order to allow the system to operate continuously without constant supervision, regular maintenance was maintained. Throughout the testing process, the operation was observed every 24 hours. During this regular maintenance period, solution was mixed at a ratio of 1 gallon of distilled water to 200 grams of pure sodium to achieve the 5% by weight salt-water solution and to fill the main solution reservoir. The waste container was dumped into a drain receptacle. In addition, the spray tower apparatus was observed to ensure that the spray system was operational and to ensure that any air buildup is purged through the main vent cap similar to how it is filled. During this time, regular photos were taken of the samples to record the effect of the mist solution. The rest of the system was examined carefully to ensure that any air bubbles in the system could be purged through any of the ball isolation valves or through the main reservoir. On a non-daily basis, the spray valve nozzles are checked in case they need to be replaced to ensure that they are not becoming corroded and that they are not clogging. This was done approximately every 230 hours. In addition, the airline to the spray valve was checked to ensure that it was not corroded since it is made of metal that was exposed to the mist-solution environment, which eventually will corrode and break, requiring the replacement of the whole airline. This was done twice during the operation of the equipment.

During the daily operation, the temperature control was observed and adjusted if the temperature deviated from the 100°F set point. In case the reading is above the set point, the heat plate can be set to “off” and allowed to cool to the set point and restarted. In case the reading is below the set point, the heat plate can be set to a higher setting until it reaches the set point after which it can be reset. In case the temperature controller and probe are exposed to water, which may short the system, they may need to be replaced. Due to constant operation and relocation, it is recommended that the temperature controller and probe be replaced to ensure that it is operating correctly and is not shorted. This is very important because an exposed electrical current could travel through the water

and interact with the person who is performing maintenance.

During testing, a primary change to the operation of the system was the salt that was used. During the first third of the testing period, salt rocks were used since they are the typical salt that is applied to roads and railways to melt snow. However, since the salt must dissolve completely in the distilled water that is used, it is necessary to crush the rock salt to make a powder. This process was labor intensive, and it resulted in particles from the crushing container being transferred to the system. Since the particles are plastic, they presented no corrosion alteration, but they did present an opportunity for clogging. Thus, the salt that was used was ground to create a fine powder which continued to provide the same corrosion effect without the additional labor and clogging opportunities.

During testing, the flow rate of the water was measured so it could be compared to the ASTM standard. In the beginning of the test, the system consumed more than 12 gallons per day. The highest measured flow rate was 16.8 gallons per day, and this measurement was achieved by logging the reservoir volume twice during a 24-hr period and extrapolating the measurement out to 24 hrs. The system used more water than the reservoir could hold. The volume of water between the outlet at the bottom of the tank and the bubbler pipe at the top of the tank is approximately 12 gallons. Multiple attempts were made to slow the flow rate. The water supply was partially closed in two locations, *i.e.*, near the reservoir and near the spray box. Both modifications resulted in fluctuations in the flow rate of the system, and the flow rate slowed to as little as one gallon per day during the fluctuations. Originally, the spray box included two sprayers. The flow rate was reduced successfully by removing one of the sprayers from the spray box. Once the flow rate slowed to a manageable level, two flow rate measurements were taken, and they are shown in **Table 2**. The flow rate was measured by recording the change in the height of the water level in the reservoir over a period of time and extrapolating the rate to 24 hrs. Although the cross sectional area of the reservoir changes slightly, it was assumed to be constant at 11.75" × 15.75".

Fluctuations remain in the flow rate. The minimum flow rate deemed acceptable for the apparatus was determined qualitatively. If the flow rate drops too low, the water level in the sprayer assembly drops. This is due to the sprayer using more water than is being supplied. In this case the sprayer intermittently produces fog and becomes unreliable. The range of flow rates observed with one sprayer did not result in a decrease in the height of the water level.

Table 2. Flow rate of the salt water.

	Area (in ²)	Height (in)	Volume (cu in)	Conversion (gal)	Time (hr)	Rate (gal/hr)	Rate (gal/day)
1	185	5.25	971.58	4.21	20.5	0.21	4.92
2	185	3.75	693.98	3.00	22	0.14	3.28

From standard ASTM B117, the ideal flow rate for 5% salt-water solution testing is defined as 1 to 2 mL/h of solution per 80 cm² of horizontal collection area. Due to the necessity of having the environmental chamber to be 3' × 4' for the sample supports to be enclosed, the resulting collection area is the 3' × 4' footprint of the environment chamber. As a result, the ideal solution use at 2 mL/hr per 80 cm² is approximately 0.074 gal/hr which can be extrapolated to 1.8 gal/day, 12.4 gal/week, 67.7 gal/915 hrs. It should be noted that this test resulted in using a higher flow rate than specified in ASTM B117. Further modification is needed to dial in the flow rate to more closely match the standard.

The duty cycle of the air compressor was measured to verify that it operates within the manufacturer's guidelines. The air compressor used is #C041H or C041H.C. The duty cycle is intended to be below 50%. On average, the compressor cycled on for 40 seconds and cycled off for 240 seconds. This results in a duty cycle of 15.4%. The sprayer was set to 20 psi, and the bubbler was set at an unknown pressure since the corresponding regulator gauge is not operational.

6. Results

It can be seen from **Figure 7** that the standard stainless steel plate showed the most prevalent red rust corrosion. The back of the plate showed that almost 20% of the surface area was covered with rust, and, while the front fared better, there was still corrosion around the edges. **Figure 8** indicates that the ArmorGalv coated plate had red rust on about 5% of its surface area on the front and the back had red rust on about 2.5% of its surface area. **Figure 9** shows that the Greenkote coated plate with ELU Passivation performed the best with <1% of its surface area having red rust. There was no visible rust on the front, and only about 1% of the back surface area had red rust. **Figure 10** shows that the Greenkote coated plate with the phosphate layer had red rust on about 1% of its front surface area, and it had red rust on about 2% of its back surface area. **Figure 11** illustrates that the galvanized plates not only had the roughest coating layer, which would imply a higher coefficient of friction, but it also resulted in the most corrosion, which further increased the roughness of the layer. The white rust could be removed by vinegar.

7. Conclusion and Recommendations

7.1. Conclusion

For railway applications, the best suited method for corrosion prevention is the Greenkote with passivation. This method provided the best overall protection against corrosion, and it has a smooth, strong finish. The galvanized option had the roughest coating layer, and it was the most reactive to the salt water solution. This makes it non-ideal for the dynamic rail environment because the increased friction of the plate could damage the supports, especially during extreme temperature situations that would cause the rail to expand or contract. Greenkote with Phosphate and ArmorGalv also provided increased corrosion prevention

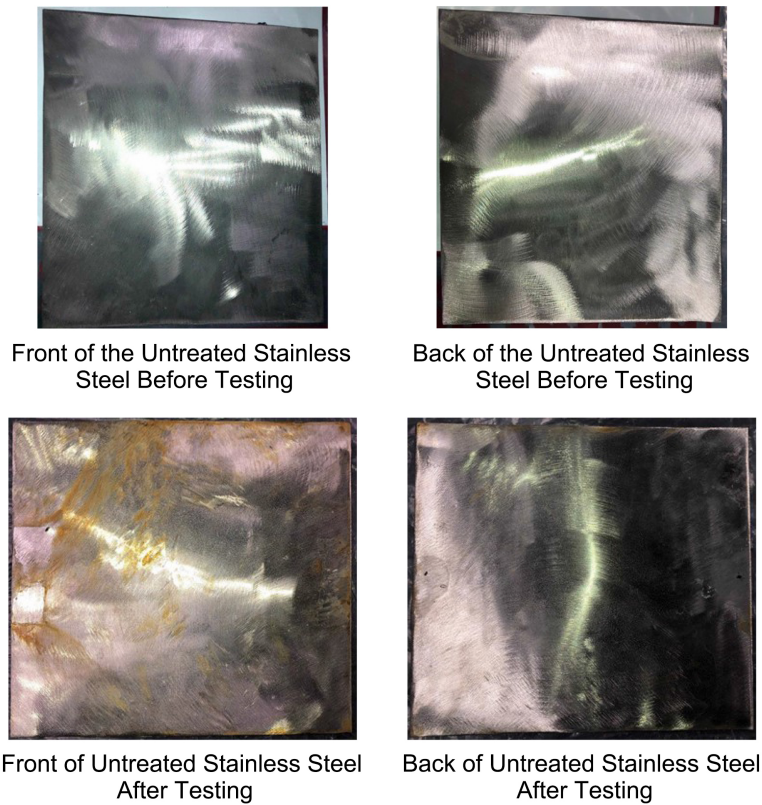


Figure 7. Front and back of untreated stainless steel plates before and after testing.

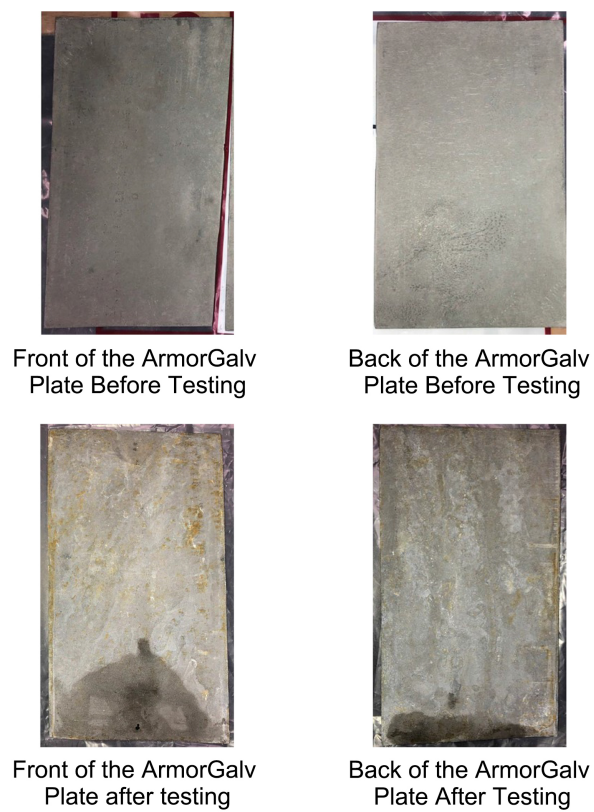
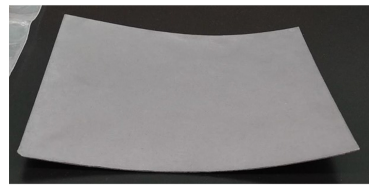
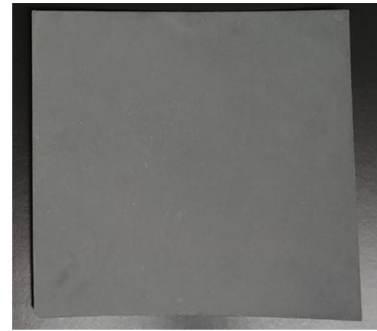


Figure 8. Front and back of the ArmorGaly treated and untreated steel plate.



Front of the Greenkote (ELU)
Plate Before Testing



Back of the Greenkote (ELU)
Plate Before Testing



Front of the Greenkote (ELU)
Plate After Testing



Back of the Greenkote (ELU)
Plate After Testing

Figure 9. The fronts and backs of the Greenkote treated and untreated steel plates.



Front of Greenkote (Phosphate)
Plate Before Testing



Back of Greenkote (Phosphate)
Plate Before Testing



Front of Greenkote (Phosphate)
Plate After Testing



Back of Greenkote (Phosphate)
Plate After Testing

Figure 10. The fronts and backs of the Greenkote (phosphate) treated and untreated steel plates.

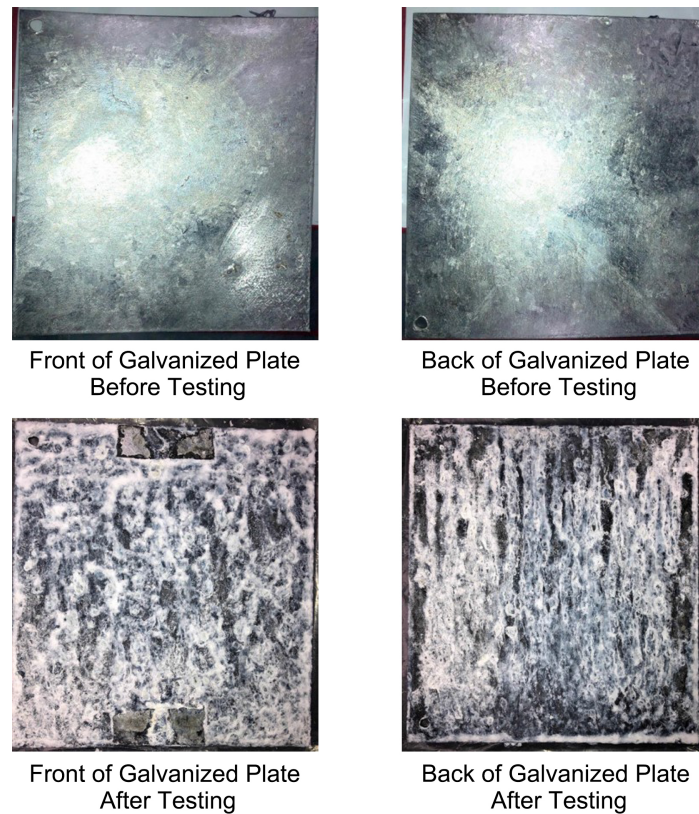


Figure 11. The front and back of the galvanized treated and untreated steel plate.

with a smooth, strong finish, but it netted more surface area rust than the Greenkote with passivation. The ArmorGalv sample had more surface area with rust than the Greenkote samples. This may not be a weakness in the ArmorGalv process; rather it is more likely the result of this particular sample missing the added protection of a colored coating. The ArmorGalv formula stresses the added corrosion protection benefits of introducing transitional metal oxides into the drum both to add color and to improve the performance of the coating.

7.2. Recommendations

While the thermal diffusion coatings provided better protection from corrosion than the bare stainless steel, the application of the coating may warp the steel plate. To be a viable alternative, the thermal diffusion coatings must not warp the small resistance plate because it must be completely flat between the rail and the tie plate. Also, the rubber would have to be reattached to the back of the plate, and the front would have to be polished to ensure the lowest resistance between it and the rail.

The corroded plates should be studied further with the use of a Scanning Electron Microscope (SEM) to determine the depth of the corrosion. This would be a more accurate measure of the seriousness of the corrosion. Future projects would require a study of the friction coefficient of each coating layer in comparison to the desired friction coefficient for the plate. Future projects should in-

clude 1) cyclic loading studies to determine the strength of the coating layer to determine if it is useful in the dynamic railway environment and 2) additional consideration also should be made concerning the effort involved in remounting any of the decided coatings on the rubber plate and in applying the smooth coating.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Zhang, H., Yan, Z., Li, Z., Li, Y. and Fang, W. (2018) Corrosion Cause and Countermeasures for Composite Tie Plate Under Small Resistance Fastening Used for High Speed Railway Ballastless Track. *Railway Engineering*, No. 5, 138-142. (In Chinese)
- [2] Li, Y., Fang, H., Tang, X. and Yang, J. (2017) Manufacture of Modified Nylon 66 Anti-friction Rail Pad for the WJ-8 Fastening System. *Railway Engineering*, **57**, 119-121. (In Chinese)
- [3] TM-584C, Revision C (1994) Corrosion Control and Treatment Manual. <https://www.wermac.org/pdf/corrosion3.pdf>
- [4] TO 1-1-691 (2021) Cleaning and Corrosion Prevention and Control, Aerospace and Non-Aerospace Equipment. <https://www.robins.af.mil/Portals/59/documents/technicalorders/1-1-691.PDF>
- [5] Bushman, J. (2010) Corrosion and Cathodic Protection Theory. Bushman & Associates Inc. https://www.idc-online.com/technical_references/pdfs/electronic_engineering/corrosion_theory.pdf
- [6] The Zinc Plating Process. <https://www.sharrettsplating.com/blog/the-zinc-plating-process/>
- [7] Corrosion Resistance of Zinc Plating. <https://www.sharrettsplating.com/blog/corrosion-resistance-of-zinc-plating/>
- [8] Distek, N.A. (2018) Thermal Diffusion Galvanizing. Cost Effective, Environment-Friendly Corrosion Protection, ASTM—A1059 A/M Powerpoint, <https://vdocuments.mx/distek-na-introduces-armorgalv-mtipm-what-is-armorgalv-thermal-diffusion.html>
- [9] Witter, G.W., Mohr, W.C., Stuart, C.D., Jeong, D.Y. and Tang, Y.H. (2013) Effects of Combined Corrosion and Fatigue on Rail Performance. *EWI Study*, 281-301. <https://eoncoat.com/wp-content/uploads/2016/09/arema.pdf>