POLYMER COATED STRUCTURAL PLATE AND FASTENER TESTING

FINAL REPORT

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Final Report

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National Corrugated Steel Pipe Association

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Background

Polymer coated corrugated steel structural plate has been developed as a more durable alternative to steel structural plate. Corrugated plate structures are assembled using threaded fasteners which also receive a polymer coating. This report describes testing performed to support the development of a new ASTM specification for polymer-coated corrugated steel structural plate.

Initial testing was performed on test panels representing combinations of plate and fastener coatings considered to be candidate materials. Coating materials were selected with performance similar that required in ASTM A742/A742M, *Standard Specification for Steel Sheet, Metallic Coated and Polymer Precoated for Corrugated Steel Pipe*. The new ASTM standard was developed to be consistent with ASTM A761/A761M, *Standard Specification for Corrugated Steel Structural Plate, Zinc-Coated, for Field-Bolted Pipe, Pipe-Arches, and Arches* while incorporating applicable requirements of ASTM A742/A742M. Follow-up testing was performed to ensure the selected product met the final specification requirements.

This report describes testing performed thought the product development. Attachment II summarizes the test results for the products which meet the requirements of ASTM A1113/A1113M.

Materials

Plate Coatings

Table 1 lists the plate coating systems tested. Coatings were applied at Lane Coatings (Carlisle, PA) before being transferred to Elzly's New Jersey testing facility.

Table 1: Plate Coatings

Base Coating	Topcoat	Coating Type
Galvanizing	Polyarmor G17	Ethylene Acrylic Acid Powder
Carbozinc 858 (zinc rich primer)	Polyarmor G17	Ethylene Acrylic Acid Powder
Carbozinc 858 (zinc rich primer)	Polyester	Polyester Powder
Galvanizing	Trenchcoat	Ethylene Acrylic Acid Laminated Film

Plate coatings were originally evaluated on two different panel geometries, with a total of ten panels being tested for each coating system. Six of the panels were sized 4-inch by 6-inch 10-gage steel panels and were used to test the plate coating by itself. The remaining four were 6-inch by 9-inch 10-gage steel panels. The larger panels were used to test the coating as well as six fastener coatings. These panels incorporated 6 evenly spaced 1" holes as shown in Figure 5.

Additional test panels of varying geometries were prepared to meet the requirements of specific ASTM test methods. These are described elsewhere in this report.

Fastener Coatings

Six different fastener coatings were applied to ASTM A449 bolt and nuts as shown in Figure 1. Sixteen fasteners were prepared with each of the coatings listed in Table 2.

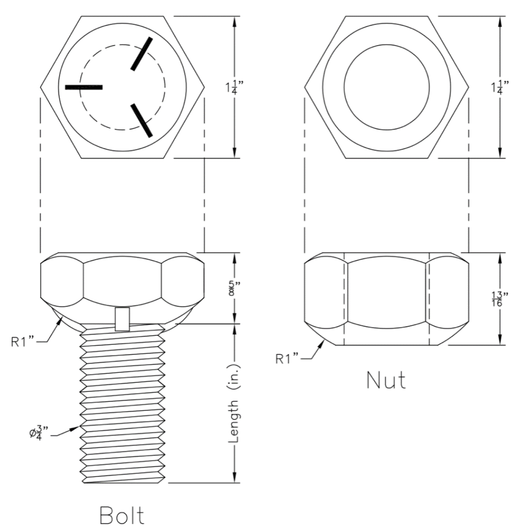

Figure 1: ASTM A449 Bolt and Nut Drawing

Table 2: Fastener Coatings

Base Fastener Material	Manufacturer	Coating	Application Notes
Galvanized	-	None	-
Galvanized	Plas-Tech	PT-24	Dip Spun
Galvanized	Plas-Tech	PT-24	Spray Applied
Galvanized	Plas-Tech	PT-193	Spray Applied
Galvanized	RanVar	TPC-515-7	Brush applied after installation
Black Steel	Leland	NZF 3000	The coating on the bolt was black and on the nut was gray.

PT-24 and PT-193 are both resin-bonded, thermally cured, single film coatings, primarily formulated for use on fasteners to prevent corrosion. PT-24 is often recommended to facilitate make-up torque while PT-193 is primarily formulated for use on offshore fasteners. PT-24 and PT-193 were applied over galvanized fasteners in a shop prior to installation. RanVar TPC-515-7 is a brush-applied, air-dry epoxy that cures to a rubbery finish applied to the installed, galvanized fasteners. NZF 3000 is a non-electrolytically applied zinc and aluminum flake fastener coating which is applied over steel fasteners in a shop prior to installation. Selected properties of each coating are listed in Table 3.

Table 3: Fastener Coating Properties

Coating	CoF	ASTM B117 *Hours*	Dielectric Strength *V/mil*	Dry Film Thickness *mils*
PT-24	0.05 – 0.10	2,000	500	0.6 – 1.0
PT-193	0.10 – 0.20	2,000	500	0.6 – 1.2
NZF 3000	Adjustable	3,000	-	0.7 – 0.9
TPC-515-7	-	-	-	1.5

Test Methods

Pull-Off Adhesion

Tensile (pull-off) adhesion testing was performed in accordance with ASTM D4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*. Testing was performed using a DeFelsko PosiTest AT-M Adhesion Tester which is a Type V self-aligning adhesion tester with an upper limit of approximately 4,000 psi. Prior to testing, the surface area where the test fixture would be adhered was lightly abraded using 220 grit abrasive paper. A two-part epoxy adhesive (Huntsman Araldite 106) was used to attach the test fixtures, which was cured under ambient conditions for 72 hours before testing. Upon failure, the force (in psi) required to remove the test fixture as well as the location of the failure within the coating system, was recorded and reported.[1]

Mandrel Bending Adhesion

Mandrel bend adhesion testing was performed following a modified version of ASTM A742/A742M, Section 9.1. Due to the panels thickness, testing was performed using an air assisted hydraulic press with a three-point bending system. The three-point bending system was specially fabricated to mimic a typical mandrel bend test. Panels were bent 180° around a ½-inch mandrel and cut along the outside of the bend to check for polymer adhesion. Testing was performed at three temperatures: ambient (88°F), cold (-9°F), and hot (122°F). After bending, any spalling or cracking of the coating was recorded, as well as disbondment from the substrate.

Further testing of the Polyarmor G17 over Carbozinc 858 coating system with was conducted in accordance with Method B of ASTM D522, *Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings* which is specified in ASTM A1113/A1113M. The test method specifies that the testing is performed on 22-gage panels. Coated panels are bent 180° around a ¼-inch mandrel then examined for any coating cracking, spalling, or disbonding.

Knife Adhesion Test

Adhesion of the fastener coatings was determined following the tape adhesion test specified in ASTM D3359. *Standard Test Methods for Rating Adhesion by Tape Test*. Flat surfaces of the fasteners are not large enough for Method B (crosshatch), so Method A (X-cut) was performed. One nut and bolt were selected for each coating type. Two tests were performed on flat faces of the nut; a third test was performed on the head of the bolt.

Direct Impact Testing

Direct Impact testing was performed in accordance with Section 9.2 of ASTM A742/A742M. Testing was performed at 88°F and at -9°F with a drop weight impact tester, and a 0.640-inch diameter punch and punch die. After testing, defects in coating were visually inspected using a handheld microscope at 25X magnification, then checked with a low voltage holiday detector at 90V to determine if the coating had been penetrated.

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[1]Adhesive failure occurs when one coating layer is removed from another or from the substrate. Cohesive failure occurs when a coating layer itself fails and "splits" within the coating layer.

Further testing of the Polyarmor G17 over Carbozinc 858 ocoating system was performed in accordance with ASTM D2794, *Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)* as required in ASTM A1113/A1113M. Testing was performed at 160 in-lbs with a 0.625-inch indenter. After testing, defects in the coatings were visually inspected using a handheld microscope at 25X magnification, then checked with a low voltage holiday detector at 90V to determine if the coating had been penetrated.

Abrasion Testing

The abrasion testing performed in this study followed a modified version of ASTM D968, *Standard Test Methods for Abrasion Resistance of Organic Coatings by Falling Abrasive*. The method involves incrementally dropping a measured volume of abrasive media from a specified height through a guide tube onto a coated surface until the coating erodes away to reveal the underlying substrate (Figure 2). Preliminary trials showed the plate coatings used in this study were highly resistant to the silica sand that is typically used in this test. As such, the standard silica sand abrasive was replaced with 25-40 mesh steel grit, which is approximately 30% harder than silica sand. The values presented in this report are shown in liters/mil representing the volume of abrasive media it takes to erode one mil of coating.

Figure 2: ASTM D986 Testing Apparatus

Plate Coatings

Testing for the plate coatings was completed using two approaches. During the first set of tests, testing was completed generally in accordance with ASTM D986, except coating thickness measurements were made at 15 random locations within the abrasive contact area before and after up to 50L of abrasive. The erosion rate was calculated based on the liters of abrasive and the averaged measured coating thickness before and after testing.

Testing was repeated using the end criteria in ASTM D986. Prior to testing, the coating thickness is measured in the test area. The steel grit was poured in 2-liter increments into a funnel with a 0.75-inch inner diameter down a guide tube 3-feet long at a stand-off distance of 1-inch from the panel. Panels were visually inspected for coating erosion after each pour. Testing was considered complete after a 4-mm spot had worn through the topcoat and the underlying zinc coating was visible. Coating thickness measurements were taken after 10, 20, 50, and 100L of abrasive. The data was curve fitted to determine an erosion rate.

Fastener Coatings

Four replicate samples of each supplied fastener coating (PT-24 dip spun, PT-24 spray applied, PT-193, and NZF 3000) underwent abrasion testing. This was accomplished by pouring the steel grit in 0.25L increments onto the bolt head until a 4-mm wide spot was worn through the coating to the substrate. Prior to testing, the coating thickness on each bolt head was recorded.

GMW14872 Testing

All test panels underwent corrosion testing in accordance with GMW 14872 using the Underbody (UB) Method 1/2, Exposure D. A full cycle of this test takes place in 24 hours and consists of:

- Ambient Stage 25°C, 35-55% RH for 8 hours
    - Salt solution sprays at 0, 90, 180, and 270 minutes from start of the stage
    - Total of 4 solution sprays per 24-hour period
- Humid Stage 50°C and 100% RH for 8 hours
- Dry Stage 60°C and 30% RH (or less) for 8 hours

GMW14872, *Cyclic Corrosion Laboratory Test*, was used as an alternative to SAE J2334, *Laboratory Cyclic Corrosion Test*. The two tests are similar, but there are a few minor differences. SAE J2334 has one salt solution spray, while GMW has four. The SAE test consists of a dry segment for 17.75 hours with a humid segment of 6 hours, and the ambient segment is 15 minutes. In the GMW test, these segments are each 8 hours.

Plate Coatings

Each test panel was scribed using a 1/8-inch diameter endmill to create a 3-inch by 3-inch "X" as pictured in Figure 3. This scribe configuration allows undercutting of the coating to be evaluated, while leaving enough coating intact to make accurate assessments of rust-through and blistering. Undercutting measurements were taken across the length of the scribe, then the scribe width was subtracted. Test panels were installed at 20° ± 5° from vertical in a non-metallic rack prior to the start of testing, pictured in Figure 4.

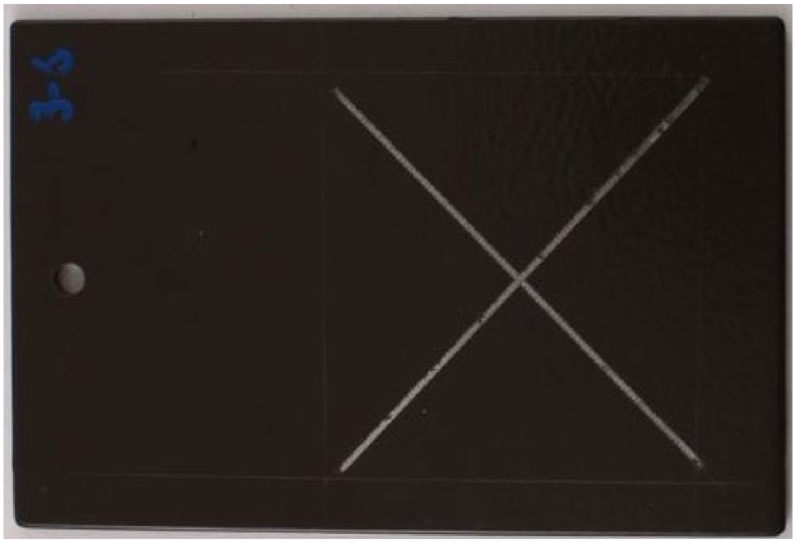


Figure 3: Scribed Panel Prior to Testing

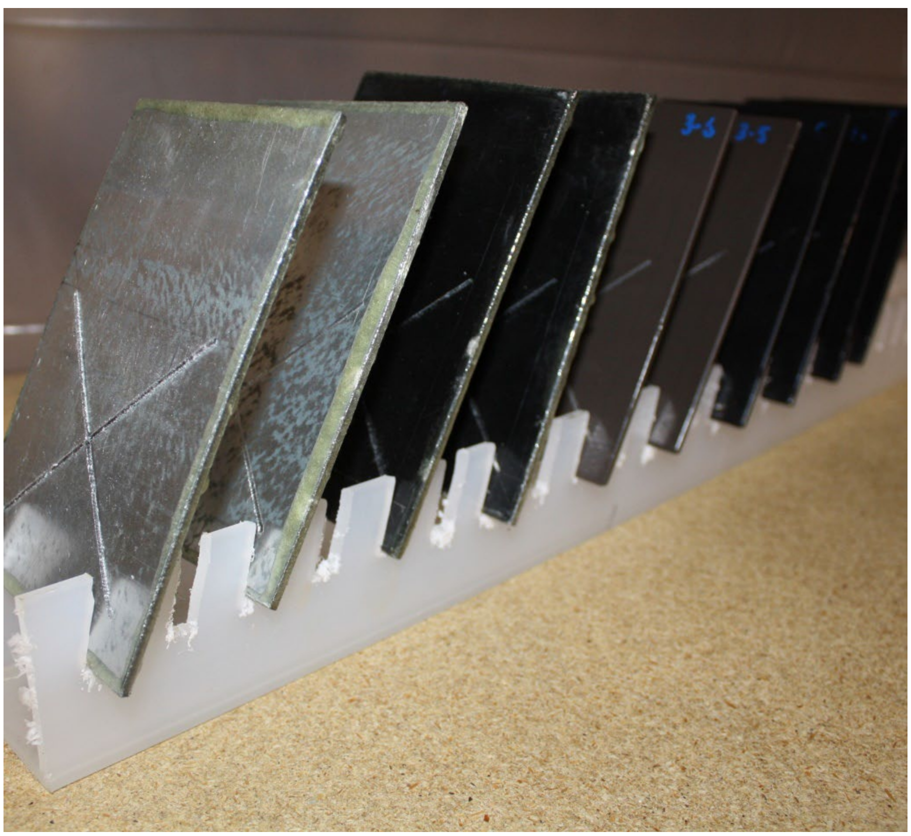


Figure 4: Panels in Rack Prior to Test

Panels were inspected after 20, 40, 60, and 75 cycles. These inspections included:

- Rust Through – Determined in accordance with ASTM D610, *Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces*.

- Blistering – Determined in accordance with ASTM D714, *Standard Test Method of Evaluating Degree of Blistering of Paints*.
- Undercutting from scribe (creepage) – Determined in general accordance with Procedure A of ASTM D1654, modified as follows:
  - Measurements are made across the scribe with the scribe width subtracted before being divided by 2.
  - The average of the 8 measurements, the maximum and minimum were reported.

Fastener Coatings

The fastener coatings were evaluated by installation into 6-inch by 9-inch steel panels with evenly spaced 1-inch diameter holes as shown in Figure 5.

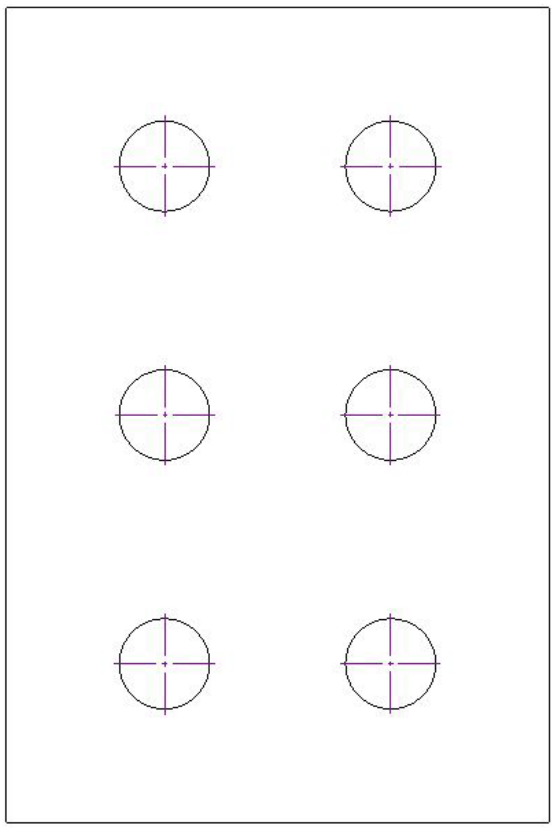


Figure 5: Fastener Coatings Test Plate Drawing

Each fastener was installed using a pneumatic impact driver (three seconds at 60 psi on the tool's medium setting) then tightened further to 150 ft-lbs using a torque wrench. This created small defects in both the panel and bolt coatings from the impact socket representative of those created in the field when installed, while also ensuring equal amounts of force at the bolt head/panel/nut interfaces for all panel and fastener coating combinations. Figure 6 shows an example of a fully assembled panel prior to testing.

Front of Panel Back of Panel

Figure 6: Representative Fully Assembled Test Panel

Test panels were installed at 20° ± 5° from vertical in a non-metallic rack prior to the start of testing with the bolt head side facing in the direction of the salt solution spray. Figure 7 shows the test panels arranged in the GM cabinet prior to any salt solution spray. Halfway through the testing (after 30 cycles), the panels were rotated so that the nut and bolt threads faced in the direction of the salt solution spray.

Figure 7: Test Panel Array in GM Test Chamber

Visual inspections per ASTM D610 were performed after 20, 40, and 60 cycles in each of three areas for each fastener (96 total):

1. Bolt head on front of panel
2. Bolt threads on back of panel
3. Nut on back of panel

After completion of testing (60 cycles), test panels were rinsed and lightly scrubbed using a soft bristle brush to remove salt deposits before they underwent a final ASTM D610 inspection.

After completion of testing, cleaning, and ASTM D610 inspection, all fasteners were fully disassembled and inspected for corrosion per ASTM D610 at the following interfaces:

1. Bolt head and panel (documented as corrosion formed on the underside of the bolt head)
2. Nut and panel (documented as corrosion formed on underside of the nut)
3. Nut and bolt threads (documented as a combination of corrosion formed on the bolt threads and nut threads)

Breaking Torque Measurements

During disassembly, each of the 96 fasteners underwent breaking torque testing by applying force with a torque wrench beginning at 30 ft-lbs and increasing in increments of 5 ft-lbs until the nut broke free of the bolt.

Chemical Resistance Testing

Chemical resistance of the coatings was determined by both spot testing and immersion testing as described in the following paragraphs.

Chemical Spot Testing

Three panels were coated with Polyarmor G17 over Carbozinc 858 to test the system for the "imperviousness" requirement of ASTM A1113 Section 8.2.4. Chemical spot testing was conducted in accordance with ASTM D1308-02(13), *Standard Test Method for Effect of Household Chemicals on Clear and Pigmented Organic Finishes*. The spot test was conducted using 10% sodium hydroxide, 10% sodium chloride, and 30% sulfuric acid (one solution for each panel). For each reagent, 3 mL was placed on the panel and covered with a watch glass. After 48 hours, the panel was rinsed with water and patted dry with a paper towel. The specimen was allowed to recover for one hour, then the surface was examined with the unaided eye for evidence of blistering, softening, or loss of adhesion.

Chemical Immersion Testing

In order to further evaluate chemical resistance of coating system, nine panels were prepared with Polyarmor G17 over Carbozinc 858 for chemical immersion testing. Immersion testing was performed in accordance with ASTM D543-14, *Standard Practice for Evaluating the Resistance of Plastics to Chemical Reagents*. Two panels were placed into an immersion vessel with the immersion solution covering 75% of the panel. A third panel exposed to the test solution by attaching a glass cell to the surface of the panel and adding an inch of solution. The panels were exposed for a period of 30 days.

Freeze/Thaw Resistance Testing

In accordance with ASTM A1113, panels coated with each system underwent freeze/thaw testing for 100 cycles. Panels were first pre-exposed by soaking in tap water at 70°F for two weeks. The panels were then placed in 100 cycles of freeze/thaw testing. Each cycle consisted of 8 hours in a freezer maintained at 0°F followed by 16 hours in the previously-described tap water bath at 70°F.

Results and Discussion

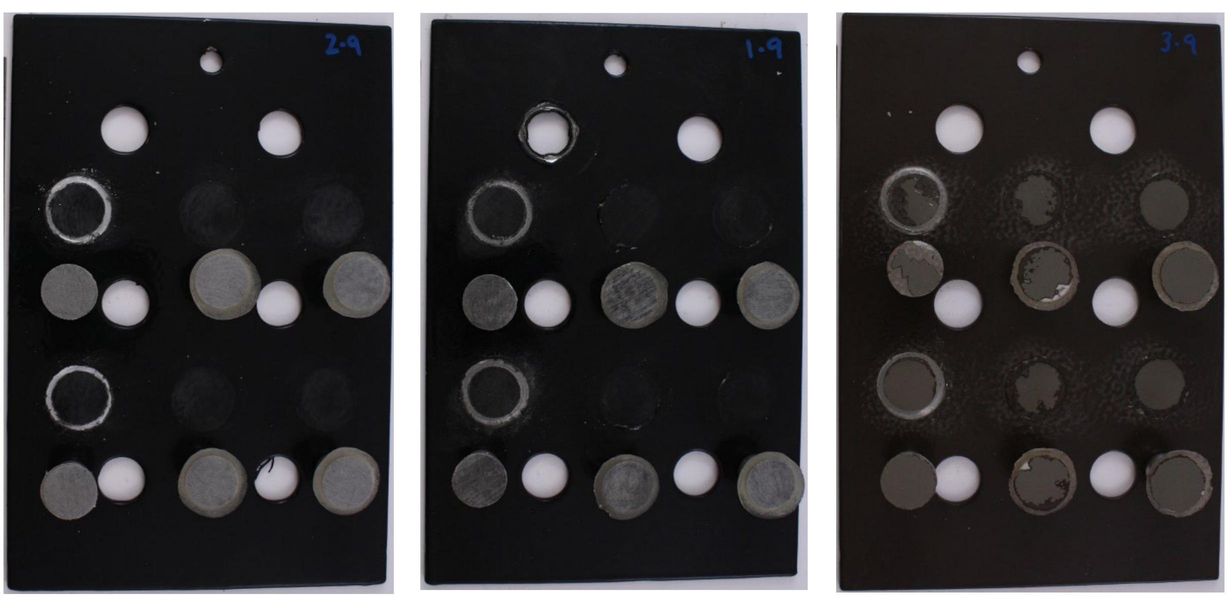
Adhesion Testing

Pull-Off Adhesion

Table 4 summarizes pull off adhesion test data. All failures in Polyarmor G17 systems and Trenchcoat occurred adhesively at the glue/topcoat interface. These results indicate that the true adhesion of the coating to the substrate exceeds the measured value. Failures in the polyester coating occurred cohesively within both the topcoat and the primer, and adhesively at the glue/topcoat interface. Figure 9 shows adhesion panels and their corresponding adhesion dollies after testing. While there are no standards for Adhesion values more than 1,000 psi are generally considered good for industrial coatings. The data suggests an acceptable level of tensile adhesion performance and suggests similar service performance related to tensile adhesion stresses.

Table 4: Adhesive Failure Locations

Coating	Cohesive (Primer)	Cohesive (Topcoat)	Glue	Failure Load (psi)
Polyester over Carbozinc 858	90%	6%	4%	1127 – 2460 psi
Polyarmor G17 over Carbozinc 858	-	-	100%	> 2066 psi
Polyarmor G17 over Galvanizing	-	-	100%	> 1150 psi
Trenchcoat over Galvanizing	-	-	100%	> 836 psi



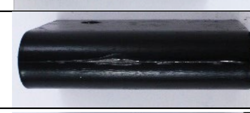
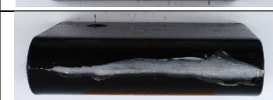
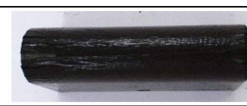
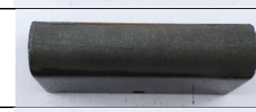
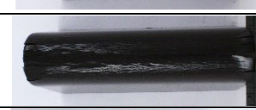
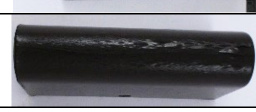
Polyarmor G17 over Galvanize | Polyarmor G17 over Carbozinc 858 | Polyester over Carbozinc 858

Figure 8: Samples Post Adhesion Testing for Plate Coatings

Mandrel Bend Adhesion

Table 5 shows the results of mandrel bending adhesion testing for the 10-gage panels. Due to limited availability of test panels, Polyarmor G17 over Carbozinc 858 was only tested at ambient temperatures. After bending, coatings were scored with a razor blade along the outside of the bend and checked for signs of spalling, cracking, or delamination. Polyarmor G17 over Carbozinc 858 delaminated within the Carbozinc 858 layer. Polyarmor G17 delaminated from the galvanizing. The polyester coating experienced severe coating cracking and delamination. The ASTM A742 polymer did not exhibit any delamination (note that it was applied to a thinner gage panel).

Table 5: Mandrel Bend Testing Summary

Coating	Panel Number	Temperature (°F)	Before Coating Removal	After Coating Removal
Trenchcoat over Galvanizing	1	88		
Polyarmor G17 over Carbozinc 858	1	88		
Polyarmor G17 over Galvanizing	1	-9		
Polyarmor G17 over Galvanizing	2	88		
Polyarmor G17 over Galvanizing	3	122		
Polyester over Carbozinc 858	1	-9		
Polyester over Carbozinc 858	2	88		
Polyester over Carbozinc 858	3	122		

Further testing of the Polyarmor G17 over Carbozinc 858 coating system with was conducted in accordance with Method B of ASTM D522, Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings using thinner coated panels. Figure 10 shows a panel coated with Polyarmor G17 over Carbozinc 858 on a thin 22-gage panel. After bending, no spalling, cracking, or disbanding was observed on the coating; the coating system accordingly passed the bending requirements of ASTM A1113/A1113M.

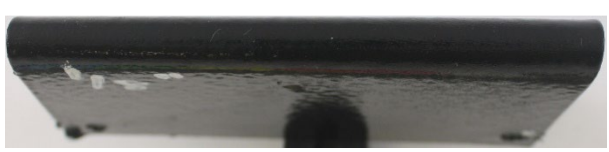
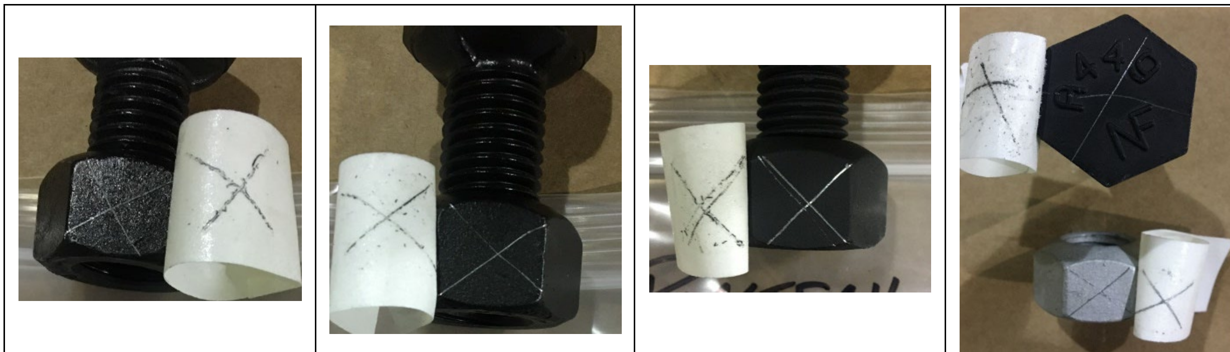


Figure 9: Polyarmor G17/Carbozinc 858 Mandrel Bend

Knife Adhesion Test

Two tests were performed on flat faces of the nut; a third test was performed on the head of the bolt. All results were “5A”, which is described as no peeling or removal. Based on this rating, all of the coatings show less than 5 % removal to substrate. Figure 11 contains representative photos of the tests.



Plas-Tech PT-24 (Hand application)	Plas-Tech PT-24 (Dip/spin application)	Plas-Tech PT-193	Leland NZF 3000

Figure 10: Representative Knife Adhesion Tests on Fasteners

Direct Impact Testing

Table 6 shows the results of direct impact testing. All 10-gage panels coated with Polyarmor G17 topcoat exhibited holidays at both temperatures and impact forces, while panels coated with the polyester coating had no holidays at both force levels at room temperature, and at 35 in·lb when cold. The polyester coating sustained damage during impact testing in that it did delaminate from the substrate in the immediate area of impact (Figure 12), but the damaged coating did not exhibit holidays (except when tested at 160 in·lb at -9°F). The Polyarmor G17 coating was pushed away from the impact site and formed a raised circular ring of coating where the underlying substrate was exposed.

Table 6: Direct Impact Testing Results

Coating	Room Temp (88°F)		Cold (-9°F)	
	35 in·lb	160 in·lb	35 in·lb	160 in·lb
Polyarmor G17 over Carbozinc 858	Fail	Fail	Fail	Fail
Polyarmor G17 over Galvanizing	Fail	Fail	Fail	Fail
Polyester over Carbozinc 858	Pass	Pass	Pass	Fail

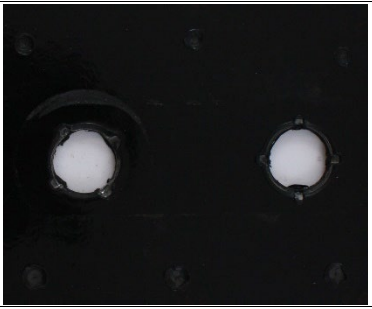
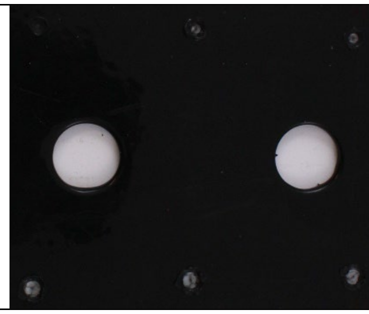
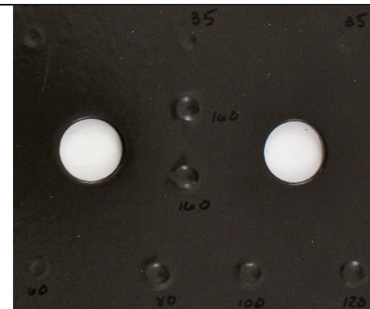
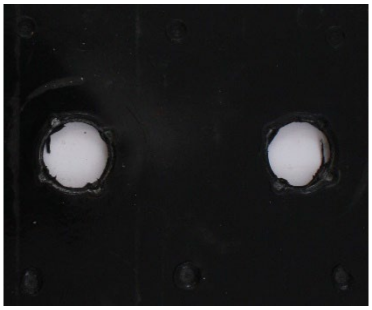
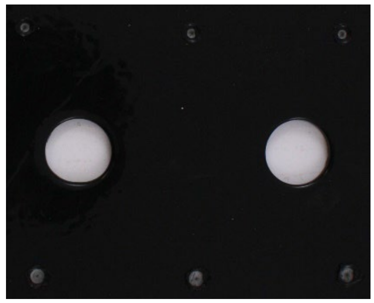
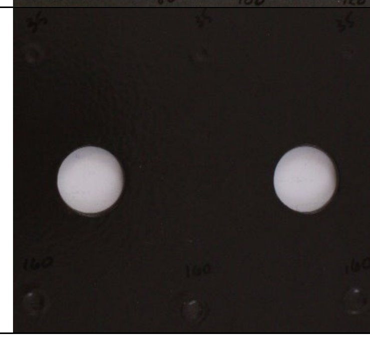
88° F			
-9°F			
	Polyarmor G17 over Carbozinc 858	Polyarmor G17 over Galvanizing	Polyester coating over Carbozinc 858

Figure 11: Panel Coatings After Direct Impact Testing

Further testing of the Polyarmor G17 over Carbozinc 858 ocoating system was performed in accordance with ASTM D2794. Figure 13 shows a panel coated with Polyarmor G17 over Carbozinc 858 on a thin 22-gage panel. After impact testing was completed, no spalling, cracking, or disbanding was observed on the coating; the coating system accordingly passed the bending requirements of ASTM A1113/A1113M.

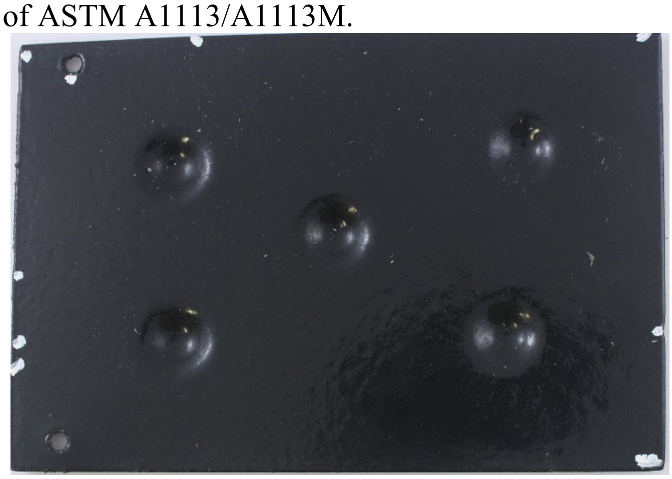


Figure 12: Re-Test of Polyarmor G17/Carbozinc 858 Impact Resistance

Abrasion Resistance

Initial Testing of Plate Coatings

Figure 14 shows the relative abrasion resistance of the supplied plate coatings in liters of abrasive per mil of coating. Both instances of the Polyarmor G17 product performed better than Trenchcoat, while the Lane Polyester coating showed to be about three times less abrasive resistant than Trenchcoat. While the relative rankings of these results is likely accurate, some error is introduced with just two sets of thickness measurements. However, the data remains useful for comparison of the coating systems and was included for completeness.

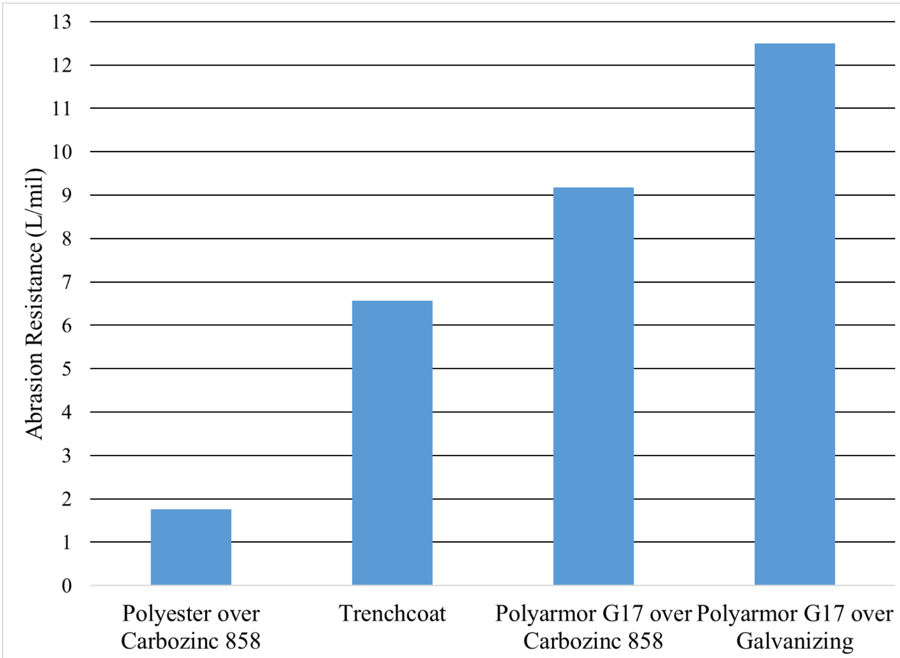
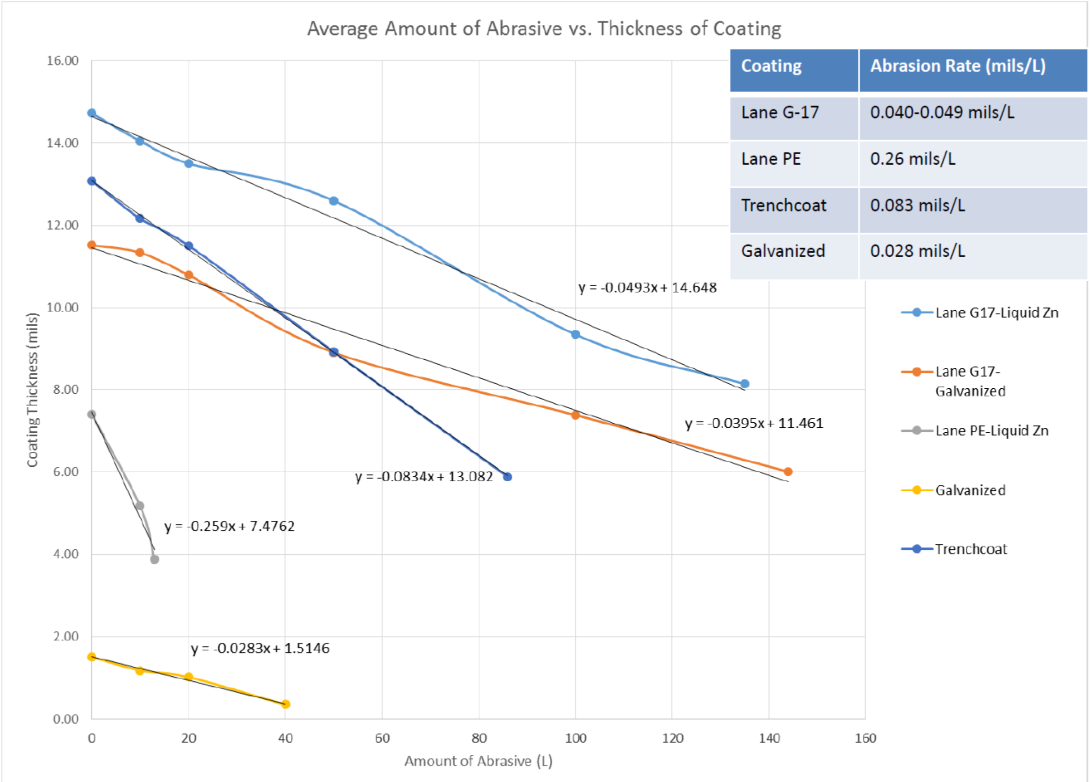


Figure 13: Abrasion Resistance of Supplied Plate Coatings

Additional Testing of Plate Coatings

Figure 15 shows the results of the second round of abrasion resistance testing; the graph shows coating thicknesses measurements taken as a function of amount of abrasive used. The fitted data is intended to improve reproducibility. Since the units were measured in mils/L instead of L/mil, a lower value meant a better abrasion resistance performance. The galvanized, Polyarmor G17 over galvanized, and Carbozinc 858/Polyarmor G17 systems demonstrated an abrasion resistance of less than 0.08 mils/L; the ASTM A742 and polyester systems did not.



Coating	Abrasion Rate (mils/L)
Lane G-17	0.040-0.049 mils/L
Lane PE	0.26 mils/L
Trenchcoat	0.083 mils/L
Galvanized	0.028 mils/L

Figure 14: Follow-On Abrasion Resistance Testing

Fastener Coatings

Figure 16 shows the relative abrasion resistance of the four supplied fastener coatings in liters of abrasive required to remove one mil of coating. Interestingly, PT-24 is approximately five times more abrasion resistant when dip-spin applied rather than spray applied. Assuming the bolt substrate surface profile was the same for both coatings prior to application, one theory for the difference in performance has to do with the way the coating wets onto the surface when applied by the two different methods. When spray applied, the coating is more likely to 'stick' to the peaks and valleys of the substrate and create a coating layer that mimics the substrate's topography. When dip spun, the coating is more likely to flow into those valleys and fill them, resulting in a smoother surface as it cures. This difference can be seen in Figure 17 which shows magnified images of untested bolt heads coated using the two application methods. The dip spun surface appears to be smoother and more uniform, while the spray applied surface shows many more undulations and appears rougher. Dry film thicknesses averaged 4.9 mils for the spray applied and 4.6 mils for the dip spun PT-24.

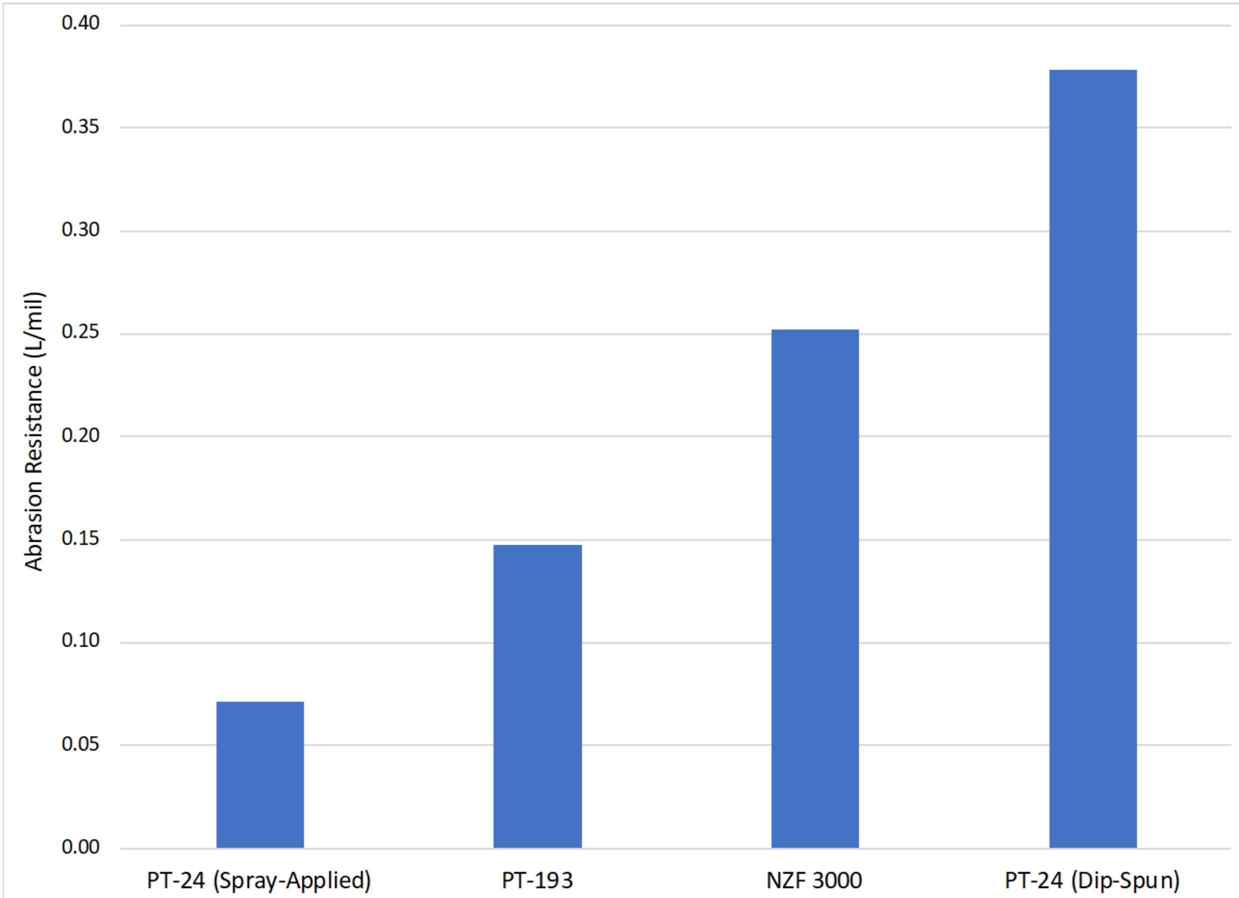
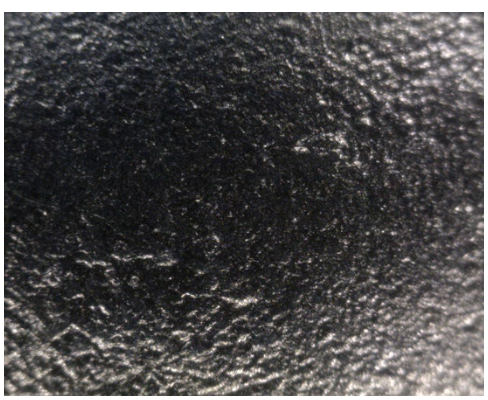
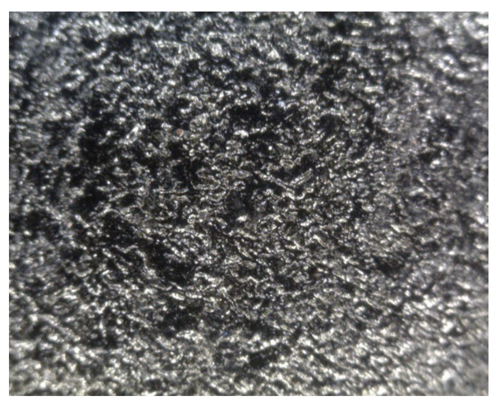


Figure 15: Abrasion Resistance of Supplied Fastener Coatings



PT-24 Dip Spun



PT-24 Spray Applied

Figure 16: Magnified Surface of PT-24 Coated Bolt Heads

GMW 14872 Testing

Plate Coatings

Before and after corrosion testing photos of representative samples from each system tested can be found in Attachment 1. Figure 18 shows undercutting from the X-cut scribe observed during

GMW testing. Undercutting is the spread of corrosion beneath a coating from the intentional scribe. Note that galvanizing doesn't undercut because it is metallurgically bonded to the steel substrate. Of the polymer coatings, Trenchcoat performed best, showing no undercutting at the completion of testing. The polyester and Polyarmor G17 over Carbozinc 858 performed well, with less than 1mm of undercutting. Polyarmor G17 over galvanizing performed notably worse than all other coating systems, with 2.8mm of undercutting.

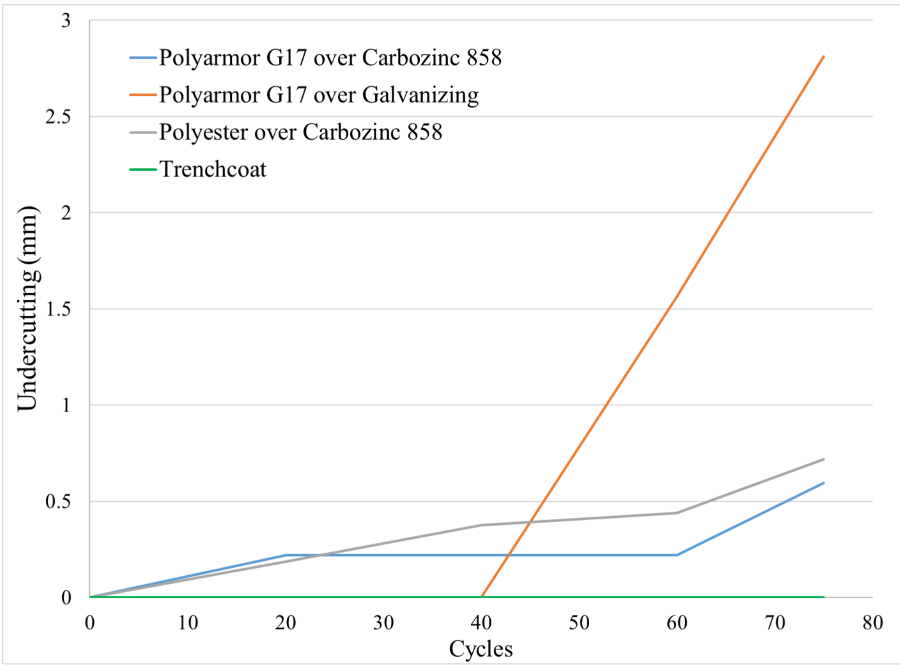


Figure 17: Visually Observed Undercutting During GWM 14872 Testing

The extent of undercutting that can be visually observed is not always the full extent of disbonded coating. To fully characterize the coating performance, the extent of disbonding was destructively evaluated at the end of 75 exposure cycles by removing the coating using a razor knife. Figure 19 summarizes these measurements.

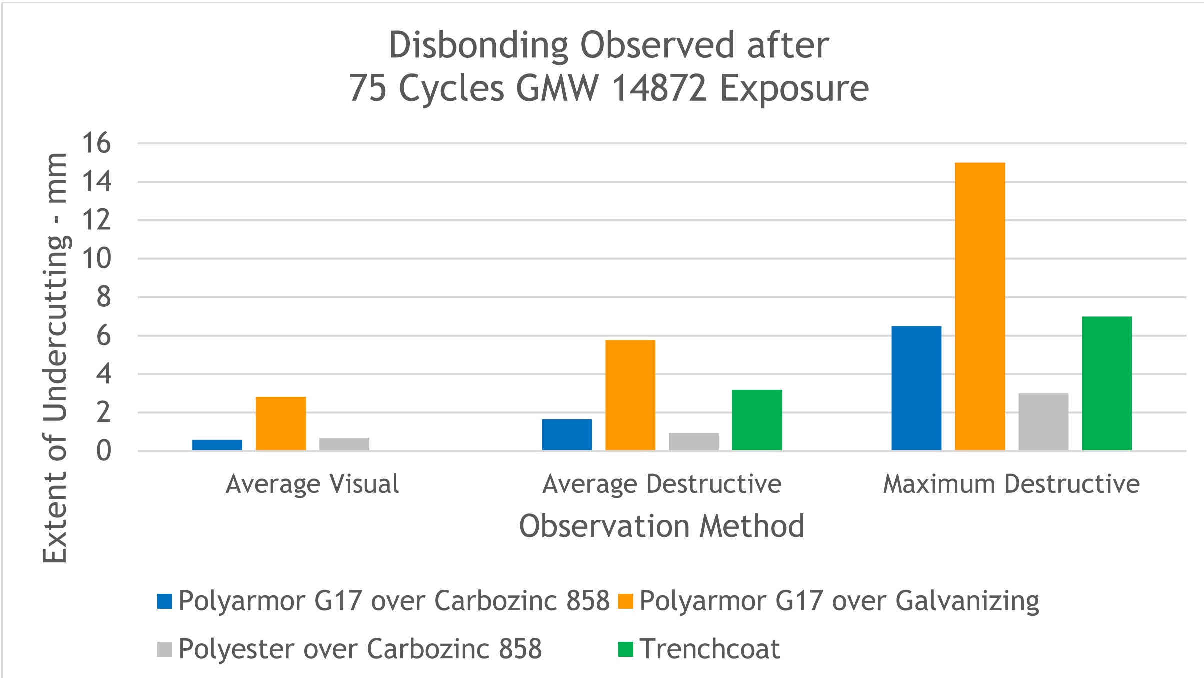


Figure 18: Observed Disbonding After 75 Cycles GMW 14872

The extent of rust-through observed for each coating was recorded at each inspection. Figure 20 shows the ASTM D610 ratings for rust-through made throughout testing. This parameter demonstrates the failure mode of the galvanized coating. After 75 cycles of exposure, the galvanized panels had an average rating of 2 which corresponds to 33.0% rust through. All polymer coatings had average rust ratings above 8, which is less than 0.1% rust-through.

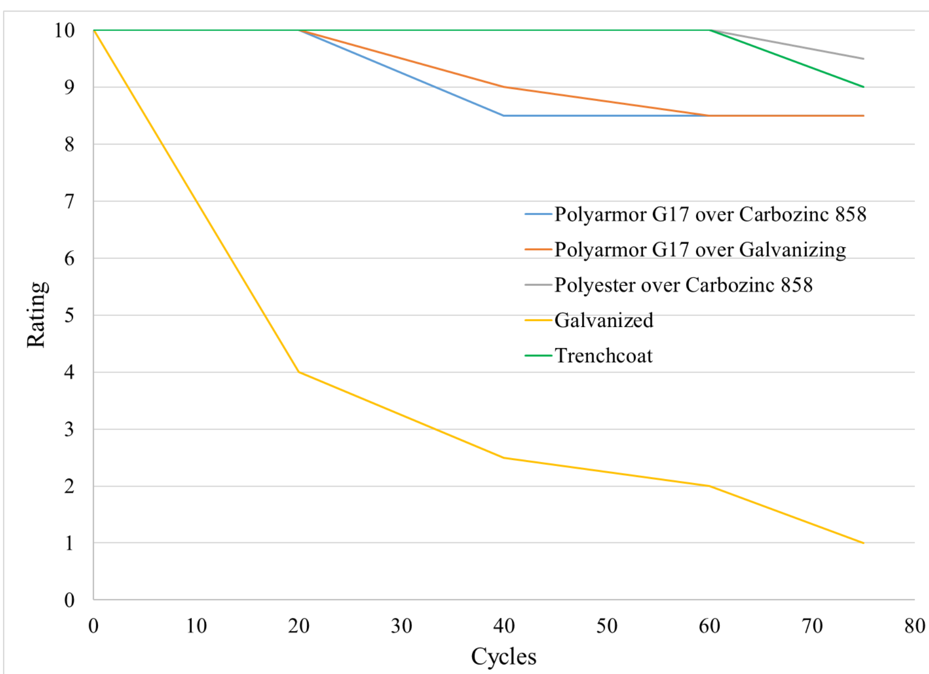


Figure 19: Average D610 Rating Over Time

Fastener Coatings

60-Cycle Visual Inspection

Each fastener was visually inspected for the presence of steel corrosion through the coating using the ASTM D610 scale in the three locations described above. Figure 21 shows the same panel as Figure 6 after 60 cycles.

Front of Panel Back of Panel

Figure 20: Example Panel After 60 Cycles

The average rating for each fastener coating is shown in Table 7 and graphically in Figure 22. The data after the completion of testing suggests that the Leland NZF 3000 and dip spun PT-24 performed similarly well with average ratings over 9.5. The uncoated galvanized fastener showed the most corrosion with a rating of 7.2. The spray-applied PT-24, PT-193, and RanVar coated galvanized bolts have intermediate ratings.

Table 7: Average ASTM D610 Rating of Fastener Coatings

Fastener Coating	Bolt Head	Nut	Threads	Overall Fastener
PT-24 Dip Spun	9.3	9.9	9.9	**9.7**
PT-24 Spray Applied	9.3	8.9	9.0	**9.0**
PT-193	8.4	8.3	8.6	**8.4**
Leland NZF 3000	9.2	9.5	10.0	**9.6**
Galvanized	7.1	7.1	7.4	**7.2**
Galvanized w/ RanVar	8.8	9.6	8.5	**8.9**

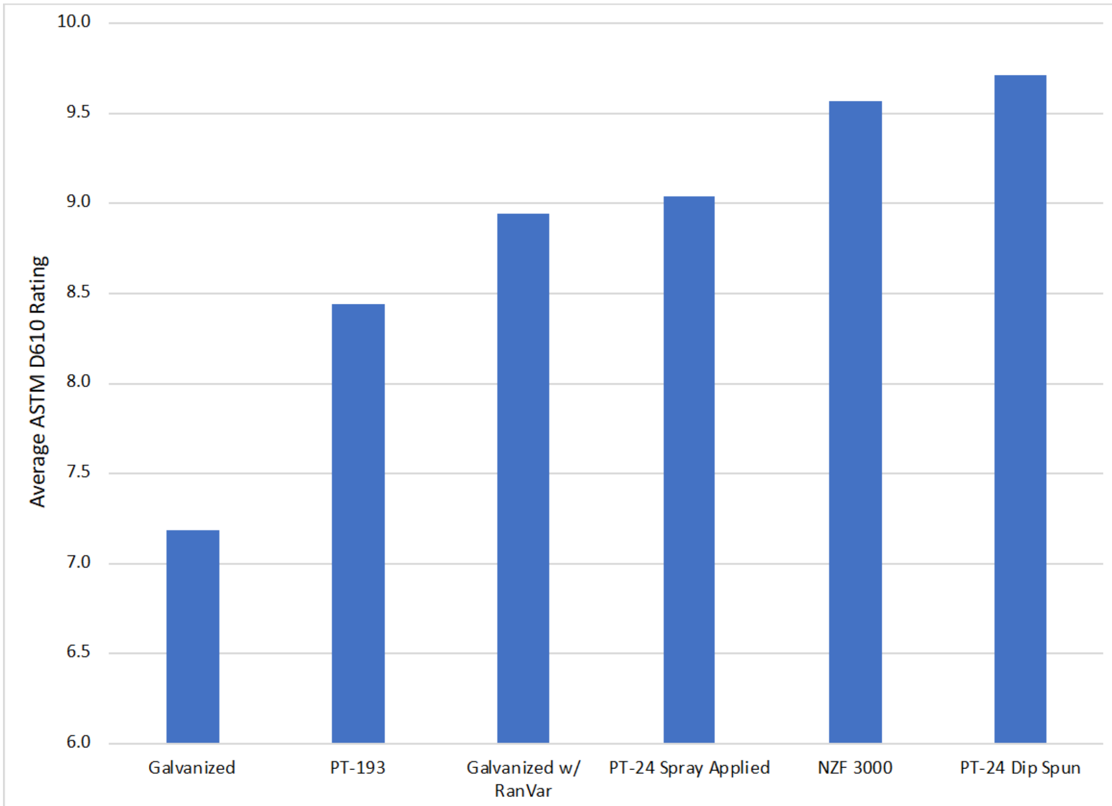


Figure 21: Average ASTM D610 Rating of Fastener Coatings

Interior Contact Areas Inspection

Table 8 shows the results of visual corrosion ratings taken on fasteners installed into the two panel groups coated with Lane's G17 powder coating. Fasteners installed into the galvanized sheet and Lane's Polyester powder coating were separated from analysis because the fastener coatings were affected by corrosion from the panel coatings, not from the fastener coatings. Panels coated with these two coatings exhibited heavy rust-though around the bolts which falsely impacted the ASTM D610 ratings on the fasteners. Table 8 shows that there is little difference in performance among fastener coatings as all interfaces performed similarly (ratings between 9.2 and 9.8).

Table 8: Visual Corrosion of Interior Contact Surfaces

Position	Fastener Coating	Head/Panel	Nut/Panel	Threads	Overall Fastener
1	PT-24 Dip Spun	9.8	9.9	9.6	**9.8**
2	PT-24 Spray Applied	9.8	10.0	8.4	**9.4**
3	PT-193	9.5	9.8	8.3	**9.2**
4	NZF 3000	9.6	9.8	9.8	**9.7**
5	Galvanized	9.9	9.8	8.9	**9.5**
6	Galvanized w/ RanVar	9.3	9.8	9.6	**9.5**

Breaking Torque Measurements

Figure 23 shows that the galvanized fasteners (both coated with RanVar epoxy and bare), required the most force to loosen from the test panel (both greater than 130 ft-lbs). The spray applied PT-24 required 35 more pounds of force than the dip spun to be loosened. The NZF 300 and PT-193 have intermediate ratings at 70 and 85 ft-lbs, respectively. Since the fasteners are not intended to be disassembled, this difference may not be significant. However, increases in breaking torque may be associated with corrosion of the galvanized coating.

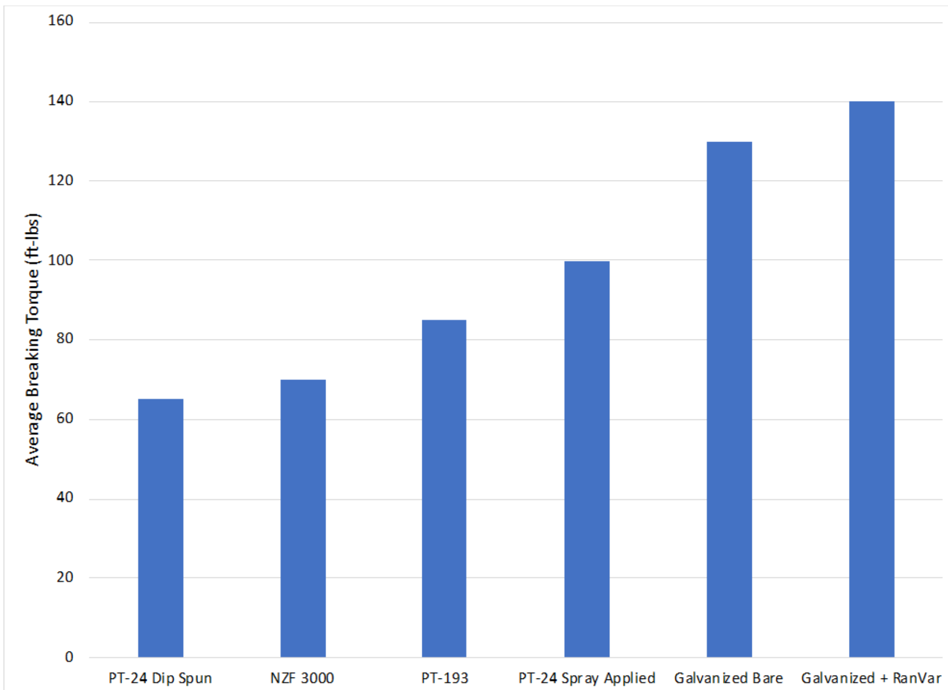


Figure 22: Average Breaking Torque of Coated Fasteners

Chemical Resistance Testing

Complete reports on the chemical resistance testing of Polyarmor G17 over Carbozinc 858 are included in Attachment III. The results are summarized below.

Chemical Spot Testing

The results of spot testing are summarized in Table 9. The imperviousness requirements of ASTM A1113 Section 8.2.4 were met; there was no loosening or separation of the coating from the substrate after a period of 48 hours.

Table 9: Summary of Chemical Spot Testing Results

Reagent Solution	Observations
10% Sodium Hydroxide	No. 8 blisters visible on top right of test area
10% Sodium Chloride	No blistering, softening, wrinkling, or loss of adhesion
30% Sulfuric Acid	No blistering, softening, wrinkling, or loss of adhesion

Chemical Immersion Testing

The results of chemical immersion testing are summarized in Table 10. Immersion in 10% sodium hydroxide solution had the greatest impact on the coating; these panels had severe blistering and delamination as well as color transfer from the coating system. Aside from one blister, the coatings immersed in 10% sodium chloride and 30% sulfuric acid were largely unaffected.

Table 10: Summary of Chemical Immersion Results

Panel ID	Reagent Solution	Observations
1	10% Sodium Hydroxide	Severe blistering, color transfer, coating has softened and delaminated from panel.
2		
10A		
3	10% Sodium Chloride	One blister, approximately 1.5 inches in diameter, was visible along bottom edge of panel. No color transfer or softening.
4		No blistering, softening, wrinkling, or loss of adhesion.
10B		
5	30% Sulfuric Acid	No blistering, softening, wrinkling, or loss of adhesion.
6		
10C		

Freeze/Thaw Testing

A complete report of the freeze-thaw testing is included in Attachment IV. After 100 cycles, the Polyarmor G17 and Polyarmor G17 over Carbozinc 858 coating systems showed no rust or disbanding. Panels coated with the ASTM A742 coating had multiple small areas of rust-through; this was the only coating system that showed any issues after testing. The Polyarmor G17 over Carbozinc 858 met the requirements of ASTM A1113.

Summary of Testing

Results from each test performed are listed below in Table 11 and Table 12.

Table 11: Summary Results of Plate Coatings

	Polyarmor G17-Liquid Zn	Polyarmor G17-Galvanized	Polyester - Liquid Zn	Galvanized	Trenchcoat
ASTM D610 (*after 80 GMW cycles*)	8.5	8.5	9.5	1.0	9.0
Coating Thickness (*mils*)	13.4	11.1	7.1	1.7	13.2
Abrasion Resistance (*L/mil*)	9.2	12.5	1.8	26.5	6.6
Improved Abrasion Resistance (*mil/L*)	0.045	0.040	0.26	0.028	0.083
GM Undercutting (*mm after 75 cycles*)	1.66	5.78	0.94	N/A	3.19
Tensile Adhesion (*psi*)	1,653	1,078	1,936	Not Performed	1,237
Direct Impact Resistance (35 in-lbs at -9°F)	Pass	Fail	Pass	Not Performed	Pass
Direct Impact Resistance (35 in-lbs at 88°F)	Pass	Fail	Pass	Not Performed	Pass
Mandrel Adhesion (-9°F)	Not Performed	Fail	Fail	Not Performed	Not Performed
Mandrel Adhesion (88°F)	Pass	Fail	Fail	Not Performed	Pass
Mandrel Adhesion (122°F)	Not Performed	Fail	Fail	Not Performed	Not Performed

Table 12: Summary Results of Fastener Coatings

Fastener Coating	ASTM D610 (Entire Bolt)	ASTM D610 (Interior Contact Surfaces)	Average Breaking Torque (ft-lbs)	Abrasion Resistance (L/mil)	Knife Adhesion
PT-24 Dip Spun	9.7	9.8	65.0	0.38	5A
PT-24 Spray Applied	9.0	9.4	68.8	0.07	5A
PT-193	8.4	9.2	83.8	0.15	5A
Leland NZF 3000	9.6	9.7	101.9	0.25	5A
Galvanized	7.2	9.5	132.5	Not Performed	
Galvanized w/ RanVar	8.9	9.5	139.4	Not Performed	

Recommended Specification Requirements

Table 13 and Table 14 present the recommended specification requirements for the plate coatings and fastener coatings, respectively.

Table 13: Suggested Plate Coating Specification Parameters

Parameter	Industry Specification	Requirement Range
Adhesion	ASTM D4541	1,400 psi
Abrasion Resistance	ASTM D968	Less than 0.08 mil/L
Corrosion Resistance	ASTM D1654	Less than 3 mm after 60 cycles GMW 14872
Elongation	ASTM D638	Greater than 450%
Impact Resistance	ASTM D2794	Pass 160 in-lb direct impact
Imperviousness	ASTM D543	No loosening or separation of polymer coating after 48 hours
Freeze Thaw Resistance	ASTM A1113	No spalling, disbanding, or other detrimental effects after 100 cycles

Table 14: Suggested Fastener Coating Specification Parameters

Parameter	Industry Specification	Requirement Range
Corrosion Resistance	ASTM D610	Greater than 8 after 60 cycles GMW 14872
Adhesion	ASTM D3359	Less than 5% coating removal to substrate
Coating Thickness	N/A	Greater than 0.75 mils
Fit and Function	N/A	Coated nut shall spin freely on coated bolt. No coating cracking or delamination when fully tightened

Attachment I – Photographs of Accelerated Corrosion Testing Panels

<table>
<tr><th>Before GMW Testing</th><th>After GMW Testing</th></tr>
<tr><td></td><td>
</td></tr>
<tr><td colspan="2">Polyarmor G17 over Galvanizing</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td colspan="2">Polyarmor G17 over Carbozinc 858</td></tr>
</table>

Before GMW Testing	After GMW Testing
	
Polyester over Carbozinc 858	
	
ASTM A742 Polymer laminate over Galvanizing	

Attachment II – Summary of ASTM A1113/A1113M Coating Testing Results

ASTM A1113/A113M Coating Testing Results

Plate Coating: Polyarmor G17/Carbozinc 858

The plate coating system consisted of the following:

- A zinc rich primer with a minimum 60 wt% zinc content (Carbozinc 858) applied with a minimum thickness of 2 mils
- A thermoplastic copolymer coating consisting of at least 85 wt% EAA copolymer (Polyarmor G17) applied at a nominal thickness of 10 mils
- Prior to coating, the steel was free of rust, mill scale and other contaminants

The coating system was applied to all surfaces of the test panels in a controlled environment using a continuous application process. All test panels were then subjected to performance testing listed in Table 15.

Table 15: Compliance of Polyarmor G17/Carbozinc 858 System with ASTM A1113

Test	Description	Requirement	Results
ASTM D5522 Method B	Adhesion	No spalling, cracking, disbonding when applied to a 22-gage panel bent around a ¼-inch diameter mandrel	Pass
ASTM D4541	Adhesion	The coating system shall demonstrate pull-off strength in excess of 1,400 psi	Pass (1653 psi)
ASTM D2794	Impact	No breaks in the film as detected with a pinhole detector when tested at 160 in-lb using a 0.625-inch indenter	Pass
ASTM D968	Abrasion	Coating erosion rate of less than 0.08 mils of coating per liter of abrasive for a minimum of 100L of abrasive	Pass (0.045 mil/L)
ASTM D543	Imperviousness	No loosening or separation of the polymer coating after exposure to the reagent for a period of 48 hours	Pass
GMW 14872/ ASTM D1654	Corrosion Resistance	After 60 cycles of the cyclic corrosion test GMW 14872, mean undercutting at the scribe shall be less than 3.0 mm	Pass (1.6 mm)
ASTM D638	Elongation	Thermoplastic copolymer shall have an elongation greater than 450%	Pass (498%)
ASTM A1113	Freeze/Thaw Resistance	No spalling, disbanding, or other detrimental effects after 100 cycles	Pass

Fastener Coating: NZF 3000

Nuts and bolts were shop coated with NZF 3000, a non-electrolytically applied zinc and aluminum flake fastener coating. The coating system was applied to all surfaces of the fastener components to a minimum dry film thickness of 0.75 mils. The coated fastener components underwent testing summarized in Table 16.

Table 16. Compliance of NZF 3000 Fastener Coating with ASTM A1113

Test	Description	Requirement	Results
ASTM D610	Corrosion Resistance	After 60 cycles of cyclic corrosion test GMW 14872, coated fastener components shall exhibit less than 0.1% red rust (Rating of 8 or better)	Pass (9.6 average rating)
N/A	Coating Thickness	The total dry film thickness of the coating system shall be a minimum of 0.75 mils	Pass
ASTM D3359	Adhesion	Where practical to evaluate (i.e., flats or bolt heads), the coating shall show less than 5% removal to substrate following the tape adhesion test	Pass
N/A	Fit and Function	The coated nut shall spin freely on the coated bolt. When fully tightened, the coating shall not crack or delaminate from the fastener surfaces	Pass

Attachment III – Chemical Resistance Test Report

Attachment IV – Freeze-Thaw Test Report