Thermally Sprayed Metallic Coatings to Protect Steel Pilings: 5-Year Performance Update

DETAILS

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Research Results Digest 344

THERMALLY SPRAYED METALLIC COATINGS TO PROTECT STEEL PILINGS: 5-YEAR PERFORMANCE UPDATE

This digest summarizes key findings from NCHRP Project 24-10(02), "Thermally Sprayed Metallic Coatings to Protect Steel Pilings: 5-Year Corrosion Study Update," conducted by Corrpro Companies, Inc., Ocean City Research Group, Ocean City, New Jersey. The digest was prepared from the project final report authored by William S. Vilda III, Corrpro Companies, Inc.

INTRODUCTION

The use of zinc and aluminum as coatings for steel began in the early 1900s, with the application of thermally sprayed metallic coatings (TSMCs) to bridge structures beginning in the 1930s (*1*). Thermally sprayed metallic coatings of zinc, aluminum, and their alloys can offer substantial advantages when compared to other coatings typically used to protect steel pilings: most importantly, generally higher mechanical damage resistance, low self-corrosion rates, and the ability to control steel corrosion via cathodic protection at defects in the coatings.

NCHRP Project 24-10, "Thermally Sprayed Metallic Coatings to Protect Steel Pilings," which was completed in 2003, developed a Thermally Sprayed Metal Coating Guide that provides TSMC application procedures for corrosion control on piles used in highway construction. The guide includes information on the selection, specification, and application of metal coatings for steel piles in freshwater, brackish, and seawater environments; it is contained in *NCHRP Report 528, Thermally Sprayed Metal Coatings to Protect Steel Pilings: Final Report and Guide,* which is available by searching for *"NCHRP Report 528"* on the TRB website (www.trb.org).

This Research Results Digest presents the results of NCHRP Project 24-10(02), which evaluated the performance of several TSMC types applied over steel in conformance with the aforementioned guide and immersed in seawater in a controlled, 5-year experiment. The complete set of 5-year experimental results is summarized in graphical form on the TRB website at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP24-10(02)_FR_AppendixA.pdf.

EXPERIMENTAL ISSUES

Alloy Selection

The most commonly used metals for the protection of steel are anodic to steel and thus provide sacrificial protection to the steel substrate and eliminate the need for a barrier completely free of pinholes (*2*). Thus, zinc, aluminum, and alloys of these two metals are favored for the protection of steel. Ideally, the alloy should have a very low self-corrosion rate and be an efficient and effective sacrificial anode.

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Aluminum TSMCs have been found to protect steel well under seawater immersion conditions (*3*). Because TSMCs are porous, sealers are often specified to reduce the porosity and improve the service life of the TSMC. Common sealers include epoxies and vinyl coatings, but this study also investigated other sealer materials.

Quality Assurance Requirements

TSMCs are sensitive to surface preparation and application conditions (*4*). Most specifications require an SSPC-SP 5 white metal surface for application of TSMCs (*5*). This surface condition can be difficult to achieve, especially if field rather than shop application is being considered. Other parameters, such as the abrasive type used for surface preparation, the required profile range, and environmental conditions during application can affect TSMC porosity, adhesion, and corrosion performance.

Damage Tolerance of TSMC

A key aspect of TSMCs is their resistance to damage during transportation, handling, and installation. Regardless of whether shop or field application is used, there is a tendency for impact and flexure damage to steel coatings.

Research Plan

The original NCHRP Project 24-10 included a 1-year seawater exposure experiment that yielded very little deterioration of the test samples. Project 24-10(02) continued the exposure for 5 additional years to allow more time for corrosion to develop. The remainder of this digest summarizes the experimental procedures, results, findings, and conclusions.

LABORATORY TEST PROCEDURES

The continuation of the Project 24-10 experiment was designed to improve the usefulness of the TSMC guide by evaluating the effects of the following materials and parameters on TSMC performance:

- Sealer materials, including high solids, high penetration epoxies, and urethanes.
- Abrasive mix.
- Angularity and methods to measure it in the field.
- Spray application parameters, i.e., standoff distance and application angle.
- Steel substrate hardness and its influence on surface preparation requirements.
- TSMC defects.
- Chloride surface contamination.

Test Panel Preparation

Test panels used in the evaluation of adhesion, sealers, abrasive mixtures, edge effects, and application parameters were prepared by CSI Coatings, Nisku, Canada (CSI) using Thermion Bridgemaster equipment. The steel used for the corrosion tests met the requirements of AASHTO M270 Grade 36 or ASTM A328. M020 steel was used for the complex corrosion test panels. Panels for the impact test were A36 steel. Other test panels were made from ASTM A569 steel.

Test panels used in the evaluation of the effects of surface contamination, alloy, and hardness were prepared using a Metco wire arc apparatus at Corrpro's Ocean City, NJ (OC) laboratory facility. Grade 36 steel was used for most testing, although ASTM A572 Grade 50 steel was used in the hardness comparison tests between A36 and Grade 50 steels. Unless otherwise specified, the panels were prepared for coating with 100% G-16 steel grit blasting. In all cases the surface finish was SSPC-SP 5 white metal with a target profile of 3 mils. Figure 1 shows the complex form of the test panels used in corrosion testing.

This study also explored the effects of grit-to-shot ratio on surface profile and the performance of zinc and aluminum TSMCs. Most current standards and guidance documents specify the use of "angular" abrasives to obtain the required surface profile; thus, an angular profile is expected. A high degree of angularity is important because most stresses

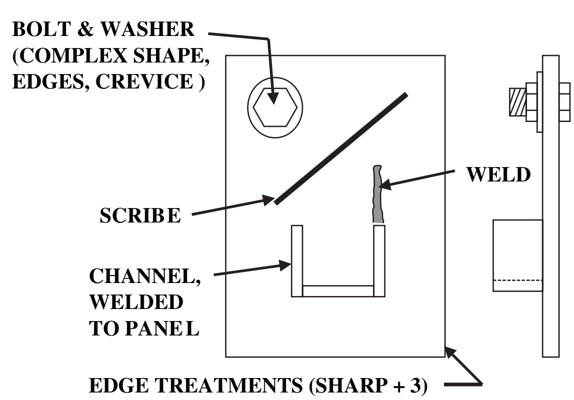


Figure 1 Test panel used for corrosion testing.

Table 1 Blast procedures investigated.

Grit/Shot	Steel Shot	Steel Grit	Rationale
Shot blast	100% S-280		Negative control.
Grit blast		100% G-16	Positive control.
Grit/shot mix	33% S-280	67% G-16	Observed in shop for TSMC project in NC.
Alternate grit/shot mix	70% S-280	30% G-16	Test the profile provided by a "low-grit" mixture.

acting to debond the TSMC are shear forces and an angular surface provides more surface area for the TSMC to adhere to. However, recycled steel shot is the preferred method of surface preparation for many steel fabricators because it is economical, although mixed steel shot and grit are often used to reduce equipment wear. These practices can result in varying levels of angular profile; this study investigated the impact of such practices by applying TSMCs over various surface roughness conditions. The most common technique for determining angularity compares magnified images of the surface to standard photomicrographs. This study also included an effort to identify a method of quantitatively measuring angularity in the field. Table 1 lists the abrasive mixes tested to prepare surfaces to an SSPC-SP 5 white metal finish for aluminum and zinc TSMCs.

TSMC Application

TSMC application was performed using wire-arc spray equipment and standard application parameters. CSI prepared the test panels used to evaluate adhesion, sealers, surface preparation parameters, edge effects, and application parameters; OC prepared the test panels used to evaluate surface contamination, alloy, and hardness effects. A target film thickness of 10 to 12 mils was specified in all cases. The standoff distance was nominally 8 to 10 in.; the application angle was 90° to the sample surface.

Testing Program

Table 2 shows the test matrix; Table 3 shows the tests conducted to satisfy the objectives of the extended project.

Quality Assurance Testing

After surface preparation, quality assurance (QA) testing was conducted on representative samples. This testing included visual inspection, surface profile evaluation, and determination of chloride contamination. The QA testing methods are discussed below.

Visual Inspection for Surface Quality

Visual inspection of the surface was made in accordance with the Society for Protective Coatings (SSPC) Standard VIS-1-89. The appearance of the prepared surface was compared to visual standards to determine if it conformed to an SSPC-SP 5 (white metal blast) condition.

Surface Profile Evaluation

The target surface profile was 3 mils (76 μm). Profile evaluation was performed on all samples for the 100% shot, 70% shot/30% grit, and 33% shot/67% grit abrasives. Select 100% grit abrasive samples were also tested. Surface profile was evaluated using two methods. Initial measurements were made using Testex™ brand replica tape. This tape is placed

Table 2 General test matrix.

Test	Sample Size (inches)	Comments
Alternate wet–dry immersion	4 × 6 × 0.125*	Representative of splash and tidal zone exposure
Constant immersion	4 × 6 × 0.125	Representative of constant immersion conditions

*Special panel containing crevice, scribe, fastener, and edge treatments

Table 3 Test variables and methods.

	Test Method						
Variable	**Thickness**	**Profile**	**Bend Adhesion**	**Tensile Adhesion**	**Corrosion**	**Drop Weight Impact**	**Micro-Structure**
Sealer	X	X	X	X	X	X	X
Abrasive mix	X	X	X	X	X	X	
Spray application	X	X		X	X		X
Steel hardness	X	X		X	X		
Coating defect	X	X			X		
Surface contamination	X	X		X	X		

over the blasted substrate and rubbed in-place to create an impression of the surface profile. A micrometer is then used to determine the overall profile (peak to valley height) of the surface. This is the most commonly used field technique to evaluate surface profile. Figure 2 illustrates this measurement.

The second method to determine the profile of the blasted surface was the use of a surface profile gauge. Two gauges (see Figure 3) were used. Samples prepared by CSI were evaluated using a Perthometer MP4 150 profilometer, while samples prepared at the OC were evaluated using a Mitutoyo SJ-201 surface roughness gauge. Both gauges can be used in the field and are capable of measuring the profile parameters shown in Table 4.

Both of these surface profile gauges use a stylus on a linearly displaced moving head to measure surface profile characteristics. This stylus follows the contour of the substrate, measuring peak height, valley depth, and their variability. Gauges were calibrated before use, and the same technician performed the profile measurements at CSI and OC. The surface profile measurements were statistically analyzed to yield values of the surface profile parameters shown in Table 4.

Figure 2 Testex™ tape to evaluate surface profile.

TSMC Thickness Measurements

TSMC thickness measurements were made on prepared samples that were cooled after TSMC application and held for a minimum of 7 days after application of sealer coats. TSMC thickness measurements were made with an Elcometer 345 eddy current thickness gauge (SSPC-PA type 2 gauge). The Elcometer 345 thickness gauge was calibrated over a representative steel panel blasted to an SSPC-SP 5 condition and a 3 mil (76.2 μm) surface profile. Calibration was performed using standard plastic shims of known thickness that bracketed the expected TSMC thickness. This calibration was performed daily, before thickness measurements were made.

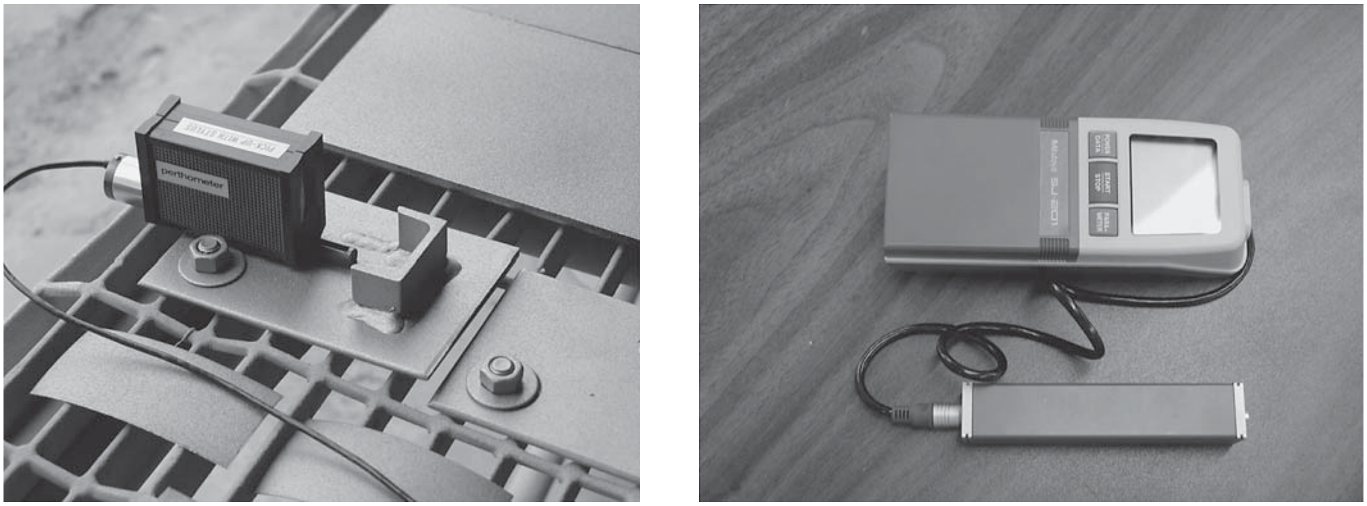
Typically, 5 thickness measurements per side were made on all test samples with the exception of the 4- by 6-in. (10.2- by 15.2-cm) complex samples that received 8 measurements per side or 16 measurements total per panel. Measurements were taken at consistent locations for each type of panel.

The thickness ranges of TSMCs applied by CSI were:

Zinc	12.9 to 20.8 mils
Aluminum	14.8 to 22.9 mils
Zinc/aluminum	14.7 to 19.5 mils

The thickness ranges of TSMCs applied to the A36 and Grade 50 panels by OC were:

Zinc	9.9 to 11.8 mils
Aluminum	12.3 to 14.2 mils



Perthometer

Mitutoyo SJ-201

Figure 3 Surface profile gauges.

Corrosion Tests

Laboratory corrosion tests consisting of alternate wet–dry seawater immersion and constant immersion were performed to evaluate the sealers, surface preparation, and TSMC application variables. Previous studies have shown that a short-term exposure test may be inadequate to differentiate the performance of TSMC/sealer systems and that such systems may be exposed to harsh environments for several years without exhibiting significant levels of corrosion. The 5-year extension to this program was meant to address this situation by allowing adequate exposure time for TSMC deterioration.

Natural seawater immersion testing was used to evaluate the performance of the TSMC and other preparation variables. Testing was conducted at Corrpro's Ocean City, New Jersey, facility using natural seawater obtained from the Inland Intracoastal Waterway adjacent to that facility. Seawater is pumped through this facility in an open-loop, once-through system. The facility is equipped to filter large debris and biological growth; otherwise, the seawater contains all chemicals naturally found at this location.

Test samples were placed in a plastic tank and held in position with plastic fixtures. Samples were oriented at 90° from horizontal and completely submerged in the natural seawater environment. To avoid stagnation, the seawater was continually refreshed using a trickle (quiescent) flow from the intake system.

Annual inspections of test samples were made to evaluate performance. These inspections included the following evaluations: (1) substrate corrosion (rusting) in accordance with ASTM D610, *Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces;* (2) TSMC blistering in accordance with ASTM D714, *Standard Test Method for Evaluating Degree of Blistering of Paints;* (3) formation of corrosion products on the samples; and (4) visible cutback from intentional holidays in accordance with a modification of ASTM D1654, *Evaluation of Painted or Coated Specimens Subjected to Corrosive*

Table 4 Surface profile characteristics.

Parameter	Description
Arithmetic mean deviation (R_A)	The average of the absolute value of the height or depth for all measurements
Root-mean-square deviation (R_Q)	The square-root of the average of the squared absolute height or depth value
Maximum profile height (R_Y)	The sum of maximum height and depth over a given area
Ten-point height irregularities (R_Z)	The sum of the mean of the five highest peaks and five lowest valleys over a given area
Peak count (R_{PC})	The number of peaks above a specified threshold limit from the mean

Table 5 Test methods to measure TSMC performance.

Performance Factor	Test Method	Description
Substrate corrosion	ASTM D610	Evaluation of percent corrosion on a test sample by comparison with visual standards (0 to 10 scale, where 10 = no corrosion)
TSMC blistering	ASTM D714	Evaluation of blister size and frequency on a test sample by comparison with visual standards (0 to 10 for size, where 10 = no blistering; F, M, MD, D for frequency, where F = few, M = medium, MD = medium-dense, and D = dense)
Corrosion products	N/A	Visual observation for corrosion at the intentional scribes, along edges, in crevices, and at welds, and general deterioration and other observations
Cutback from holidays	Modified ASTM D1654	Measurement in millimeters of visible coating (TSMC or sealer) disbondment from intentional holidays evidenced by disbondment, blistering, or rusting

Environments. After 5 years, destructive cutback evaluation was performed. These test methods are briefly described in Table 5.

For analytical purposes, the ASTM D714 rating is converted to a composite blistering rating. A numerical rating from 0 to 10 derived from the size and density of the blisters is given to the sample. Table 6 presents this composite blister index.

After sample preparation and sealer cure, the test samples intentionally were given either a linear scribe or a circular holiday in which the TSMC and sealer materials were removed down to the steel substrate. This action created a known defect at which to measure the coating system's ability to resist additional corrosion damage.

Figure 1 illustrates the type of panel to which a linear scribe or a circular holiday was applied; Figure 4 shows representative examples of linear scribes and circular holidays (the holidays are highlighted). Scribes and holidays are commonly used in corrosion testing to accelerate the natural degradation of samples. The linear scribe was a diagonal line cut through the TSMC with a sharp-pointed, hardened-steel tool to ensure that the steel substrate was exposed. The panel edges were used to examine the effect of different edge treatments. Circular holidays were used to heighten the potential performance differences between zinc and aluminum TSMCs. The holidays were 1.5 in. (3.81 cm) in diameter; they increase the stress on the test samples and evaluate the throwing power[1] of the TSMC applied to the panel. A large-diameter holiday increases the anode-to-cathode surface area ratio and, thus, the sacrificial protection requirements of the TSMC. The anode-to-cathode surface area ratio was nominally 48 to 0.18 for linear scribes and 48 to 1.8 for circular holidays.

Table 6 Composite blister index.

Blister Size	Dense	Medium Dense	Medium	Few
1	0.00	1.00	2.00	3.00
2	0.35	1.65	2.60	3.78
3	0.55	2.10	3.20	4.56
4	0.75	2.50	3.80	5.33
5	0.90	3.00	4.40	6.11
6	1.10	3.70	5.00	6.89
7	1.60	4.60	6.25	7.67
8	3.50	6.00	7.50	8.44
9	4.80	8.00	8.75	9.22
10	10.0	10.0	10.0	10.0

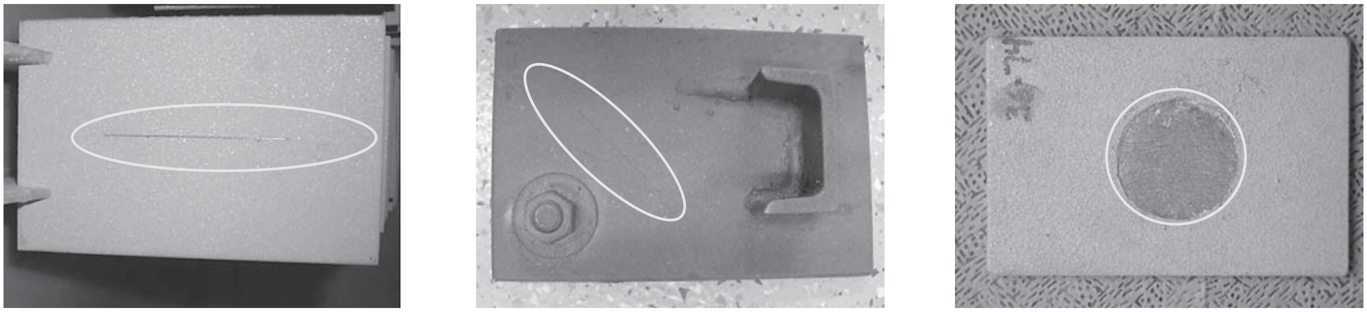
Constant Seawater Immersion

The constant seawater immersion test is indicative of a fully immersed environment for metalized piles. Panels were immersed continuously except during evaluation periods.

Alternate Wet–Dry Seawater Immersion

Alternate (or cyclic) wet–dry seawater immersion simulates the tidal action of natural waters, which can accelerate the corrosion of structures.

[1] Defined in metallurgy as the ability of an electroplating solution to deposit metal uniformly on an irregularly shaped cathode.



Scribe (4 × 6 inch) | Scribe (4- × 6-inch complex) | Circular Holiday (4 × 6 inch)

Figure 4 Representative scribes and holiday.

Test samples were immersed in natural seawater for approximately 15 minutes followed by 75 minutes exposure to a harsh marine environment.

This test was conducted in the same tank used for constant immersion. An automated timer was used to cycle immersion and atmospheric exposure in this zone only. (Constant immersion samples were continually submerged in natural seawater.) The presence of natural seawater in the lower half of this tank created an atmospheric environment similar to that expected during naturally occurring periods of low tide.

Similar to the constant immersion samples, alternate wet–dry immersion samples were inspected annually for deterioration as described in Table 5.

LABORATORY TEST RESULTS

Sealer Tests

Sealers are specified to seal the pores in TSMCs and improve their performance. Five commercial sealer products of the types shown in Table 7 were tested along with unsealed TSMC control samples. The sealers were tested on steel panels coated with both zinc and aluminum TSMCs. Two different low surface energy, high solids sealer products (Product Codes C and D) were selected because they were both recommended by the Virginia DOT according to an applicator interviewed in the original study.

Table 7 Sealer types.

Product Code	Generic Type
A	Chromate vinyl wash primer
B	Epoxy (coal tar epoxy or equivalent)
C	Low surface energy, high solids sealer
D	Low surface energy, high solids sealer
E	Low viscosity penetrating urethane

The sealers were applied using air-spray equipment in accordance with the manufacturers' recommendations for mixing and thinning. All sealers were applied with a maximum target dry-film thickness of 1 mil or as specified by the manufacturer (if less than 1 mil). The samples were scribed as described above.

Corrosion Tests Comparing Sealers

Overall, the results from the constant immersion testing through the 5-year extension period indicated that the presence of sealer provides some benefit in reducing cutbacks if the proper type is chosen. However, little or no effect of the presence of sealer was found in the results of the corrosion and composite blister tests.

Specifically, the overall corrosion rating for unsealed zinc TSMC was 8 (on a rating scale of 0 to a maximum of 10) and that for unsealed aluminum TSMC was 1. Overall corrosion ratings for sealed zinc and aluminum TSMC were 7 and 1, respectively. Composite blister ratings for unsealed zinc and aluminum TSMC were 5 and 9 (on a rating scale of 0 to a maximum of 10), respectively. Composite blister ratings were 4 and 8 for sealed zinc and aluminum TSMC, respectively, with the notable exception of the Code D sealer over aluminum, for which the rating was 0.

Sealed zinc TSMC showed decreased cutback across the board. The amount of cutback ranged from about 1 mm to 4 mm versus 8.5 mm for unsealed zinc TSMC. Aluminum TSMC performed well both sealed and unsealed. The exception again is the Product Code D sealer, although for this product the extensive cutback (34 mm) was likely more heavily influenced by the near total blistering of the surface. For zinc TSMC the optimum sealers for constant immersion service appear to be the sealer products coded A, C and D, and E, each of which had a final cutback average of 2 mm. The chromate vinyl wash primer (Product A) contains hexavalent chromium, which is regulated as a hazardous waste product, and its use may be limited by regulation. There are alternative conversion coating formulations, but their performance was not tested in this research. The performance of aluminum TSMC appears unaffected by the use of a sealer.

The corrosion test results for the alternate immersion environment yielded a varied range of performance. The overall corrosion rating for unsealed zinc TSMC (7.5) was slightly higher than for sealed (6.5). However, sealed aluminum TSMC performed much better than unsealed, with ratings of 6 and 2, respectively. Composite blister ratings for sealed and unsealed aluminum TSMCs were comparable (both about 8.5), and unsealed zinc TSMC had a slightly higher overall blister rating of 8 versus 6.5 for sealed. Both zinc and aluminum TSMCs benefited from sealer in terms of final cutback. The best performing sealer for zinc TSMC in the alternate immersion environment was the chromate vinyl wash primer (Product A), while aluminum TSMC benefited most from the low surface energy, high solids sealer (Product D). This is an interesting observation given the poor performance of aluminum TSMC with Product D in the constant immersion testing. The epoxy sealer (Product B) also performed well with aluminum TSMC.

In summary, the results after the 5-year exposure period indicate that the performance of aluminum and zinc TSMCs in constant and alternate immersion environments varies widely with different sealer types. Overall, zinc TSMC benefited most from the chromate vinyl wash primer in both environments. This is unfortunate due to the health concerns noted above about the presence of hexavalent chromium in this product. Product C, one of the two low surface energy, high solids sealers tested, also performed well over zinc TSMC. An epoxy sealant (Product B) performed well over aluminum TSMC in the alternate immersion environment. While little benefit was seen from any sealer in constant immersion over aluminum TSMC, the epoxy sealer did not have a detrimental effect and therefore may be appropriate for either environment.

Abrasive Mix Effects

Adhesion Tests

Figure 5 presents the surface profile measurements made using Testex™ replica tape on the samples prepared by CSI using different abrasive mixes (Table 1). The confidence interval was estimated using the Student's t-distribution by the equation:

$$Confidence = \frac{t \times StdDev}{\sqrt{n}}$$

where t = 3.182 for a 95% confidence for 3 degrees of freedom and n = number of data points. (Confidence intervals shown on other graphs in this report were calculated in the same way.)

The results in Figure 7 show that 100% grit and the 33% shot/67% grit mixture produced deeper profiles than did 100% shot or the 70% shot/30% grit mixture. The average profile produced by the 33% shot/67% grit mix is deeper than that produced by 100% grit, but there is overlap in confidence intervals for the data.

Profile Measurements

As described above in "Laboratory Test Procedures," surface profile characteristics were measured with a profilometer to yield values of the parameters R_A, R_Y, R_Z, and R_Q (as defined in Table 4). Figure 6 shows the values of R_A, R_Y, R_Z, and R_Q, and Figure 7 shows the values of R_{PC} obtained on the A36 steel panels prepared by CSI Coatings. Similar measurements were performed on the OC-prepared A36 and Grade 50 samples.

All profilometer data, except peak count, showed definite increases in the R_A, R_Y, R_Q, and R_Z values for abrasive containing more angular grit. Beyond that observation, the overlaps in the confidence intervals preclude any conclusions with regard to the utility of the profilometer measurements to define performance. As shown in Figure 8, peak count for the panels prepared by CSI showed significant overlap between the various abrasive mixes, precluding the possibility of distinguishing among abrasive mixes. The values of R_A, R_Y, R_Q, and R_Z for the A36 and Grade 50 steels on panels prepared by both CSI and OC all have significant overlaps in the confidence intervals; the only significant difference between the abrasive mixes was the lower values for shot-blasted panels compared to grit blasted.

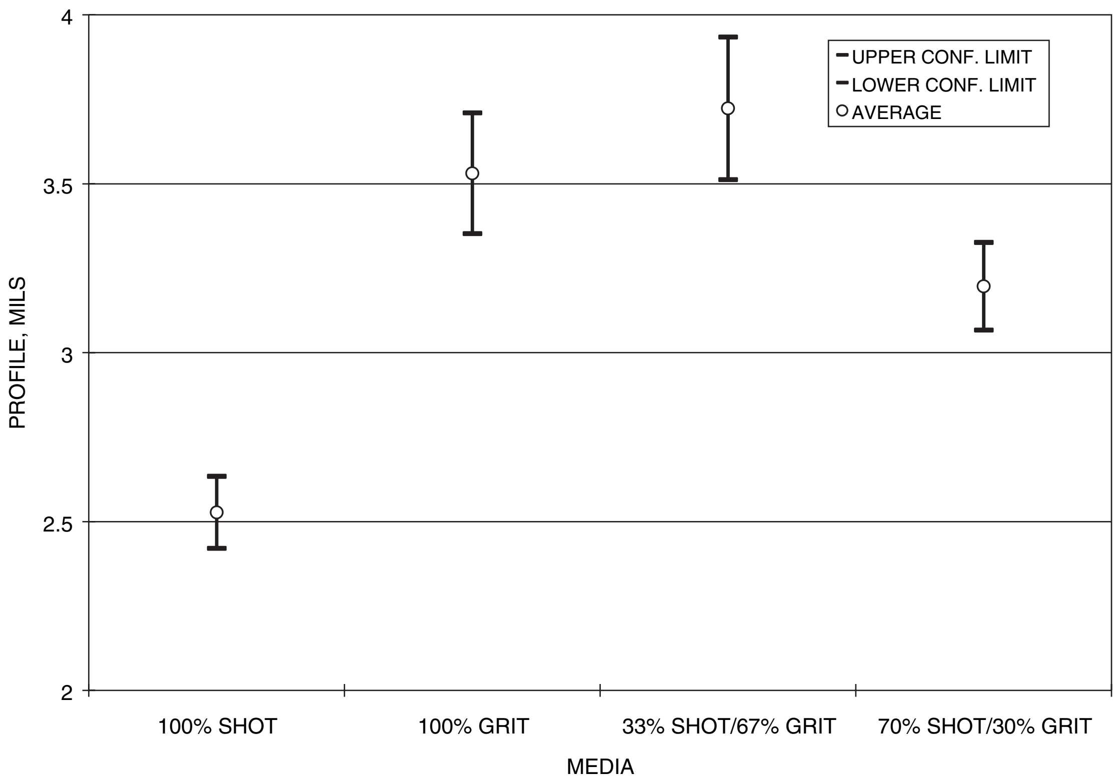


Figure 5 Testex™ replica tape profile ranges (CSI-prepared test panels).

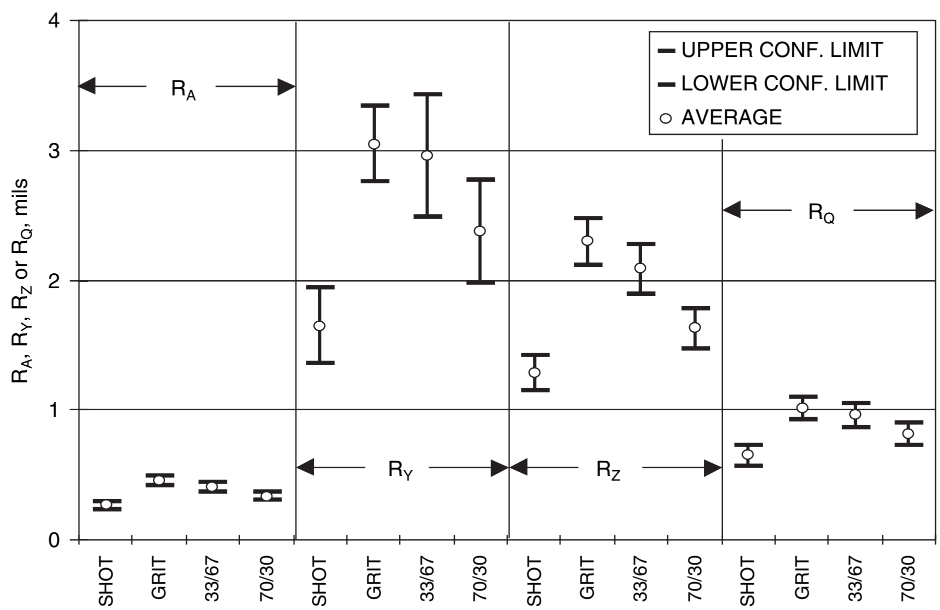


Figure 6 Average values and 95 percent confidence ranges for R_A, R_Y, R_Z, and R_Q profilometer data on A36 panels prepared with different abrasive mixes.

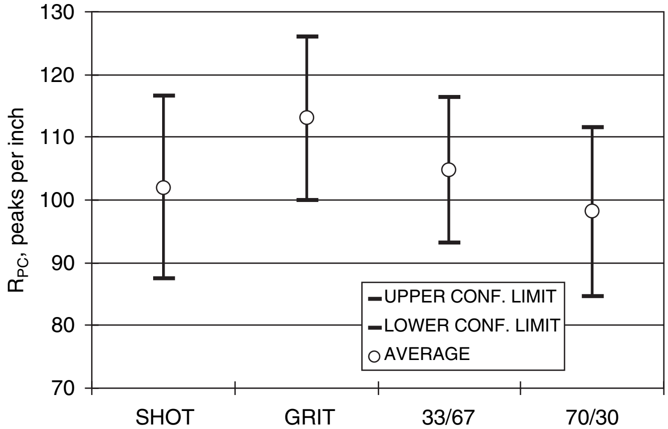


Figure 7 Average values and 95 percent confidence ranges for R_{PC} profilometer data on A36 panels prepared with different abrasive mixes.

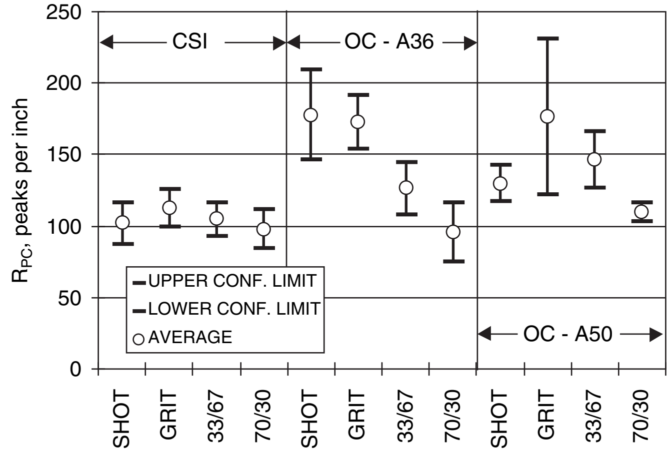


Figure 8 R_{PC} versus abrasive mix and applicator.

Interestingly, the values of R_{PC} are generally higher and the values of R_Q lower on the panels prepared by OC than on those prepared by CSI. Average R_{PC} for the grit-blasted CSI panels is 113 peaks/inch, and the average peak counts for the OC-prepared panels are 173 and 176 peaks/inch for A36 and Grade 50 steel, respectively. Figure 9 shows the graphs of R_Q versus abrasive mix and applicator, and Figure 8 shows the similar graphs of R_{PC}. The variable or variables—abrasive equipment, abrasive source, profilometer instrument, or steel type—that are responsible for the differences in R_Z, R_{PC}, and R_Q could not be determined from the available results. Comparison of the adhesion strength values and their corresponding confidence intervals indicates that the adhesion strengths are higher for the panels with higher R_{PC} values and lower R_Q values. This is true for the grit-blasted aluminum TSMC and for the zinc TSMC panels blasted with 70% shot/30% grit and 33% shot/67% grit mixtures, but not for the grit-blasted zinc or shot-blasted TSMC panels.

All thermal spray guides and specifications call for the surface profile to be "angular," but there is no general definition of what angularity limits or methods of measuring angularity are acceptable. Angularity is often measured by (1) the number of peaks per unit area, and (2) the rate of change of the shape of the peaks and valleys; these measurements can be obtained in part through the use of surface profilometers. Values of R_{PC} and R_Q showed promise in

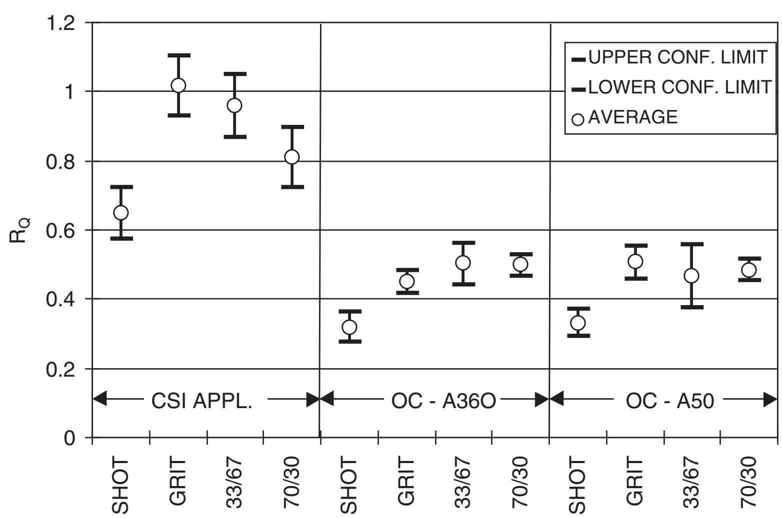


Figure 9 Values of R_Q versus abrasive mix and applicator.

the original NCHRP Project 24-10 as indicators of good angularity. However, the results reported here suggest that the characteristics of the abrasive used to prepare the surface for TSMC may be the best—albeit indirect—measure of angularity.

Corrosion Tests Comparing Abrasive Mixes

The aluminum TSMC in alternate immersion tests performed best when the surface was prepared with a 33% shot/67% grit abrasive mixture. This mixture resulted in an improved corrosion rating, no blistering, and very little cutback. In the constant immersion tests, results were mixed. The 100% grit yielded the least blistering and cutback, but the most corrosion (2.8). A 70% shot/30% grit mixture yielded the best corrosion rating (5). In both environments, 100% shot was associated with poor performance.

The performance of zinc TSMC in alternate immersion tests was closely tied to the percentage of shot in the abrasive mixture. One hundred percent grit showed the least blistering and cutback and an overall corrosion rating of 7.5. A 33% shot/67% grit mixture improved the corrosion rating somewhat (8.5) at the expense of blistering and cutback. The other two shot/grit mixtures performed relatively poorly.

The zinc TSMC in constant immersion tests had similar corrosion ratings (7–8) for all abrasive mixtures. However, as with the alternate immersion, increasing percentages of shot led to decreased performance as measured by blistering and cutback. Composite blister ratings were 6 for 100% grit, 5.5 for 33% shot/67% grit, 3 for 70% shot/30% grit, and 4 for 100% shot after 5 years. Cutback followed a similar trend ranging from 6.3 mm with 100% grit to 17.8 mm with 100% shot.

In summary, these results showed that after 5 years of exposure, both zinc and aluminum TSMCs performed better when applied to a surface prepared with either 100% grit or an abrasive mixture with a high grit percentage.

Effects of Application Parameters on Metallurgical Characteristics and Performance

Metallography

Most guides and specifications for wire arc spray application of TSMCs call for the tip of the gun to be within a standoff distance of 6 to 8 in. of the work surface and at an application angle between 90° (optimum) and 45° (maximum) to the work surface. Such ranges of distance and deposition angle account for field situations where it may be difficult for the TSMC to reach the work surface, such as the inside flange surfaces of H-piles. To test whether the extremes of these ranges are detrimental to TSMC performance, tests were conducted to measure how application parameters affect porosity, oxide content, adhesion, and corrosion performance. Table 8 shows the application parameters tested.

Corrosion Tests Comparing Application Parameters

Corrosion test results for aluminum TSMC in both constant and alternate immersion yielded unexpected results. Samples with a 45° application angle at a standoff distance of 12 in. had the best overall performance, with a corrosion rating of 7 for both immersion types; moreover, no blistering was observed and cutback remained minimal at 2–4 mm. The worst overall performance in both immersion types came at a 45° application angle and a standoff distance of 8 in.; the corrosion rating was 5 to

Table 8 Test protocol for application parameter study.

Alloy	Application Rate (lbs/hr)	Wire Diameter (in.)	Standoff (in.)	Deposition Angle (°)
Aluminum*	20	1/8	8	45
			12	90
Zinc*	80	1/8	8	40
			12	90
85% Zn/15% Al	60	1/8	8	45
			12	90

*Commercial purity wire

5.5, blistering was 8.5, and cutback remained low at 2.5–3.5 mm. The results for an application angle of 90° fell between the extremes found with a 45° application angle.

Zinc TSMC performance was better overall for a 90° application angle and a standoff distance of 8 inches, although increased cutback was observed in constant immersion. Corrosion ratings for all combinations were comparable at 7 to 8. Blistering was prevalent on all alternate immersion samples; ratings ranged from 1.5 to 3, as opposed to 4 to 6 for constant immersion. For constant immersion, cutback was reduced for samples with an application angle of 45°, while samples with a standoff distance of 8 in. performed better in alternate immersion regardless of the application angle.

Both zinc and aluminum TSMCs in constant immersion showed similar levels of corrosion (7 to 8) for all sets. However, a significant benefit in terms of blistering and cutback was observed at a standoff distance of 8 inches. Ratings for 8- and 12-in. standoff distances averaged 7 and 4 respectively for blistering and 1.25 mm and 6 mm for cutback. Alternate immersion samples showed similar corrosion and blister ratings for all combinations of application angle and standoff distance. Cutback was slightly less for a standoff distance of 12 in.

The results at 5 years of exposure would suggest that zinc TSMC benefits from conventional parameters, i.e., an application angle of 90° and a standoff distance of 8 in. Strict adherence to these parameters may be less critical for aluminum TSMC. A zinc/aluminum TSMC mixture seems more sensitive to standoff distance than to application angle, performing better at a closer overall distance.

Effect of Carbon Steel Hardness

The effects of small differences in steel alloy hardness were investigated by measuring the surface profile and adhesion of TSMCs on ASTM A36 and ASTM A572 Grade 50 steel panels that received the same abrasive blasting. The tensile strength of ASTM A36 steel can range from 58 to 80 ksi, and the tensile strength of ASTM A572 Grade 50 is specified as 65 ksi. Since there can be overlap in hardness between the two materials, we measured the actual hardness of the samples used and found that the A36 and Grade 50 steels had Rockwell B (R_B) hardness of 90.8 and 75, respectively.

Corrosion Tests Comparing Steel Hardness

In constant immersion, both alloys performed similarly to each other, with the notable exception of the blister rating for aluminum TSMC. When aluminum TSMC was applied over A36 steel, the average blister rating was 9 across all grit mixtures, compared to a rating of 6 for Grade 50 steel. This difference was not specific to any particular grit mixture, but was consistently lower for all sets tested.

In alternate immersion, no clear difference was apparent between the two alloys. Results vary slightly depending on the parameter of interest, but overall performance is similar.

The corrosion test data indicate that, with the exception of blistering of aluminum TSMC in constant immersion, the steel hardness does not affect TSMC performance.

TSMC Defects

Several samples (with and without chloride contamination) were prepared with a 1.5-inch diameter intentional holiday prior to testing. These samples were tested to determine the throwing power of the two TSMCs. Five additional years of constant immersion produced some differentiation. Holidays on two-thirds of the zinc TSMC samples remained corrosion free after 5 additional years of exposure, as opposed to one-half of the aluminum TSMC samples. Average ratings were 7.75 for aluminum TSMC and 9 for zinc.

Much more corrosion was observed on samples of both TSMCs in alternate immersion. The average rating for holidays on aluminum TSMC samples was 6, while zinc TSMC samples averaged 4. This behavior is to be expected, as during the drying process the electrolyte bridge between sacrificial TSMC and steel substrate may be lost while areas of the steel are still wet.

Surface Contamination

Surface contamination can decrease the performance of a coating system, liquid, or TSMC. However, some coatings are more tolerant to contamination and their performance is not as significantly degraded. The experience in this research was that performance degradation generally begins at chloride levels above 5 μg/cm^2 and significantly affects TSMC performance at 10 μg/cm^2.

To determine if the aluminum and zinc TSMCs are significantly affected by surface chloride contamination, a series of panels was purposefully contaminated to achieve surface chloride levels of 5 and 10 μg/cm^2. Specifically, A36 steel panels abrasive-blasted using 100% steel grit were immersed in a sodium chloride solution prepared with deionized water. The contamination level was verified by measuring chloride concentration with the Bresle method. This method uses a latex rubber patch, which is adhesively backed for application to a steel substrate. During this test an extraction fluid is injected into the area of the patch exposed to the steel substrate and the patch is massaged to dissolve the available chloride ions into solution. The extraction fluid is then removed and titrated to determine chloride ion content. The nominal 5 μg/cm^2 panels had actual chloride levels of 5 to 7 μg/cm^2, and the nominal 10 μg/cm^2 panels had actual chloride levels of 9 to 11 μg/cm^2.

Corrosion Tests Comparing Surface Contamination

The zinc TSMC in constant immersion exhibited a corrosion rating of 7 at the 10 μg/cm^2 chloride level compared to an average of 7.5 at the 5 and 0 μg/cm^2 levels. The presence of a holiday decreased the average rating. The composite blister ratings varied, with the highest rating being 7 at 5 μg/cm^2 and the lowest 4.5 at 0 μg/cm^2. In alternate immersion tests, the zinc TSMC performed better at lower contamination levels. Corrosion ratings ranged from 8 at 0 μg/cm^2 to 6.5 at 10 μg/cm^2. The composite blister ratings were fairly constant (9 to 10). Cutback measurements were comparable for all chloride levels.

The aluminum TSMC in both constant and alternate immersion tests were largely unaffected by higher chloride levels. Indeed, corrosion ratings were actually lower for cleaner substrates (varying by 1 to 2 points in both immersions) while blister and cutback were comparable with a variation of 1 point or less.

In general, zinc TSMC appeared to perform better than the aluminum TSMC with regard to overall corrosion rating but worse with respect to blistering and cutback. The performance of both TSMCs in constant immersion varied depending on the metric being evaluated. The presence of holidays in the TSMC did not appear to affect overall performance away from the holiday. Overall, aluminum TSMC appears to be more tolerant of surface contamination. Of course, it is good practice to avoid TSMC application on a contaminated substrate.

INTERPRETATION, APPRAISAL, AND APPLICATION OF RESULTS

The continuation of the corrosion testing begun in NCHRP Project 24-10 over an additional 5 years provided several important findings on surface preparation and TSMC application.

Surface Preparation for TSMC

The use of 100% grit provides better corrosion performance in the long term than does 100% shot. Using a 100% grit abrasive also tends to provide better performance than grit/shot mixtures, although a 67% grit/33% shot mixture also performed relatively well. Grit/shot mixtures are sometimes used to increase the service life of blasting equipment because the shot is not as aggressive to the equipment. However, the findings of this research suggest using shot or grit/shot mixtures with high shot proportions for initial surface cleaning and a 100% grit abrasive for final surface preparation.

The surface contamination levels used in this study did not lead to clear differences in TSMC performance over the 5-year test period. However, based on the initial work carried out in NCHRP Project 24-10, starting with a clean surface is advantageous.

Application of TSMC

The research found no appreciable difference in the performance of zinc TSMC applied over A-36 or Grade 50 steel. However, there may be an incompatibility between aluminum TSMC and Grade 50 steel in constant immersion as evidenced by increased levels of blistering.

TSMC application angle and standoff distance were found to directly affect the performance of zinc and zinc/aluminum alloy TSMCs. Aluminum TSMCs may be more tolerant of non-ideal application conditions, within reason. While TSMCs are capable of protecting the substrate at narrow defects due to their ability to cathodically protect the steel, larger defects present a problem, especially in the alternate immersion environment where electrolyte continuity between sacrificial coating and steel substrate may be lost during the drying process while pockets of electrolyte are still present on the steel surface. TSMC defects larger than relatively narrow scratches should be repaired.

Confirmation of Preliminary Results from NCHRP Project 24-10

The original NCHRP Project 24-10 encompassed a wide range of activities to characterize the application and performance of TSMCs, including a broad literature search, adhesion testing, metallographic analysis, impact resistance, and corrosion testing. While definitive results could be obtained for many of that project's components in its relatively short period of performance, the inherent effectiveness of TSMCs in preventing corrosion on the underlying steel substrate did not result in significant performance differences among the different sample sets after only 1 year of exposure. More time was needed in order for benefits and detriments to performance to become apparent in the immersion environment, and to either validate or revise the initial findings. Based on the results of 5 more years of constant and alternate immersion exposure, the initial findings appear generally accurate.

FINDINGS AND CONCLUSIONS

The following are key findings and conclusions of this research:

1. Sealers may be beneficial to zinc or aluminum TSMCs under constant immersion if the proper type is chosen. Corrosion and blister ratings were generally lower for sealed samples than for unsealed samples, with a few exceptions. Chromate vinyl wash primer imparted a slim benefit to zinc TSMC.
2. In alternate immersion, the chromate vinyl wash primer showed the most benefit to zinc TSMC. An epoxy sealer greatly benefited aluminum TSMC under alternate immersion, raising the corrosion rating from 2 to 6.
3. Overall, if a sealer is specified, chromate vinyl wash primer seems most compatible with zinc TSMC, whereas an epoxy sealer has shown the most benefit to aluminum TSMC in this study.
4. Based on corrosion testing over an additional 5-year period, increased performance is seen in both zinc and aluminum TSMCs when high proportions of grit are used for abrasive surface blasting, as opposed to shot. This finding supports the results of the original study.
5. Zinc TSMC showed better corrosion performance across the board in both types of immersion when the surface was prepared with 100% grit abrasive blasting. A 67%/33% grit/shot mixture also performed well.
6. Aluminum TSMC appeared to be more tolerant of shot in the blast mixture, with best performance in alternate immersion resulting with a 67%/33% grit/shot abrasive mixture. In constant immersion some variation was seen, with 100% grit yielding the best blistering and cutback results, while a 70%/30% shot/grit mixture resulted in the least corrosion.
7. Zinc TSMC benefits from the conventional recommendation of 90° application angle at a standoff distance of 8 inches.
8. Aluminum TSMC showed no clear trend in response to variation in application angle and standoff distance. The best performance resulted with an application angle of 45° at a standoff distance of 12 inches, while the worst performance came at a combination of 45° and 8 inches. Results for a 90° application angle fell in between these extremes.
9. Both zinc and aluminum TSMCs appear less sensitive to application angle than to standoff distance. Samples coated from a distance of 8 inches had better overall performance.
10. Testing indicated that with the exception of increased blistering of aluminum TSMC over Grade 50 steel in constant immersion, alloy hardness has no appreciable effect on TSMC performance.
11. The galvanic behavior of the TSMC protects small, narrow defects exposing the substrate. However, TSMC cannot provide complete cathodic protection to larger holidays, especially in the alternate immersion environment.
12. Aluminum TSMC did not show a clear performance difference across the different levels of contamination studied here.
13. Zinc TSMC performs slightly better with a clean substrate, especially in the alternate immersion environment, although performance varied by parameter.
14. In summary, the results of this research suggest that zinc TSMC performs better than alu-

minum TSMC with respect to corrosion, but zinc TSMC is more susceptible to blistering and cutback from damaged sections. Aluminum TSMC is more tolerant of surface contamination, although a clean substrate is always recommended for TSMC application.

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