NCHRP
REPORT 528

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Thermally Sprayed Metal Coatings to Protect Steel Pilings: Final Report and Guide

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Thermally Sprayed Metal Coatings to Protect Steel Pilings: Final Report and Guide

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SUBJECT AREAS
Bridges, Other Structures, and Hydraulics and Hydrology • Soils, Geology, and Foundations • Materials and Construction • Maintenance

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Corrpro Companies, Inc., performed this research under NCHRP Project 24-10. The work was performed at Corrpro Companies, Inc., facilities in West Chester, Pennsylvania, and in Ocean City, New Jersey. Mr. James A. Ellor, P.E., and Mr. Walter T. Young, P.E., were the Principal Investigators for this project. Mr. John Repp, P.E., conducted the laboratory tests. Dr. Richard Knight of the Materials Engineering Department at Drexel University in Philadelphia, Pennsylvania, provided consultation on thermally sprayed metal coating issues.

FOREWORD

By Timothy G. Hess
Staff Officer
Transportation Research Board

NCHRP Report 528 consists of two documents: (1) a final report that presents the findings of a research project investigating thermally sprayed metal coatings (TSMCs) and (2) a guide for the application of TSMCs to protect steel pilings from corrosion. This report will be of immediate interest to professionals in the public and private sectors responsible for designing, installing, inspecting, and maintaining steel pilings. The report will also be of interest to those charged with specifying TSMC materials and methods for the application of TSMCs.

Thermally sprayed metal coatings (TSMCs) are available as alloys of base metals such as aluminum and zinc. TSMCs can offer substantial advantages when compared with other types of coatings commonly used to protect steel pilings primarily because of their resistance to corrosion and handling damage. However, available publications do not provide sufficient guidance for highway agency personnel on TSMC materials and the use of TSMCs for steel pilings. Without this information, there is reluctance to use this technology. There has been a need for research on the use of TSMCs to protect steel pilings. Conclusions concerning the performance and potential benefits of TSMCs are needed as is a guide to assist state highway agencies in properly specifying and applying TSMCs. A guide can help highway agency personnel responsible for steel pilings to consider TSMCs and to make more rational decisions about the use of protective pile coatings.

Under NCHRP Project 24-10, Corrpro Companies, Inc., investigated the existing state of knowledge pertaining to TSMCs and developed a guide addressing the application of TSMCs for the protection of steel pilings. The guide was developed as the result of investigating existing standards and specifications, coating applicators, and widely used practices pertaining to TSMCs. Laboratory work was performed to refine critical areas not adequately addressed in current literature and practice such as abrasive mix, edge geometry, sealers, and steel hardness variations.

The final report for this project includes a literature review, a synthesis of existing practice, a presentation of laboratory results, and four supporting appendixes:

- Appendix A: List and Description of Existing TSMC Specifications,
- Appendix B: List and Description of Existing TSMC Guides,
- Appendix C: Literature Review References and Summaries, and
- Appendix D: Bibliography.

The Thermally Sprayed Metal Coating Guide, which is the primary product of this research, includes procedures for the application of TSMCs for corrosion control on piles used in highway construction. The guide provides information for a user to select, specify, and apply a metal coating for steel piles in freshwater, brackish, or seawater environments. The guide will significantly enhance the capabilities of highway agencies in using TSMCs to protect steel pilings from corrosion.

CONTENTS

THERMALLY SPRAYED METAL COATINGS TO PROTECT STEEL PILINGS: FINAL REPORT AND GUIDE

SUMMARY

Zinc and aluminum have been used as steel coatings since the early 1900s, with early application of thermally sprayed metal coatings (TSMCs) to bridge structures in the 1930s. TSMCs have been used widely in the European bridge industry, the U.S. Navy, and on offshore oil exploration drill platforms for quite some time. TSMCs of zinc, aluminum, and their alloys can offer substantial advantages when compared with other coatings typically used to protect steel pilings. Organic coatings can fail prematurely as a result of corrosion progression from coating defects. Transportation, handling, installation, or simple long-term material deterioration may cause these defects. TSMCs offer advantages in generally higher mechanical damage resistance, low self-corrosion rates, and the ability to provide steel corrosion control via cathodic protection at coating defects. The objective of this research was to develop a guide for highway agency personnel on the selection and use of TSMCs on highway pilings that would be suitable as an AASHTO reference.

The extensive body of information on TSMCs, including existing guides, was researched so as not to repeat basic research and development work or conflict with industry standards where those standards are applicable. Applicable portions of existing materials were used in the preparation of the guide. This study also sought to resolve any issues that were unclear concerning the use of TSMCs on steel pilings. These issues have included sealer materials, the effects of abrasive mixes, standoff distances, gun-to-surface angles, steel hardness, edges, coating defects, and surface contamination.

The study confirmed the positive impact of the use of sealers and that all of the sealers tested in the study would be beneficial in improving performance. Tests on grit and shot/grit mixtures show that 100-percent grit provides the best adhesion, followed by the shot/grit mixtures, and then by 100-percent shot. Further research into parameters for angularity and its effect on performance is recommended. A simple field-friendly measurement technique for angularity was not found in this study. Further work is recommended to determine if surface profilometer measurements of peak count (R_{PC}) and root-mean-square (R_Q) (these variables are further described in Table 7) can be used effectively and, if so, what the optimum values should be. Meanwhile, classifications of abrasive angularity should be used.

The study was able to define the effect of hardness with carbon steel and high-strength, low-alloy (HSLA) steel on adhesion and coating performance as well as the effects of sharp edges, defects, and surface contamination on the coating.

Areas of further research are recommended, including establishment of a definition of acceptable limits of angularity and a standard for angularity. Continued monitoring of the test panels currently in immersion and alternate (cyclic) immersion testing at Corrpro's Ocean City facility is also recommended. The Thermally Sprayed Metal Coating Guide, the primary product of this study's research, includes all of the information gathered from the literature, industry research, and laboratory testing.

FINAL REPORT

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

Zinc and aluminum have been used as steel coatings since the early 1900s, with early application of thermally sprayed metal coatings (TSMCs) to bridge structures in the 1930s (*1*). TSMCs have been used widely in the European bridge industry, in the U.S. Navy, and on offshore oil exploration drill platforms for quite some time. TSMCs of zinc, aluminum, and their alloys can offer substantial advantages when compared with other coatings typically used to protect steel pilings. Organic coatings can fail prematurely as a result of corrosion progression from coating defects. Transportation, handling, installation, or simple long-term material deterioration may cause these defects. TSMCs offer advantages in generally higher mechanical damage resistance, low self-corrosion rates, and the ability to provide steel corrosion control via cathodic protection at coatings defects. The objective of this research was to develop a guide for highway agency personnel on the selection and use of TSMCs for highway pilings that would be suitable as an AASHTO reference. The Thermally Sprayed Metal Coating Guide, containing all of the information gathered from the literature, industry research, and laboratory testing, is the primary product of this research.

The extensive body of information on TSMCs, including existing guides, was researched so as not to repeat basic research and development work or conflict with industry standards where those standards are applicable. Applicable portions of existing materials were used in the preparation of the Thermally Sprayed Metal Coating Guide. This study also sought to resolve any issues that were unclear concerning the use of TSMCs on steel pilings.

ISSUES OF CONCERN

Alloy Selection

There are several TSMC alloys available. Most commonly used metals for the protection of steel are anodic to steel. This eliminates the need for a completely pinhole-free barrier because the TSMC provides sacrificial protection to the steel substrate (*2*). Zinc, aluminum, and alloys of the two metals are thus 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. Aluminum TSMCs have been found to protect steel well under seawater immersion conditions (*3*). The excellent barrier properties and low rate of self-corrosion for the aluminum coating make it attractive for seawater exposure. Because TSMCs are porous, sealers are often specified to reduce the porosity and improve the service life of the coating. Common sealers include epoxies and vinyl coatings. Because of the advances in coating technology, part of this study was to investigate other sealer materials.

Quality Assurance Requirements

TSMC materials are sensitive to surface preparation and application conditions (*4*). Most specifications require surface preparation and application conditions that meet the Society for Protective Coatings Surface Preparation Specification 5 (SSPC-SP-5), “White Metal Blast Cleaning,” for application of a TSMC (*5*). This can be difficult to achieve in all conditions, especially if field coating is being considered rather than shop coating. Other parameters, such as abrasive type for surface preparation, required profile range, and acceptance environmental conditions, can affect porosity, adhesion, and corrosion performance of the coating.

Damage Tolerance of the Coating

A key aspect of the coatings is their resistance to damage in transportation, handling, and installation. Regardless of whether shop or field coatings are used, there is a tendency for there to be impact and flexure damage to the coatings. The performance of the alternative alloys and application conditions must be qualified in these regards.

RESEARCH PLAN

The research plan consisted of eight tasks, briefly described below.

Task 1—Collect and Review Domestic and Foreign Literature and Information

The review of existing literature and other information included the following:

- Existing specifications and guides on coatings for steel pilings and for metallizing in general,
- Published research studies of metallized coating performance in immersion environments,
- Interviews with suppliers of metallizing materials and application equipment and review of their literature,
- A visit by researchers to a coating fabrication shop where steel piles were being coated,
- Laboratory studies to perform certain basic testing on TSMC, and
- Interviews with coating applicators.

Task 2—Evaluate and Summarize the Literature

This consisted of the evaluation of information gathered in Task 1 to determine the completeness and relevance of existing information. From this evaluation, a detailed work plan was developed that would provide the information necessary for the guide to TSMCs.

Task 3—Develop a Detailed Experimental Work Plan

The purpose of Task 3 was to develop an experimental work plan built around key issues related to TSMC performance. It was anticipated that the work plan would consist of laboratory tests designed to provide information to supplement the literature in the areas of surface preparation, sealers, and application parameters.

Task 4—Interim Report

The interim report presented the results of Tasks 1 through 3. As a result of the interim report, the panel determined that an expanded literature search was needed. The panel directed that a draft guide to TSMCs be prepared incorporating all of the information available to date and delineating areas requiring further research. They also asked that a second interim report be prepared.

Task 5—Work Plan Execution

The work plan execution consisted of conducting laboratory tests to provide additional information about the effectiveness of sealers, different sealer materials, surface preparation materials, and the application variables on performance. The tests consisted of both standard laboratory tests and seawater exposure tests. Researchers also intended to perform field inspections of several TSMC structures, including some existing structures operated by the U.S. Army Corps of Engineers. The inability to access these structures without extensive dewatering procedures prevented this from occurring.

Task 6—Final Guide to TSMCs

This task consisted of preparing the final guide on the basis of the combined results of the literature search and laboratory tests.

Task 7—Long-Term Validation Plan

The objective of this task was to develop a long-term implementation plan for the use of TSMCs for pilings. The plan was to have the guide to TSMCs accepted as an AASHTO guide by demonstrating the usefulness and applicability of the guide and TSMCs to state DOT officials.

Task 8—Final Report

This report contains a discussion of all of the work described in Tasks 1 through 7.

CHAPTER 2

FINDINGS

COLLECT AND REVIEW DOMESTIC AND FOREIGN LITERATURE

Literature Review

A comprehensive information search was conducted to obtain and review information relevant to the design, specification, and installation of coated steel pilings. Literature was obtained by using available government, university, and industry databases. The search included the following:

- The Transportation Information Research Service (TRIS),
- The National Technical Information Systems Database,
- AASHTO Listings of Research in Progress,
- The Current Technologies Index,
- Engineered Materials Abstracts,
- Federal Research in Progress,
- International Conference Papers Abstracts,
- The Federal Highway Administration,
- The U.S. Army Corps of Engineers,
- The Soil Conservation Service,
- State DOTs,
- The National Institute for Standards and Technology,
- The American Society for Testing and Materials,
- The National Association of Corrosion Engineers (NACE) International,
- The Society for Protective Coatings (SSPC),
- The American Welding Society (AWS),
- The Materials Information Society (ASM), and
- The Thermal Spray Society.

This literature included performance data in technical papers and reports and specifications for the application of TSMCs. This literature was sorted, and the most relevant reports were reviewed. Of primary interest were data related to the performance of TSMCs in natural waters, application factors affecting the life of TSMCs, and appropriate quality assurance tests. Literature of significant value was abstracted and is included in the report appendixes.

Although the literature identified several available thermal spray systems, the ones used most frequently were wire-arc spray and wire-flame spray. Also, these two systems are often the most practical application methods for TSMC on pilings. However, wire-arc spray techniques generally allow for hotter particles, faster output, and superior adhesion than do flame spray techniques (*2, 6–12*).

Various thermal spray coating materials are available for use over steel. Table 1 lists and categorizes some of the materials commonly used for metallizing, as well as typical wire gauges that are available. Zinc, aluminum, and their alloys are commonly used as TSMCs on steel in water immersion. The sacrificial corrosion protection that they offer, in combination with their relatively low corrosion rates, make them suitable for such harsh environments (*2, 7, 9, 11, 13–19*). Thus, zinc, aluminum, and an alloy of the two metals (85 : 15 weight percent [wt%] zinc/aluminum) were selected for testing under this program. Table 2 lists some of the properties of these three TSMCs commonly used on steel in water immersion.

Thermally sprayed zinc and aluminum coatings are commonly used without sealers in mild environments. However, TSMCs inherently contain porosity that has a major effect on corrosion performance. When exposed to harsh environments, such as marine atmospheres and/or freshwater or saltwater immersion, the application of a sealer on top of the thermally sprayed coating is generally recommended (*2, 7, 20–23*). The purpose of the sealer is to mitigate corrosion caused by the penetration of moisture and corrosive ions through pores. Sealers are often used to enhance the appearance of the coated structure as well as to extend the life of the thermal spray coating. Previous studies have involved dozens of different sealers, and the studies generally agree that an important property of the sealer is to adequately fill the pores in the thermally sprayed coating (*2, 8, 9, 14, 16, 22, 24*). Some of the more common sealers tested include vinyls, silicones, epoxies, urethanes, phenolic resins (may react with zinc [*24*]), and aluminum pigmented silicone (for high temperature) (*7, 8, 20*).

Previous studies have indicated that corrosion rates of steel in marine environments are lower in the immersed and intertidal zones than in the splash zone (*25*). The lower corrosion rates in the immersed and intertidal zones are believed to be, in part, the result of the attachments of various organisms and marine growth. Marine fouling is not as prominent in the splash zone. Because of this lack of fouling and the wet/dry cycling in the splash zone, corrosion rates tend to be highest in this area. Unprotected steel corrosion rates in the splash zone generally range from 4 to 10 mils (102 to 254 µm) per year.

Corrosion of steel pilings in a marine environment may also be the result of exposure to variable oxygen concentrations.

TABLE 1 List of materials commonly available as TSMCs

Classification	Materials/Wire	Comments
Anodic	Al99.0%—11 and 14 gauge and 1/8-in. wire Zn 99.9%—11 and 14 gauge and 1/8-in. wire	Aluminum and zinc are available pre-alloyed or can be pseudo alloyed with the proper metallizing system. These coatings offer sacrificial galvanic protection to a steel substrate.
Corrosion Resistant	Cu 99.8%—14 gauge Cu 9Al 1Fe—14 gauge Fe 13Cr 0.5Si 0.5Ni 0.5Mn 0.35C—14 gauge Fe 18Cr 8.5Mn 5Ni 1Si 0.15C—14 gauge Fe 28Cr 5C 1Mn—14 gauge Ni 5Al—14 gauge Ni 5Mo 5.5A1—14 gauge Ni 5Mo 5.5A1—14 gauge Ni 18Cr 6A1—14 gauge Sn 7.5Sb 3.5Cu 0.25Pb—14 gauge C 276 Ni Alloy—14 gauge	While these coating systems are considered corrosion resistant, they are all cathodic to steel and, thus, offer no sacrificial protection to a steel substrate at coating defects.
Hard Coatings	Chromium Tungsten-Carbides	These TSMCs are generally used in applications where abrasion resistance is a desired property.

NOTE: 1 in. = 2.54 cm. Al = aluminum, Zn = zinc, Cu = copper, Fe = iron, Cr = chromium, Si = silicon, Ni = nickel, Mn = manganese, C = carbon, Sn = tin, Sb = antimony, Pb = lead.

Corrosion will be more severe at zones with low oxygen content and lower at more aerated zones. Highly localized corrosion known as macrocell corrosion, or oxygen concentration cell corrosion, can result. This phenomenon is believed to be the primary cause of corrosion of piles in heterogeneous soils (*26*). Other studies have also concluded that macrocell corrosion is involved in the corrosion of steel in the tidal zone (*25*). In oxygen-deficient areas, excess metal dissolution occurs, and the local pH falls; in oxygen-rich areas, oxygen reduction of hydroxide ions occurs, and the local alkalinity increases. Severe concentrated corrosion can occur just below the low tide zone as a result of oxygen concentration cells.

The edge retention of coating systems is a property that can affect the overall system performance. If the edges of a structure are not coated well, the system may not be acceptable for complex shapes or assemblies. Edge retention is defined as the percentage of the flat surface film thickness that covers an edge of the substrate. As an example, if the nominal dry film thickness (DFT) of a coating over an "I beam" were 10 mils (254 µm) and the minimum DFT over an edge of the beam were 5 mils (127 µm), then the edge retention would be 50 percent. Most liquid coatings tend to "pull back" or flow away from sharp edges during application. This further exaggerates the low film thickness encountered at the edges of a part. Many coating specifications make up for this lower edge coverage by adding "stripe coats" over all edges and nonuniform surfaces (e.g., bolts and welds). TSMCs are applied via a "line-of-sight process" (very similar to conventional and airless spray of liquid coatings) yet do not "flow" as many liquid coatings do. TSMC deposition only occurs when the metal particles collide with a surface. As a TSMC application gun is turned away from perpendicular to the surface, the deposition efficiency decreases dramatically. Unlike spraying liquid coatings, in which the "wet" material may have more of a tendency to adhere from a severe angle or long spray distance, TSMC relies on impact energy and a short molten

TABLE 2 Properties of commonly used TSMC materials

TSMC	Metal Alloy	Alloy Rational
1	99.9% pure Zn	Excellent cathodic protection properties, harder than aluminum, life proportional to thickness, not for acidic environments or high temperatures.
2	99% pure Al	Low self-corrosion rate, good seawater performance, high-temperature resistance, lightweight, acid (pollution) resistant.
3	85:15 wt% Zn-Al	Harder than aluminum, has shown better atmospheric performance than zinc or aluminum.

NOTE: Al = aluminum, Zn = zinc.

phase for adhesion, so a TSMC particle has a greater tendency to "bounce" from the surface. Over an edge, where the angle of application will stray from perpendicular, a TSMC will deposit with less efficiency than on a flat surface, so a reduced thickness on the edge is expected. The sharpness of the edge will also affect TSMC deposition on the edge. A very sharp, 90-degree edge will retain less coating thickness than a chamfered or "broken" edge.

While many liquid coating systems rely on stripe coatings to build the film thickness at edges, a TSMC that is anodic to steel may not need additional edge coverage because of the sacrificial protection offered by the other areas of TSMC. However, because piles often have several different edge configurations, edge retention was considered during the laboratory phase of the project.

Although the literature identifies various coating systems for potential application in natural waters (predominately seawater), there are three principal systems that have received the most consideration: commercially pure aluminum, commercially pure zinc, and 85:15 wt% zinc-aluminum. Table 3 shows the TSMC materials of interest tested most frequently within the literature.

Of these primary TSMC materials, the material most often suggested as having superior performance in seawater and freshwater environments is aluminum. Aluminum is listed as the outstanding candidate by the National Materials Advisory Board at the National Academy of Sciences in their report, *Metallized Coatings for Corrosion Control of Naval Ship Structures and Components*, in the American Welding Society (AWS) 19-year report on metallized coatings, and in several papers dealing with TSMC used in the offshore industry (i.e., used in seawater) (*7, 8, 11, 12, 14, 22, 27–31*). Other papers have also concluded that aluminum is an excellent performer in freshwater environments (*12, 24, 28*).

From a material property standpoint, the corrosion rate of all the TSMCs is quite low. These general corrosion rates appear in the 0.1- to 0.4-mpy (2.5- to 10-μm/yr) range. The literature suggests corrosion rates of 0.13 mpy (3.3 μm/yr) for aluminum TSMC. The same literature suggests corrosion rates of 0.31 mpy (7.8 μm/yr) for 85:15 wt% zinc-aluminum. These corrosion rates agree quite well with measurements obtained as part of this program on samples from both the laboratory and the field. These data are discussed below. Such low corrosion rates are consistent with the findings of field exposure testing listed in the literature (i.e., 12-mil [300-μm] coatings lasting for 20 years with little to no base-metal deterioration).

Several materials, as discussed above, exhibit the findings of low corrosion rate and extended service life. This extended service life is in the range of 20 years or more. Several systems, properly applied, seem to be able to meet this criterion. Thus, inherent material corrosion rate is not a key issue for the better performing materials; the key issue becomes the coating process needed to obtain a coating that meets this performance expectation. This is a specification and quality assurance issue as opposed to a material selection issue.

The most common defect cited in the deterioration of TSMCs is inter-coat "blistering" or delamination. In this process, significant section loss of the TSMC is observed. Extensive propagation of such delamination can impact the useful service life of the material. It appears that delamination may be related to inter-coat corrosion occurring at selected pores or defects in the coating. This may occur along oxide boundaries or, in the case of mixed-metal TSMC, at differing alloy phases/compositions.

On a visit to test piles at the North Carolina DOT test site at Ocracoke, North Carolina, defects in thermally sprayed aluminum (99.5%) coating were visible, as shown in Figure 1, after 2 years of service in a seawater piling application. The defect appears as a split in the coating at the bend in the sheet piling. Similar inter-coat defects with a slightly different configuration also appeared on an 85:15 wt% zinc/aluminum piling treated with TSMC at the same site. A 70:30 wt% zinc/aluminum pseudo-alloy TSMC appeared in the best shape at

TABLE 3 Materials and frequency of testing

Material	Percent of Time Tested
Pure Al	75
Pure Zn	60
85:15 wt% Zn-Al	25
65:35 wt% Zn-Al	5
55:45 wt% Zn-Al	5
90:10 wt% Al-Al_2O_3	10
95:5 wt% Al-Mg	10
60:40 wt% Zn-Fe	5
Al-Zn-In	5

NOTE: Al = aluminum, Zn = zinc, Al_2O_3 = aluminum oxide, Mg = magnesium, Fe = iron, In = indium.

Figure 1. Thermal spray aluminum (99.5 percent) coating in seawater after 2 years exposure.

the site, free of such delaminations through 2 years of service. Yet, some areas of the piling appeared to exhibit incipient blisters. Similar types of defects have often been the deciding factor in the ultimate rating of TSMCs. If the occurrence of such defects can be related to specific application parameters, then the life of the coating can be extended considerably. Historically, appropriate sealer coats are often listed as reducing the tendency for these types of defects.

Several thermal spray systems were reviewed for testing under this program. Some of these systems include wire-arc spray, wire-flame spray, powder flame spray, high-velocity oxygen-fuel (HVOF) spray, and plasma spray. Wire-arc spray generally provides faster output and superior adhesion when compared with flame spray techniques (*8*). Production rates of up to 90 and 300 lb (41 and 136 kg) per hour have been obtained for wire-arc sprayed aluminum and zinc, respectively (*15*). Various other thermal spray techniques, including HVOF and plasma spray, are also available. However, these alternative thermal spray systems, when compared with wire-arc spray, generally do not offer the same levels of output and cost-effectiveness.

There are also reports in the literature that using a larger-diameter feed wire can increase productivity (*32*). However, other technical papers suggest that as wire diameter is increased, porosity also increases (*9*). This may lead to more coating defects. Any such tradeoffs between productivity and coating performance need to be considered in testing.

Surface preparation is considered the most important part of thermally sprayed coating application. Typical requirements include an SSPC-SP-10, "Near-White Blast Cleaning," or SSPC-SP-5, "White Metal Blast Cleaning," producing a 2- to 4-mil (25- to 102-µm) profile with angular grit. Testing under this program included variations in surface preparation quality to determine the influence of such factors as surface profile and surface contamination.

Initial Testing and Field Surveys

One of the initial laboratory tests was a galvanic current test in which polyvinyl chloride (PVC) panels were coated with thermally sprayed aluminum and zinc by wire-arc spray. These panels, which were 2 in. (5 cm) in diameter, were electrically coupled to bare steel panels ($^1/_{32}$ in. × 4 in. × 6 in. [0.079 cm × 10.2 cm × 15.2 cm]) and immersed in natural seawater. Current flow between the coated PVC panels and the bare steel panels was monitored and plotted as a function of time, as shown in Figure 2. The preliminary electrochemical data indicated that while zinc may be more active initially, its corrosion rate gradually decreases to a level closer to that of aluminum. Visual observations indicated that the steel panel coupled to the aluminum coating exhibited significantly more corrosion (red rust) than did the panel coupled to the zinc coating. Figure 2 shows that the galvanic current flows from the aluminum- and zinc-coated panels were at the same level after 3 weeks of immersion. These data indicate that the corrosion rate of zinc, relative to aluminum, in long-term exposure, may not be as high as much of the liter-

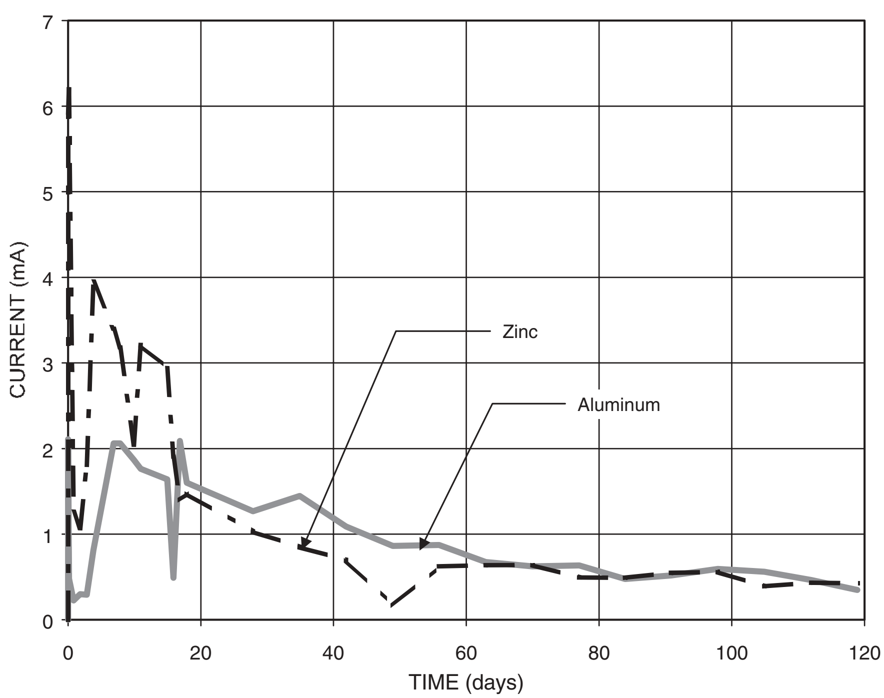


Figure 2. Galvanic current data for TSMC materials (zinc and aluminum) coupled to steel panels in seawater.

ature suggests. The conclusions in the literature that zinc will corrode at higher rates may be somewhat misleading because of the lack of data from long-term exposures. However, according to the AWS "Corrosion Test of Flame-Sprayed Coated Steel—19 Year Report," unlike aluminum, the service life of zinc thermal spray coatings is dependent on coating thickness (*28*).

A test piling was set up outside of Corrpro's Ocean City laboratory to evaluate corrosion mechanisms associated with a seawater environment. Seven steel segments were exposed to various zones in seawater—mud, immersion, tidal, and splash zones. Five of the segments were coated with zinc applied by wire-arc spray. Two segments, one below the mudline and one in seawater immersion, were bare steel. The five zinc-coated segments were electrically connected with the bare steel segment below the mudline. Current flow between the segments was monitored periodically. Current data indicated that the majority of the sacrificial protection to the bare steel segment came from the zinc-coated segment below the mudline. One of the zinc-coated segments in the seawater immersion zone was consistently receiving protective current. This lack of uniform galvanic current flow is indicative of macrocell corrosion effects. These results imply that, as a design agent, long-term local corrosion driven by the macrocell corrosion, as well as the general corrosion rate of the material, are corrosion mechanisms that need to be considered. The majority of long-term piling tests have focused on the visible corrosion at or above the water line. The segmented piling data imply that corrosion below the water line, via macrocell corrosion, may be a factor in determining the service life of a coated piling. These results lead to the question of whether the piling should be coated below the mudline to limit galvanic interaction.

Corrpro personnel performed a field survey of existing test pilings installed in late 1997 by the North Carolina Department of Transportation (NCDOT) at the South Side Cape Hatteras Ferry Dock on Ocracoke Island in North Carolina. Five steel test pilings had been exposed for about 2 years at the time of the field survey. The test piles consisted of the following TSMCs:

- Arc-sprayed aluminum and sealer,
- Arc-sprayed 70:30 wt% aluminum-zinc and sealer,
- Arc-sprayed 85:15 wt% zinc/aluminum and sealer,
- Inorganic zinc-rich paint, and
- Bare steel.

In addition, the propeller wash piling wall is coated with coal tar. The results of the field survey are summarized as follows:

- Electrochemical data indicated that the uniform corrosion rates of the thermally sprayed coating materials were relatively low; however, visual observations indicated localized areas of deterioration.
- The primary source of coating deterioration was intercoat cracking and delamination between the base metal and coating.
- Deterioration occurred at rolled corners.
- Electrochemical data confirmed that the seal coats were not effective electrical barriers. Seal coats are not intended to behave as full barrier coatings.
- A 2-year exposure period is inadequate to extrapolate the coating performance over a 20-year period.

Interviews with Coating Applicators

Six thermal spray coating applicators were contacted. Of these, three were willing to discuss the TSMC procedures. Structural Coatings, Inc., was visited in July 1999, at the beginning of the project, to view some pipe piles being coated and to obtain some initial information. Structural Coatings, Inc., was visited again on February 20, 2001, and questionnaires were submitted to the other two applicators. Information gathered included types of abrasive used, use of mixed abrasives, treatment of flame-cut edges, spray techniques used, types of application equipment, types of sealers used, quality control procedures, and qualifications. The three applicators provided useful information, which helped to focus and reduce the amount of laboratory testing needed. The thermal spray applicators contacted were the following:

Jupiter Painting
1500 River Rd.
Croydon, PA 19020
215-785-6920
Contact: Paul Tsourous

Structural Coatings, Inc.
P.O. Box 334, Highway 70 E
Clayton, NC 25720
919-553-3034
Contact: Ray Hails

CSI Coatings
2102 5 Street
Nisku, Alberta T9E7X3 Canada
780-955-2856
Contact: Wayne Duncan
(CSI Coatings is a wholly
owned subsidiary of Corrpro
Companies, Inc.)

As a result of the literature search and field and initial laboratory studies, the following focus was determined for follow-on research:

- Further testing should be limited to the most commonly used alloys for corrosion control, that is, the anodic coatings of "pure" aluminum and zinc and the 85:15 wt% zinc/aluminum alloy. Properly applied, these materials show every indication of being able to meet the intent of the program (i.e., to significantly extend the life of steel piling materials in immersion in natural waters).
- As opposed to testing an increased variety of TSMC base materials, a significant testing focus should be appropriate

sealers and sealing techniques. This investigation should include the use of 100-percent solids materials with reportedly higher "pore-penetrating" abilities. This includes the newer classes of maintenance painting primers designed to penetrate cracked and aged organic coatings.
- The study should examine the effect of abrasive mixes on TSMC performance.
- The program should also focus on those application parameters that may affect the occurrence of critical pore sizes, pore geometry, and alloy micro-segregation or inter-coat oxide formation that will impact performance.
- The program should focus on wire-arc spray applications of the materials to obtain optimal application rates. The program should include some focused study of the effects of increased productivity on material performance.

PROCEDURES USED IN LABORATORY TESTS

Laboratory testing was designed to improve the usefulness of the guide to TSMCs in several basic areas. These were the following:

- Tests on sealer materials, including high solids, high-penetration epoxies, and urethanes.
- Testing of the effects of different abrasive mixes on the performance of TSMC to examine the effects of angularity on performance and to examine methods to measure angularity in the field.
- Evaluation of the spray parameters of standoff distance and application angle on coating microstructure and performance.
- Testing of the effects of the hardness of the steel substrate on surface preparation requirements.
- Testing of the effects of high-strength, low-alloy steel versus carbon steel substrate on TSMC performance.
- Testing of the effects of edge geometry on coating retention and TSMC performance.
- Testing of the effects of coating defects on TSMC performance.
- Testing of the effects of surface contamination (chlorides) on coating performance.

Test Panel Preparation

Test panels to evaluate adhesion, sealers, different abrasive mixes, edge effects, and application parameters were prepared by CSI Coatings in Nisku, Canada, using Thermion Bridgemaster equipment. The steel used for the corrosion tests met the requirements of AASHTO M-270 Grade 36 or ASTM A-328. M/020 steel was used for the complex corrosion test panels and had a nominal analysis of 0.17 to 0.24 carbon (C), 0.25 to 0.56 manganese (Mn), 0.04 max phosphorus (P), and 0.05 max sulfur (S). Panels for the impact test were A36 steel with an actual analysis of 0.16 C, 0.84 Mn, 0.004 S, 0.010 P, 0.04 silicon (Si), 0.29 copper (Cu), 0.11 nickel (Ni), 0.08 chromium (Cr), 0.005 vanadium (V), 0.002 cobalt (Cb), 0.030 molybdenum (Mo), 0.032 aluminum (Al), and 0.034 titanium (Ti). Other test panels were made from ASTM A569 steel having an actual analysis of 0.07 C, 0.46 Mn, 0.007 P, 0.004 S, and 0.02 Cu.

Test panels were prepared using a Metco wire-arc apparatus to evaluate surface contamination and alloy and hardness effects at Corrpro's Ocean City, New Jersey (OC) laboratory facility. Grade A36 steel was used for most of the testing, and ASTM A572 Grade 50 steel was used in the hardness comparison tests between A36 and Grade 50. Figures 3 and 4 show the panels being prepared at both facilities. Figure 5 shows the complex test panel used in the corrosion testing.

Aluminum TSMC

Zinc TSMC

Figure 3. TSMC application at CSI.

Aluminum TSMC

Zinc TSMC

Figure 4. TSMC application at Corrpro's laboratory.

Surface Preparation

Unless otherwise specified, the test panels for this study were prepared using 100-percent G-16 steel grit. In all cases, the surface finish was SSPC-SP-5 white metal with a target profile of 3 mils (76µm).

This study also explored the effects of grit-to-shot ratio on surface profile and coating performance using aluminum and zinc TSMCs. This is important because 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 of the debonding stresses acting on the coating are shear forces, and an angular surface provides more surface area for the coating to adhere to. However, many steel fabricators employ recycled steel shot as the preferred (and economical) method of surface preparation and often use mixed shot and grit in order to reduce equipment wear. Varying levels of angular profile may result. This work investigated the impact of such practices by metallizing over various surface roughness conditions. The most common technique for determining angularity compares magnified images of the surface to standard photomicrographs. Part of this work included tests to try to identify a field-friendly method of quantitatively measuring angularity. Table 4 lists the abrasive mixes tested using aluminum and zinc thermally sprayed coatings. The surfaces were prepared to an SSPC-SP-5 white metal finish.

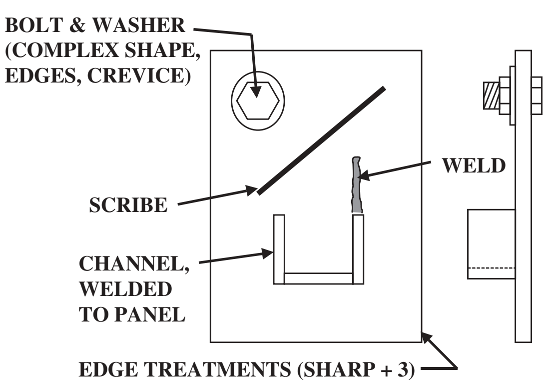


Figure 5. Test coupon used for corrosion testing.

TSMC Application

TSMC application was performed with wire-arc spray equipment using standard parameters for the application equipment. Test panels to evaluate adhesion, sealers, surface preparation parameters, edge effects, and application parameters were prepared by CSI Coatings. Test panels prepared to evaluate surface contamination and alloy and hardness effects were prepared at Corrpro's laboratory facility. During this application, a target film thickness of 10 to 12 mils (254 to 305 µm) was specified. The standoff was nominally 8 to 10 in. (20 to 25 cm), and the gun angle was 90 degrees from the sample.

Testing Program

Table 5 shows the test plan and Table 6 shows the tests applied to the various objectives of the test program.

Quality Assurance Testing

After surface preparation, quality assurance testing was conducted on representative samples. This included visual

TABLE 4 Blast procedures investigated

Grit/Shot	Steel Shot	Steel Grit	Rationale
Shot Blast	100% S-280		Negative Control.
Grit Blast		100% G-16	Positive Control.
Shot/Grit Mix	33% S-280	67% G-16	Observed in shop for TSMC project in North Carolina.
Alternate Shot/Grit Mix	70% S-280	30% G-16	Test the profile provided by a “low-grit” mixture.

TABLE 5 General test matrix

Test	Coupon Size[1]	Specification Reference	Comments[1]
Microstructure Analysis	1 in. x 3 in. x 0.125 in.[2]	ANSI/AWS A5.33-98	Porosity, segregation, oxides, and sealer penetration.
Tensile (Pull-Off) Adhesion	4 in. x 6 in. x 0.125 in.	ASTM D4541 “Pull-Off Strength of Coatings Using Portable Adhesion Testers”	Requires a 15–20 mil (375–500 µm) TSMC thickness to prevent adhesive from reaching substrate.
Bend Adhesion	2 in. x 4 in. x 0.063 in.	ANSI/AWS C2.18-93 MIL-STD-2138A	Coated coupons are deformed 180° around a 0.5-in. (13-mm) mandrel and inspected for cracking and delamination.
Alternate Wet/Dry Seawater Immersion	4 in. x 6 in. x 0.125 in.[3]		Representative of splash and tidal zone exposure.
Full Seawater Immersion	4 in. x 6 in. x 0.125 in.		Representative of complete immersion conditions.
Drop Weight Impact	6 in. x 12 in. x 0.25 in.	Modified ASTM D2794, “Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)”	A 16-lb spherical weight is dropped onto the panel. Height will be increased as necessary using a longer guide tube. This method has higher impact energy than ASTM D2794 provides.

NOTE: 1 in. = 2.54 cm.
[1] The tests will be replicated three times except for the corrosion tests, which will be replicated two times.
[2] One sample from the beginning of the coating application run, one from the middle, and one from the end.
[3] Special panel containing crevice, scribe, fastener, and edge treatments—see Figure 5.

TABLE 6 Tests applied to the objectives

Testing Objective	TEST						
	Thickness	Profile	Bend adhesion	Tensile adhesion	Corrosion	Drop weight impact	Micro-structure
Sealers	X	X	X	X	X	X	X
Abrasive mixes	X	X	X	X	X	X	
Spray parameters	X	X		X	X		X
Effect of steel hardness	X	X		X	X		
HSLA[1] steel v. carbon steel	X				X[2]		
Edge geometry effects	X	X			X		X
Coating defects	X	X			X		
Surface contamination	X	X		X	X		

[1] HSLA = high-strength, low-alloy.
[2] Existing coupons from a previous study and laboratory polarization tests used to evaluate.

inspection, surface profile evaluation, and chloride contamination. Methods for these evaluations 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 the visual standards to determine if it conformed to an SSPC-SP-5, "White Metal Blast Cleaning," condition.

Surface Profile Evaluation. The target surface profile was 3 mils (76 microns). Profile evaluation was performed on all samples for the 100-percent shot, 70/30-percent shot/grit, and 33/66-percent shot/grit abrasives. Selected 100-percent-grit abrasive samples were tested. Surface profile was evaluated using two methods. Initial measurements were made using Testex brand replica tape. This tape is placed 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 6 shows this measurement.

The second method was the use of a surface profile gauge to determine the profile of the blasted surface. Two gauges were used on the basis of their availability during sample preparation. Samples prepared by CSI Coatings were evaluated using a Perthometer MP4 150 profilometer. Samples prepared at the Ocean City laboratory were evaluated using a Mitutoyo SJ-201 surface roughness gauge. Both models are field usable and capable of measuring various aspects of the profile, which are shown in Table 7. Figure 7 shows the two gauges used to evaluate the profile of these samples.

Both 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 the variations of these. Both profilometers were calibrated before use, and the same individual performed the profile measurements at both locations. Both instruments are relatively operator independent. These measurements and their statistical manipulation are used to calculate the values shown in Table 7.

Figure 6. Testex tape to evaluate surface profile.

Coating Thickness Measurements. DFT measurements were made on samples after preparation and cure (after cooling for TSMC samples and a minimum of 7 days after sealer coats were applied). Coating thickness measurements were made using an Elcometer 345 eddy current thickness gauge (SSPC-PA [paint application] Type 2 gauge). Before thickness measurements were made, the Elcometer 345 thickness gauge was calibrated for measurement over a blasted surface. Using 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 coating thickness. This calibration was performed daily.

Calibration thickness measurements were made on each test sample. Typically five measurements per side were made on all test samples with the exception of the 4- × 6-in. (10.2- × 15.2-cm) complex samples (8 measurements per side and 16 measurements in total were made on these panels). Measurements were taken at consistent locations with each type of panel.

The thickness ranges of the TSMCs applied by CSI coatings were 12.9 to 20.8 mils (327 to 528 μm) for zinc, 14.8 to 22.9 mils (376 to 582 μm) for aluminum, and 14.7 to 19.5 mils

TABLE 7 Surface profile characteristics

NAME	ABBREVIATION	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.
10-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.

Perthometer *Mitutoyo SJ-201*

Figure 7. Surface profile gauges.

(373 to 495 µm) for zinc/aluminum. The thickness ranges of the TSMCs applied to the A36 and Grade 50 panels at Ocean City were 9.9 to 11.8 mils (251 to 300 µm) for zinc and 12.3 to 14.2 mils (312 to 361 µm) for aluminum.

Tensile (Pull-Off) Adhesion. Pull-off adhesion testing was performed on selected test samples. Adhesion is commonly used to monitor coating quality. MIL-STD-2138A specifies that a "good" aluminum TSMC should have a minimum adhesion strength of 1,500 psi (10.3 MPa) for individual samples and 2,000-psi (13.8-MPa) average (MIL STD paragraph 5.3.3.3) (*4*). Adhesion testing measures the bond strength at the weakest point in a coating system, with both strength (stress per unit test area) and failure location reported.

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 Patti Jr. pneumatic adhesion tester. Aluminum pull stubs (dollies) were adhered to the topcoat surface (TSMC or sealer coat) using a two-part epoxy adhesive. Following complete cure (24 hours after adhesive application), the pull stub was mounted in the tester, and air pressure was used to disbond the stub from the test sample.

This system uses an air bladder to apply an upward (normal) force to the pull stub until disbondment or the limit of the apparatus is reached. This apparatus uses an approximate 40 : 1 ratio to apply a maximum upward force (normalized to pull-stub contact area) of approximately 4,000 psi (28 MPa) from a 100-psi (0.7-MPa) air source. Figure 8 shows a diagram of this apparatus. Once disbondment occurs, the air pressure is recorded along with the location of failure for comparative analysis. The air pressure is then converted into adhesion strength from tabulated values.

The tensile adhesion strength of TSMC on a 100-percent grit-prepared surface was 895 psi (6.2 MPa) with a 36-psi (0.25-MPa) standard deviation for zinc and 1,514 psi (10.4 MPa) with a 263-psi (1.81-MPa) standard deviation.

Mandrel Bend Adhesion Test. Mandrel bend testing is used to determine the flexibility and adhesion of a coating material. For liquid coatings, mandrel bend results for a "good" coating typically have minimal or no cracking because of their inherent flexibility. However, TSMCs are more rigid. Because of this, mandrel bend test requirements are less stringent and allow some cracking of the coating. Figure 9 shows examples of passing and failure conditions for TSMCs.

Mandrel bend testing was performed on the samples indicated in Table 5. Testing was conducted on the 2- × 4- × $^{1}/_{16}$-in. (5- × 10- × 0.16-cm) samples, which were bent around a $^{1}/_{2}$-in (1.27-cm)-diameter cylindrical mandrel. Samples were bent approximately 180 degrees around this mandrel, creating a "U" shape similar to that shown in Figure 9. Immediately after testing, samples were evaluated for cracking and disbondment. No disbondment was observed on zinc or aluminum TSMCs prepared by grit blasting.

Other Tests

Additional tests were conducted in order to provide input to the objectives of the laboratory program. The specific tests used are listed below.

Falling Weight Impact

The falling weight impact test was performed to determine the ability of the coating to resist damage caused by rapid deformation (impact). Testing was performed both with and

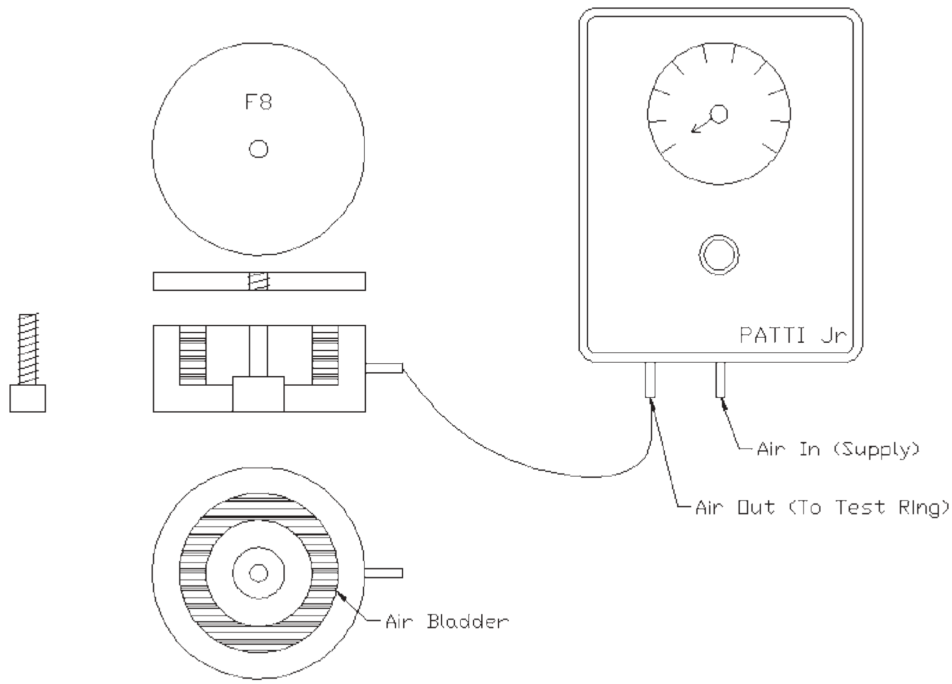


Figure 8. Pneumatic adhesion test apparatus.

without a sealer on aluminum and zinc TSMCs. For the test, a 12.5-lb (5.67-kg) steel ball (weight) was dropped from successive heights under natural gravitational acceleration at sea level (32.2 ft/s [9.81 m/s]), through a 15-ft (4.6-m) guide tube, onto the test panel, which was place horizontally.

During this test, the 12.5-lb (5.67-kg) weight was dropped from varying heights. After each impact, the panel was inspected for signs of coating (TSMC and/or sealer) penetration. Testing was continued until the height of the drop (to the nearest 6 in. [15.2 cm]) at which the coating just resisted penetration by the weight was determined. Five replicate tests were performed at this height to confirm the failure end point. The total energy ft-lb (N-m) that the coating could withstand without penetration was reported. Figure 10 shows this test apparatus.

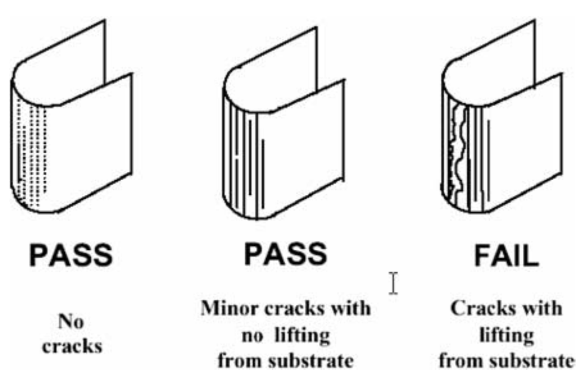


Figure 9. TSMC mandrel bend pass/fail examples.

Microstructure Analysis (Metallography)

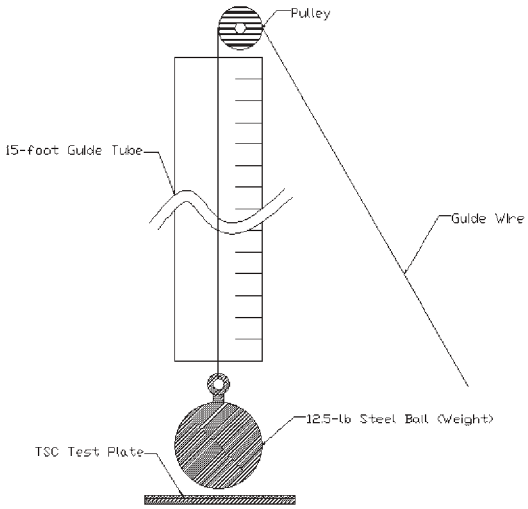
Microstructure analysis was performed on untested and post-simulation test samples as identified in Table 5. This analysis was performed using visual microscopy (metallography) to determine

- Porosity—size, distribution, geometry, and interconnection;
- Compositional phases—number present;
- Oxide inclusions—number, size, and distribution; and
- Coating substrate interface characteristics—trapped grit, disbondment, and so forth (general evaluation on untested samples, local characteristics adjacent to the scribe on post-test samples).

Lehigh Testing Laboratories, Inc. (New Castle, Delaware) performed the microstructure analysis. Data were generated using photomicrographs, visual observations, and the point-count method for porosity and oxide distributions. The samples were examined in their unetched state for porosity and oxide evaluation and in their chemically etched state to show the presence of multiple phases. This did not identify the chemistry of such phases, but showed whether one or more different phases were present. Two samples from each test were examined.

Corrosion Tests

Laboratory tests consisting of alternate wet-dry seawater exposure and constant immersion were performed to evaluate



Sketch

Test Apparatus

Figure 10. Falling weight impact test apparatus.

the sealers, surface preparation, and application variables in this program. On the basis of results from previous studies, it is recognized that a short-term exposure test may be inadequate to differentiate the performance of TSMC/sealer systems. Thermally sprayed coating systems may be exposed to harsh environments for several years without exhibiting significant levels of corrosion.

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

Test samples were placed in a non-metallic (plastic) tank and held in place with plastic holders. Samples were oriented at 90 degrees from horizontal and completely submerged in the natural seawater environment. To avoid stagnation, the seawater in this tank was continually refreshed using a trickle (quiescent) flow from the intake system.

During this test, periodic inspections (nominally every 3 months) were made to evaluate performance. This included evaluations for substrate corrosion (rusting) in accordance with ASTM D610, coating blistering in accordance with ASTM D714, formation of corrosion products on the samples, and visible cutback from the intentional holidays. The test methods used for these evaluations are presented in Table 8.

For analytical purposes, the ASTM D714 rating is converted to a composite blistering rating. On the basis of the size and density of the blisters, a numerical rating from 0 to 10 is given to the sample. Table 9 shows this composite blister index.

Figure 5 illustrates the type of panel used. The scribe was a diagonal line cut through the metallized coating with a hardened steel tool with a sharp point to ensure that the steel substrate was exposed. The panel edges were used to examine the effect of different edge treatments.

After sample preparation and sealer cure, an intentional scribe (removal of all coating materials to the steel substrate)

TABLE 8 Coating deterioration inspection techniques

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

TABLE 9 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

was placed into the test samples. This was performed to create a known defect and measure the coating systems' ability to resist additional corrosion damage at this location. This technique is commonly used in laboratory testing to accelerate the natural degradation of samples. In addition to linear scribes, some samples also had circular holidays made through the TSMC. These holidays were 1.5 in. (3.81 cm) in diameter and were used to further stress the test samples. These relatively large holidays (compared with the linear scribes) were used to evaluate the "throwing power" of the TSMCs applied (aluminum and zinc). This large-diameter holiday increases the anode-to-cathode surface area ratio, thus increasing the sacrificial protection requirements of the TSMC. These scribes represent an order-of-magnitude increase in anode-to-cathode surface area of 48 to 0.18 square in. (scribed) to 48 to 1.8 square in. (circular holiday). Use of a larger-diameter holiday will emphasize performance differences between TSMCs. Figure 11 shows examples of the intentional scribe and circular holidays used (holidays and scribes highlighted).

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

Alternate Wet-Dry Seawater Immersion. Alternate wet-dry (or cyclic) seawater immersion was similar to constant immersion, except that immersion was intermittent. Test samples exposed in this environment were immersed in natural seawater for approximately 15 minutes followed by 75 minutes of exposure to a harsh marine environment. This cycle was used to simulate the tidal action of natural waters, which can accelerate the corrosion of structures with their wet-dry cyclic actions.

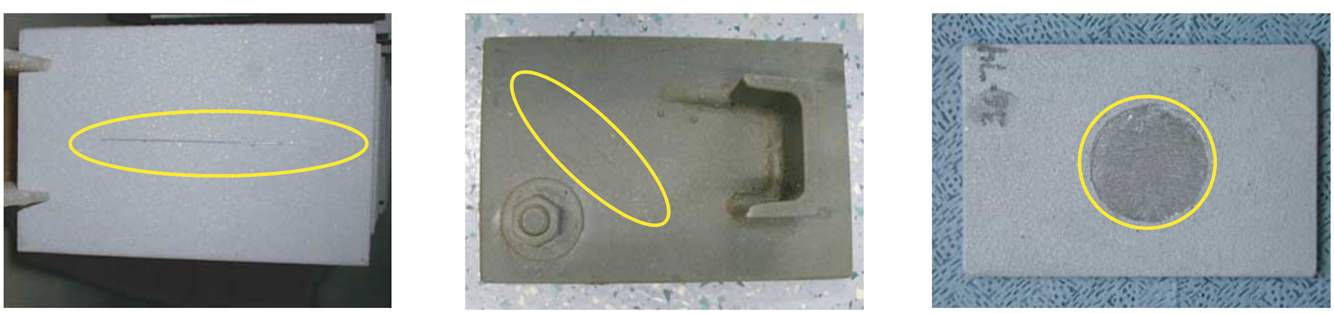
This test was conducted in the same tank used for constant immersion, with test samples placed just above this environment. An automated timer was used to cycle immersion and atmospheric exposure in this zone only (constant immersion samples were continually submerged in natural seawater). The presence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

Similar to the constant immersion samples, cyclic samples were periodically (nominally every 3 months) inspected for deterioration. These samples were inspected for the same deterioration as constant immersion samples using the test methods described in Table 8, above.

RESULTS OF THE LABORATORY TESTS

Sealer Tests

Sealers are usually specified to seal the pores in TSMCs to improve coating performance. The U.S. Army Corps of Engineers thermally sprayed coating guide lists vinyl, coal tar epoxy, aluminum-pigmented epoxy mastic, tung-oil phenolic aluminum, vinyl-butyral wash primer, aluminum silicone, and silicone alkyd. This test program tested three new sealers along with two standard sealers and unsealed metallized samples (controls). The sealers were tested on thermally sprayed aluminum-coated steel panels and zinc-coated steel panels. Unsealed metallized samples were also tested and served as controls. Table 10 lists the sealers tested. Two low-surface-energy, high-solids sealers were selected for testing because they are different formulations and because they are both recommended by the Virginia DOT, according to one of the applicators interviewed.



Scribe (4 x 6 in.) *Scribe (4 x 6-in. complex)* *Circular Holiday (4 x 6 in.)*

Figure 11. Representative intentional holidays (1 in. = 2.54 cm).

TABLE 10 Sealers tested

GENERIC TYPE	SUPPLIER
Zinc chromate vinyl wash primer (control material)	Elite 1380
Epoxy (coal tar epoxy or equivalent)	Devoe BarRust 235
Low-surface-energy, high-solids sealer	Devoe 167 Pre-prime
Low-surface-energy, high-solids sealer	Carboline Rustbond
Low-viscosity penetrating urethane	Xymax Monolock PP

The sealer coats were applied using air spray equipment. Application was performed in accordance with the manufacturers' recommendations for mixing and thinning. All systems were applied with a maximum target DFT of 1 mil (25.4 µm) or as specified by the manufacturer (if less). The samples were scribed as described above.

Adhesion

Comparison of tensile adhesion strength with each of the five sealers tested showed similar ranges as those observed for aluminum and zinc TSMC samples applied over a 100-percent grit-blasted substrate. However, the primary failure location for the sealed samples varied from substrate to adhesive failures. This differs from the failures of the unsealed TSMCs; for unsealed samples, all primary failures occurred at the substrate. The change in failure location was observed to be primarily related to sealer although some variations were observed between the aluminum and zinc TSMCs. Table 11 shows the primary failure location and average strength for each sealer.

The average tensile adhesion strengths fall within the range of values for unsealed 100-percent grit-blasted steel, which indicates that the use of these sealers does not reduce the overall strength of the coating system. The change in failure location for several of the sealers from substrate (complete) to adhesive (used to attach aluminum pull stubs) or intra-coat (between sealer and TSMC) failures suggests that some benefit is gained by using a sealer coat. In these cases, the adhesion bond between the TSMC and substrate is greater than the reported value.

Figure 12 shows the results of the U-bend adhesion tests on the 100-percent grit-blasted sealed zinc panels. The results of the bend tests on the abrasive mix variations are given later in this report. Cracking was observed on almost every sample that was evaluated using this test procedure. However, disbondment was observed on only four of the five sealer coats over zinc (Xymax did not show any disbondment). No disbondment was observed on the sealed aluminum TSMC U-bend specimens.

Falling Weight Impact Tests

Results from this testing showed that without a sealer coat, all TSMCs had failures at 12.5 ft-lb (16.9 N-m), which was the lowest energy application possible with the test apparatus.

The results of the drop weight impact tests showed that when a sealer coat was applied all samples had no failure at 187.5 ft-lb (254.2 N-m) (highest energy application possible with the test apparatus). This was determined by visual observation, where marring of the coating occurred, but no penetration of the TSMC to the steel substrate was recorded. These results suggest that in high-impact or mechanical wear areas, a sealer coat would improve abrasion- and impact-resistance performance.

Sealer Coverage and Penetration

Several methods were investigated to attempt to quantify sealer coverage and penetration. Successes and limitations were encountered with each method, all of which are discussed below.

Chemical Indicator Solutions. Sealer coverage and penetration can be determined by using chemical solutions that react with specific metal alloys to indicate the presence of these metal alloys. The chemical solutions cannot be used

TABLE 11 Tensile adhesion results for sealed TSMC samples

Sealer	Aluminum TSMC		Zinc TSMC	
	Strength, psi (MPa)	Location	Strength, psi (MPa)	Location
Elite 1380	1,575 (10.9)	Substrate	1,126 (7.8)	Substrate
Devoe BarRust 235	1,507 (10.4)	Adhesive	1,214 (8.4)	Substrate
Devoe 167 Pre-prime	2,167 (14.9)	Adhesive	1,698 (11.7)	Adhesive
Carboline Rustbond	1,527 (10.5)	Substrate	1,303 (9.0)	Adhesive
Xymax Monolock PP	1,330 (9.2)	Intra-coat	1,276 (8.8)	Intra-coat

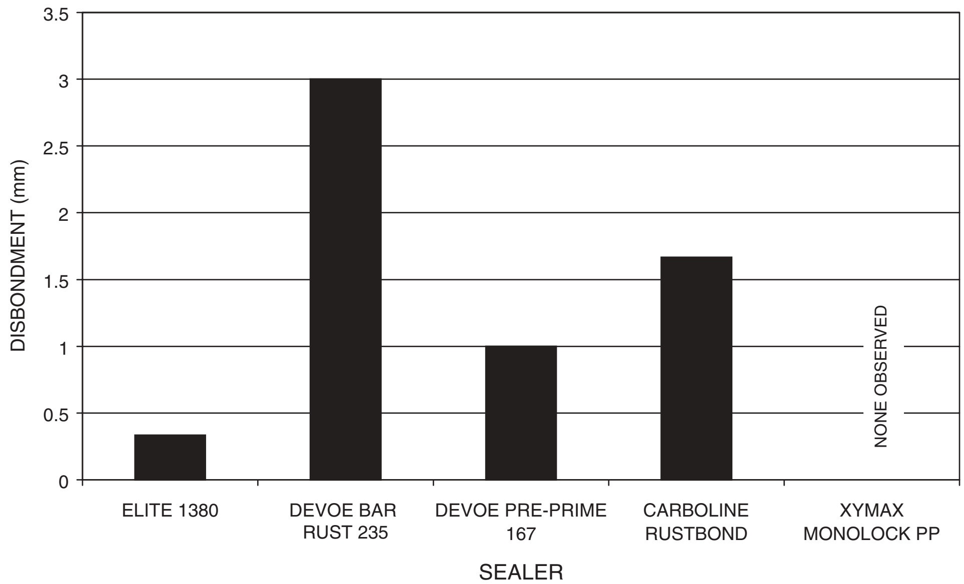


Figure 12. Average U-bend disbondment results for grit-blasted sealed zinc TSMC panels.

to determine the thickness of the sealer. Reaction of the chemical solution with the TSMC (aluminum or zinc) would indicate inadequate or incomplete coverage by the sealer. Two chemical solutions were used to verify coverage of the aluminum and zinc TSMCs. These were sodium hydroxide (NaOH) and saturated copper sulfate ($CuSO_4$) solutions. Sodium hydroxide is used to detect the presence of aluminum as evidenced by a foaming reaction. Copper sulfate is used to detect the presence of zinc, which changes color to black when copper sulfate is applied.

These indicator solutions were applied to representative samples for each coating to determine if complete coverage of the TSMC was achieved. Solutions were applied using brush and roller techniques, and the samples were visually monitored for the above-described reactions. The percentage of the surface area not covered by the sealer was determined on the basis of these chemical reactions. Table 12 shows a list of the sealers and the estimated percentage of the surface area covered for each TSMC.

For zinc TSMC, area estimation was more readily performed than with the aluminum TSMC samples. This was primarily because the chemical reaction—a change in color—was easily observed. The reaction caused by the sodium hydroxide solution on the aluminum samples often obscured coated areas. Chemical indicator solutions are easily employed and can be implemented in field evaluations, but the reaction of the sodium hydroxide solution on the aluminum TSMC may prevent an accurate measurement of exposed metal.

The data presented in Table 12 suggest that most sealers provided near complete coverage of the aluminum and zinc TSMCs, with the possible exception of Devoe 167 Pre-prime and Carboline Rustbond on the aluminum TSMC. The lower values are the result of the thin sealer coat (about 1 mil [25.4 μm]) and a rougher aluminum TSMC surface, which, of course, is the same situation encountered in the field.

Metallographic Evaluation. Visual metallography was tested as a method to determine sealer thickness, coverage, and penetration on cut sections of test samples. Evaluation of these samples was difficult because the thin, lightly tinted sealers were not easily discernable from the TSMC. A second evaluation of freshly cut samples was conducted with a thin black coating applied on top of the sealer coats. This was used as a contrasting color to distinguish between the TSMC and sealer

TABLE 12 Percent surface area covered by sealers as shown by chemical indicator solutions

Sealer	Surface Area, % Aluminum	Surface Area, % Zinc
Elite 1380	99.0	95.0
Devoe BarRust 235	98.0	100
Devoe 167 Pre-prime	45.0	100
Carboline Rustbond	75.0	97.0
Xymax Monolock PP	99.5	100

coats. This also was used to prevent the sealer coat from disappearing into the background as can often occur when performing metallography on thin coatings. Despite these efforts, the sealer coats could still not be readily viewed using visual microscopic techniques.

Optically Stimulated Electron Emission Evaluation. Optically stimulated electron emission (OSEE) was tested to quantify the coverage of the sealer coats over aluminum and zinc TSMCs. This technique uses photon emission technology to measure coating quality. An ultraviolet light source is focused on a specific area of a conductive, coated substrate. The reflection and absorption of photons is measured as a current value (OSEE value) to determine coating quality. Figure 13 shows a picture of this test apparatus.

OSEE is a comparative technique, which can be used to determine the general coverage of material or substrate. Conductive coatings (such as TSMCs) will have a higher value, while tinted coatings will have a lower value. Voids, thin spots, or other coating anomalies will allow for increased photon transmission and thus result in values closer to an unsealed TSMC. This technique returns a dimensionless value, which is used for comparison between sealer coats. The relative ranking of sealers using this method was compared with other test methods to determine if OSEE provides an accurate ranking of the sealers and which sealer provides optimal coverage.

Figure 14 shows the average OSEE measured values for the sealers applied over aluminum and zinc TSMCs. The 95-percent confidence interval for the data was also calculated and found to be very close to the averages shown in the graph. In general, the addition of a sealer reduced the OSEE values by an order of magnitude. The average differences between the samples were minimal, and overlap of the confidence intervals suggests that these sealer coats have similar electron emission characteristics. Compared with the indicator solution results, similar electron emission characteristics might be explained by the relatively high percentage of surface area coverage (demonstrated by this visual technique). While the OSEE method can detect whether a sealer is present, further work is needed to determine if the method can be used to provide an estimation of sealer quality.

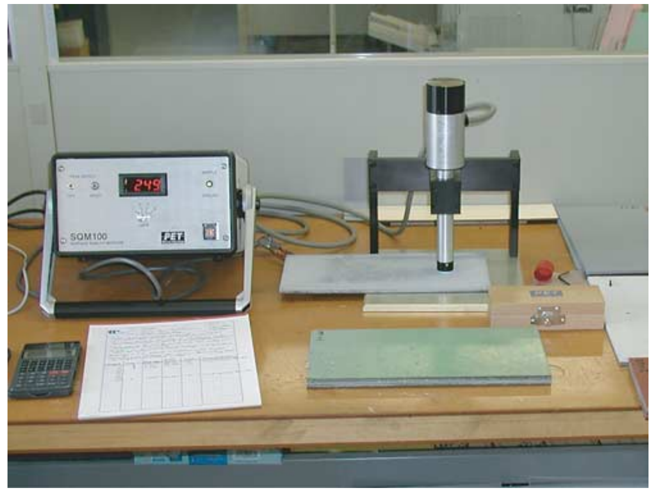


Figure 13. OSEE test apparatus.

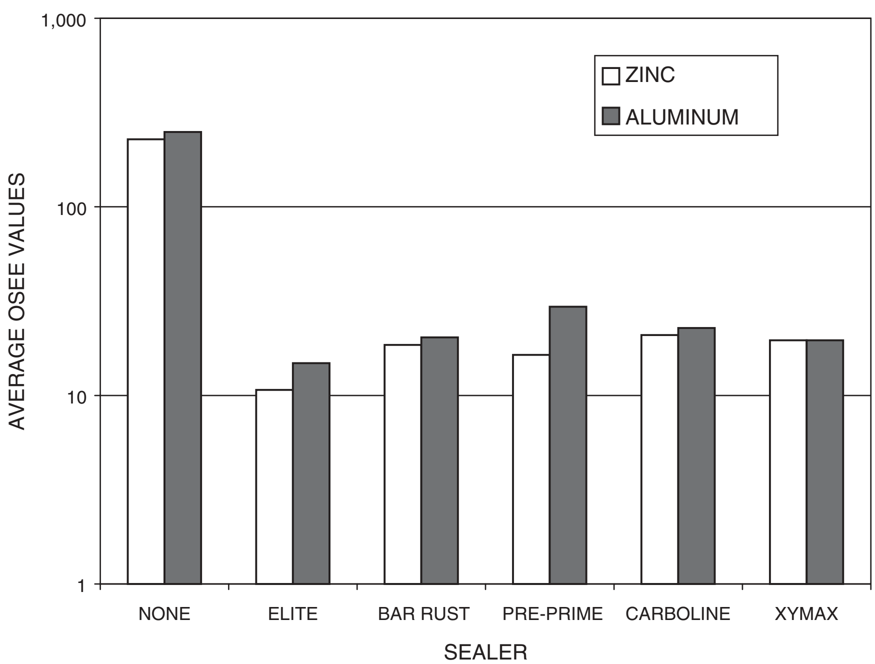


Figure 14. Average OSEE measured values for the sealers applied over aluminum and zinc TSMCs.

Visual Evaluation. Visual evaluations were performed with the unaided eye and under 5x magnification to determine overall sealer quality and coverage. During this inspection, the coatings were observed for apparent voids, cracking, checking, blistering, color, and uniformity. Variations in general appearance and coating quality were recorded.

Visual evaluation techniques were not well suited for determining sealer coverage, especially when lightly tinted sealers were used. Here, the sealer coat was difficult to distinguish from the rough TSMC surface. Although in most cases the presence of the sealer coat could be verified, complete coverage was difficult to determine.

Corrosion Tests Comparing Sealers

The results from constant immersion testing after 12 months suggest that the presence of a sealer coat is beneficial for reducing corrosion and blistering. The overall corrosion rating for unsealed zinc TSMC was 8, and the rating for unsealed aluminum TSMC was 9. Overall corrosion ratings for sealed aluminum and zinc TSMCs were 9 to10. Composite blister ratings for unsealed zinc and aluminum TSMCs were 6.9 and 10, respectively. Composite blister ratings for the sealed TSMCs remained at 10 for both TSMCs except for Carboline Rustbond, for which the rating was 7.5. Zinc TSMC showed increased cutback with all but the Elite 1380 sealer. The amount of cutback ranged from about 0.03 in. (0.76 mm) to 0.12 in. (3 mm). Aluminum TSMC was not observed to have the same cutback issues and performed well both sealed and unsealed. For zinc TSMC, the optimum sealer for immersion service appears to be a conversion coating. Note that chromate conversion coatings use hexavalent chromium, which is regulated as a hazardous waste product. Its use may not be possible in all areas. Alternative conversion coatings are a suggested alternative, but their performance in these environments is untested. Aluminum appears unaffected by the use of a sealer.

Following 12 months of exposure in a cyclic immersion environment, none of the sealed samples experienced any significant deterioration. Corrosion ratings for both zinc and aluminum TSMCs were an average of 9 (out of a possible 10) or higher for samples (including unsealed controls), and composite blister ratings were greater than 9.5 for all sealers (the control zinc average was below 5.5). Similarly, none of the samples experienced any cutback from the intentional scribe. In total, the results suggest that the presence of a sealer coat may be beneficial over zinc TSMC by reducing blistering in cyclic immersion service. The presence of a sealer coat did not appear to be beneficial or detrimental when applied over aluminum TSMC.

The results after 12 months of exposure indicate that the performance of aluminum TSMC may not be improved by using a sealer, but that the performance of zinc TSMC might be improved. Differences were relatively small, however, and the 12 months of exposure time does not afford enough time for a meaningful comparison of sealer materials. The plan is to keep all of the corrosion test panels in testing long enough for significant differences to be observed.

Abrasive Mix Effects

Adhesion Tests

Figure 15 presents the surface profile measurements made using Testex replica tape on the samples prepared by CSI Coatings using different abrasive mixes (see Table 4). Figure 15 presents the average of the profile data and the confidence interval. The confidence interval was estimated using the Student *t* distribution, where the confidence interval is given by the following equation:

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

where

Mean = statistical mean of the data points,
StdDev = Standard Deviation of the data points,
t = the Student's *t* variable at a 95-percent confidence and 3 degrees of freedom, and
n = number of data points.

Other graphs in this report showing a confidence interval were generated in the same fashion. The results show that the 100-percent grit and 67-percent grit mixtures produced deeper profiles than did the 100-percent shot or 70-percent shot mixture. The average profile produced on the 33-/67-percent shot/grit mix is deeper than the profile produced on the 100-percent grit, but there is overlap in the data.

Figure 16 provides the tensile adhesion data for zinc and aluminum TSMCs on the panels prepared with different abrasive mixes. The results show clearly that there is an increase in adhesion strength going from the shot blast profile to 100-percent grit blast profile. The results also show that the abrasive mixtures result in decreased adhesion strength, but they do not show whether this will reduce the effectiveness of the coating.

The U-bend adhesion test specimens showed cracking on almost every sample that was evaluated using this test procedure. However, disbondment was only observed on specific samples. Disbondment occurred on aluminum and zinc TSMCs prepared with 100-percent shot and zinc TSMC prepared with grit/shot mixtures. No disbondment was observed on aluminum or zinc TSMCs applied to 100-percent grit-prepared coupons. Figure 17 shows a plot of average disbondment length for each surface preparation method. This figure demonstrates that zinc TSMC is more susceptible to disbondment on surfaces prepared with less angular abrasives than 100-percent grit.

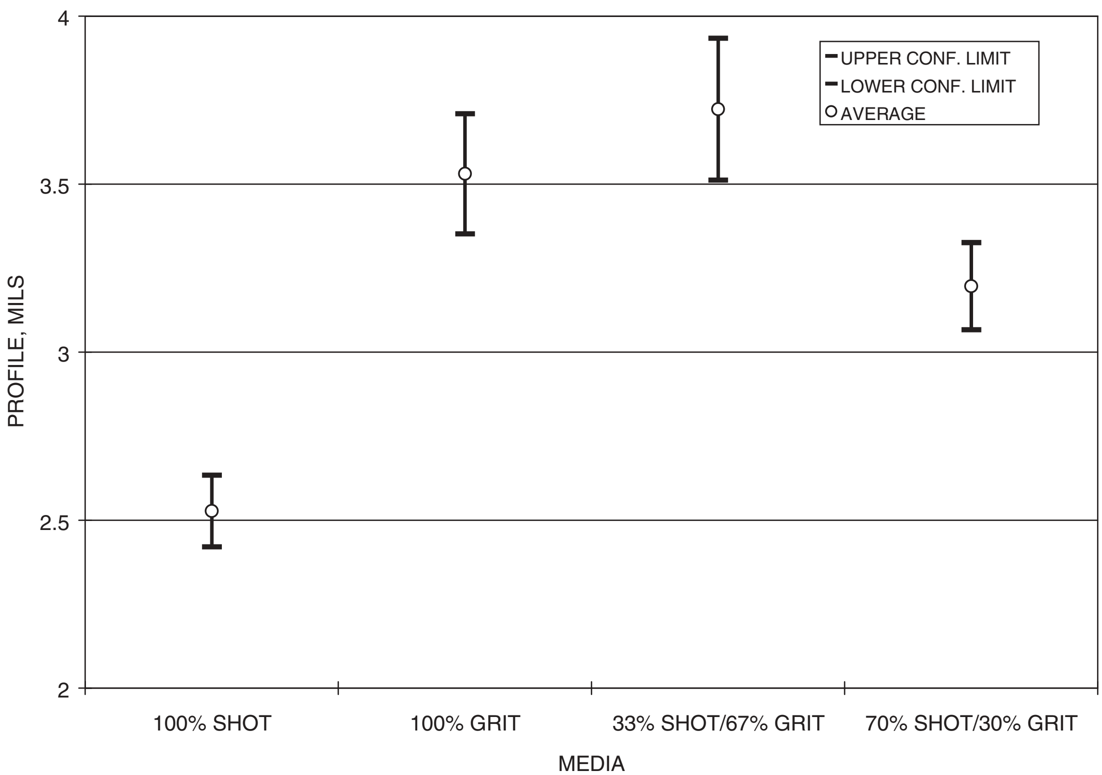


Figure 15. Testex replica tape profile ranges (panels prepared by CSI).

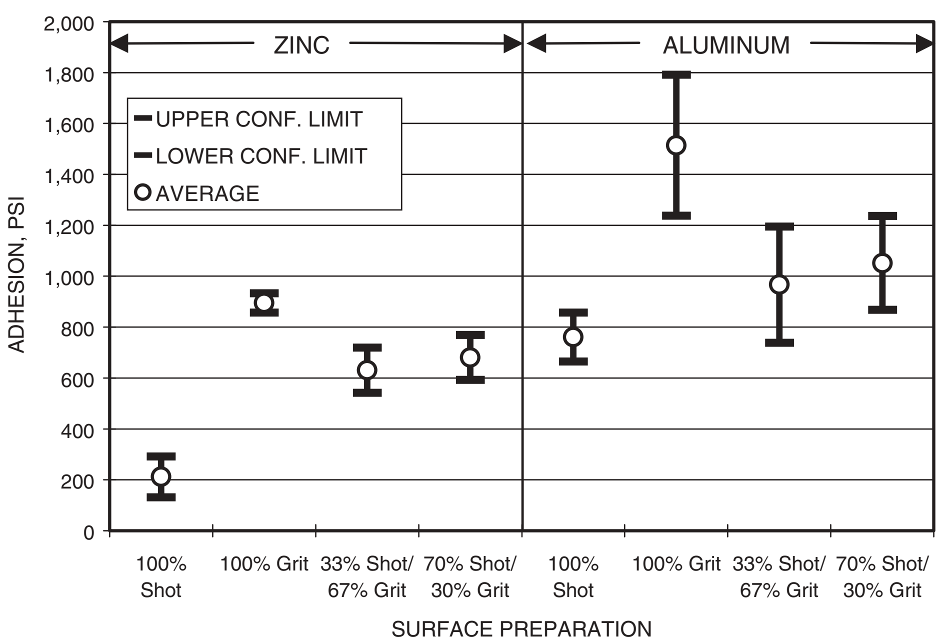


Figure 16. Tensile adhesion of zinc TSMC versus abrasive mix (panels prepared by CSI, 1 psi = 6.89 KPa).

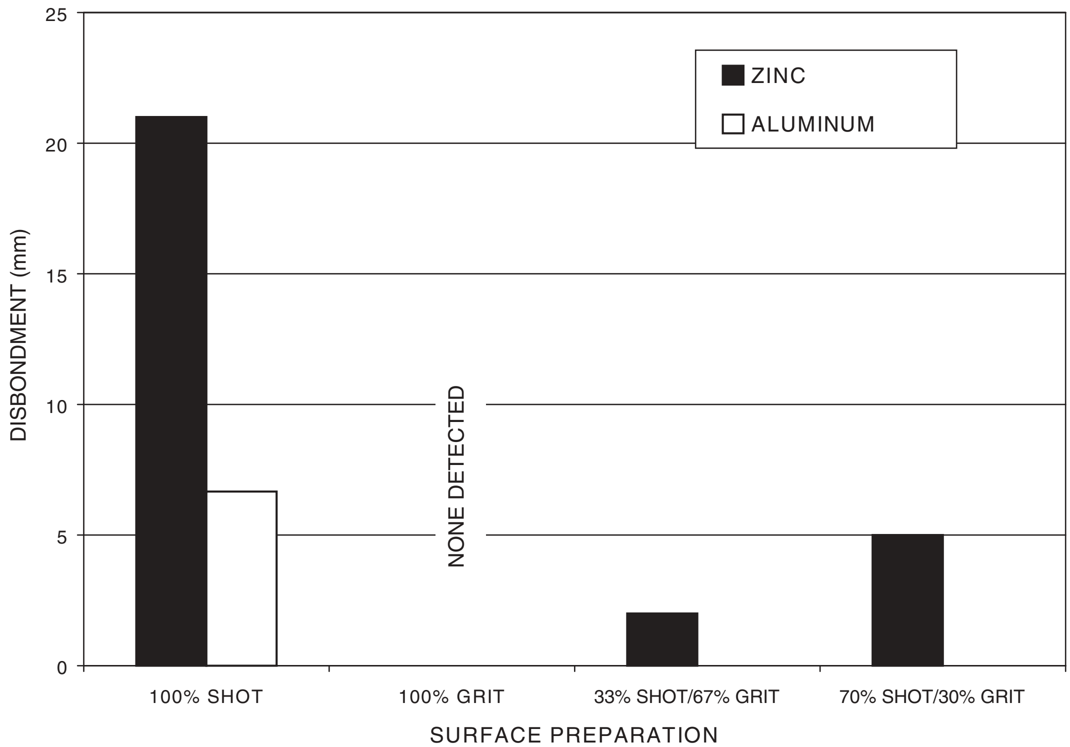


Figure 17. Average U-bend disbondment results for unsealed TSMC panels.

Profile Measurements

As described in the section on procedures, surface profile characteristics were measured with a profilometer for the values of R_A, R_Y, R_Z and R_Q (see Table 7 for the definitions of these values). Figure 18 shows the values of R_A, R_Y, R_Z and R_Q, and Figure 19 shows the values of R_{PC} on the A36 steel panels prepared by CSI Coatings. Similar measurements were performed on the A36 and Grade 50 samples prepared at the Ocean City lab. The values of R_A, R_Y, R_Q, and R_Z for the A36 and Grade 50 samples on the CSI-prepared panels all have significant overlaps in the confidence bands. No distinction

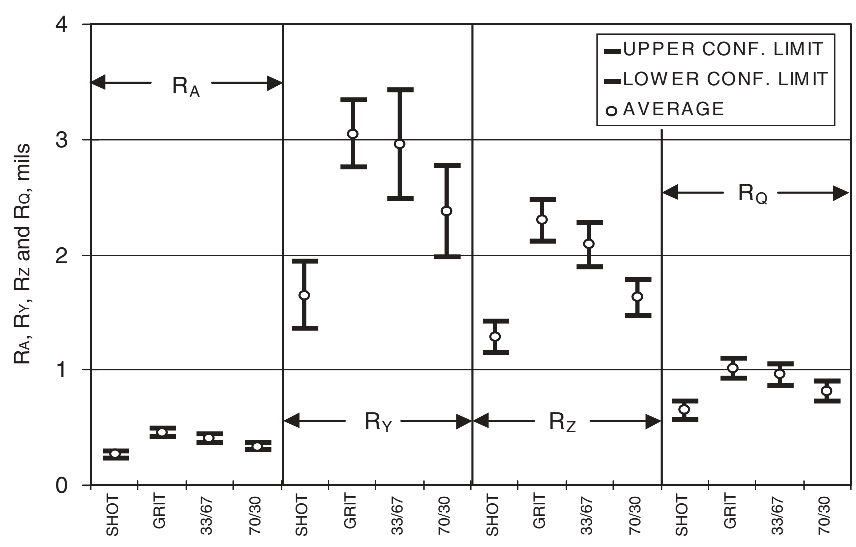


Figure 18. Average values and 95-percent confidence ranges for R_A, R_Y, R_Z and R_Q profilometer data on A36 panels prepared with different abrasive mixes (1 mil = 25.4 μm).

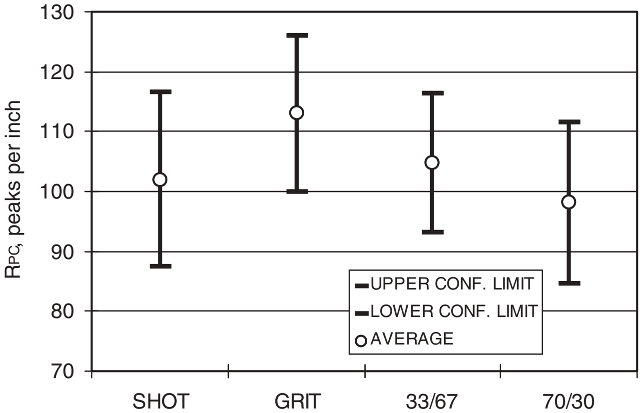


Figure 19. Average values and 95-percent confidence ranges for R_{PC} profilometer data on A36 panels prepared with different abrasive mixes (1 in. = 2.54 cm).

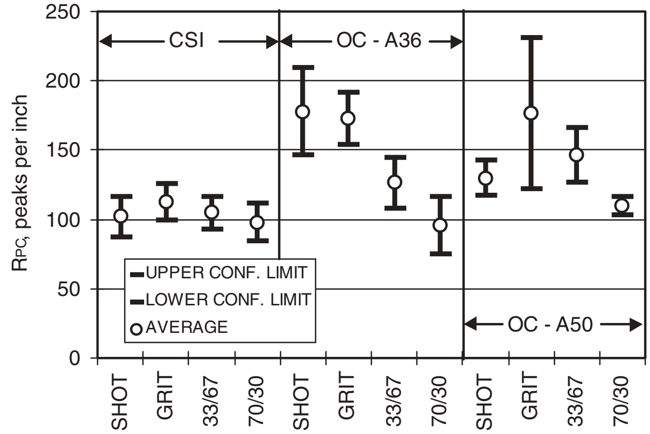


Figure 21. R_{PC} versus abrasive mix and applicator (1 in. = 2.54 cm).

can be made between the abrasive mixes except that the shot-blasted panels have significantly lower values than the grit-blasted panels. The panels prepared by the Ocean City laboratory exhibited the same characteristics.

For all profilometer data except peak count, definite increases in the R_A, R_Y, R_Q and R_Z values are seen for abrasive containing more angular grit. Figure 20 shows the graphs of R_Q versus abrasive mix and applicator, and Figure 21 shows the similar graphs of R_{PC}. Peak count on the panels prepared at CSI, as seen in Figure 21, showed significant overlap between the abrasive mixes used, and no definite distinction between mixes could be made.

Interestingly, the values of R_{PC} are generally higher and the values of R_Q are lower on the panels prepared at Ocean City than are the values of R_{PC} and R_Q on panels prepared by CSI. Average R_{PC} for the coated grit-blasted panels prepared at CSI is 113 peaks/in., and the average peak counts for the panels prepared at Ocean City are 173 and 176 peaks/in. for A36 and Grade 50 steel, respectively. Variables were abrasive equipment, abrasive source, profilometer instrument used, and steel, so which variable(s) are responsible for the differences in R_{PC} and R_Q cannot be ascertained from the existing data. Comparison of the adhesion strength values along with 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 holds true for the grit-blasted aluminum and 70-/30-percent shot/grit and 33-/67-percent shot/grit zinc TSMC panels, but not the grit-blasted zinc or shot-blasted panels. Figure 22 shows the tensile adhesion values versus abrasive mix and applicator for A36 steel.

The importance of peak count on coating performance has been emphasized by several authors (*33–36*). Generally, a higher peak count results in higher adhesion (as found in this study) as long as the coating can wet the prepared surface. The increase in adhesion strength occurs because the peaks and valleys cause the disbondment forces to change from tension to shear. However, if the coating bridges the valleys rather

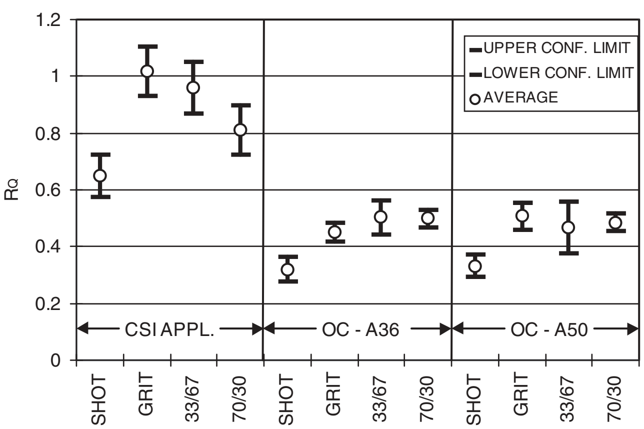


Figure 20. Values of R_Q versus abrasive mix and applicator.

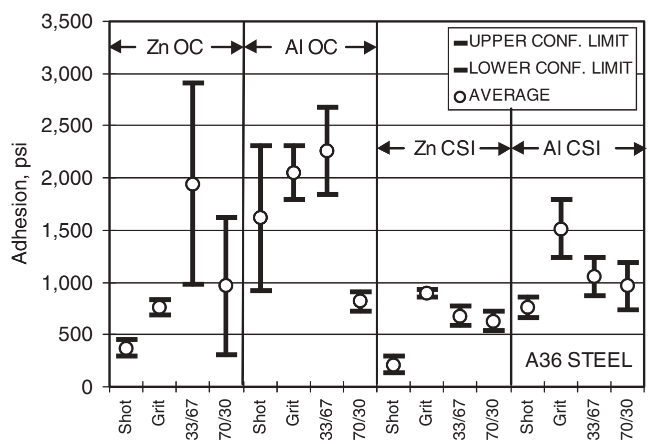


Figure 22. Tensile adhesion for aluminum and zinc TSMCs on A36 steel versus abrasive mix and applicator (1 psi = 6.89 KPa).

than wetting the surface, the adhesion could be worse with a high-peak density than with a low-peak density. Data in the literature show that finer abrasive size (shot or grit) produces higher peak counts (*33*), but optimum peak counts for TSMCs have not been found in the literature. The laboratory data for this study seem to suggest that a peak density of about 175 peaks/in. increases adhesion; however, the data are far from consistent, and the confidence bands in both the R_{PC} data and adhesion data are much larger for the samples prepared in Ocean City. R_{PC} might have value as a field measurement for predicting TSMC adhesion performance. Additional work is required to develop this concept and determine optimum values of R_{PC} for TSMCs.

All thermal spray guides and specifications call for the surface profile to be "angular," but do not define acceptable angularity limits or methods of measuring angularity. Angularity is defined not only by the number of peaks per unit area but also by the rapidity, or sharpness, of how peaks and valleys change shape. Part of this measurement can be obtained through the use of surface profilometers. R_{PC} and R_Q values have shown promise in this study as indicators of good "angularity." Work reported recently by the U.S Army Corps of Engineers indicates that this profilometer data may not be adequate *(37)*. Angularity can be quantified using scanning electron microscopy, but this is hardly a field-friendly method. It might be that the best measure of angularity is indirect—characterizing the abrasive used. A chart that compares the roundness of abrasive grains can be found in a 1994 article by Hansink (*38*). According to the results presented in the U.S. Army Corps of Engineers study mentioned above, very angular, angular, and subangular shapes produced similar adhesion strengths (*37*).

Corrosion Tests Comparing Abrasive Mixes

The aluminum TSMC in cyclic immersion tests appeared to be tolerant of the use of various shot/grit mixture ratios in the constant immersion test. The corrosion and blister ratings were 10 for all abrasive mixtures tested, and no cutback was observed. In the constant immersion tests, the corrosion and blister ratings were 9, and there was no cutback for all the abrasive mixes tested. The aluminum TSMC appears to be insensitive to the abrasive mixture, at least up to 12 months of exposure.

The zinc TSMC in cyclic immersion tests had a corrosion rating of 9 for all abrasive mixes tested. Blistering of the zinc TSMC was observed for all shot/grit mixtures, and visual cutback was observed for all mixtures except the 70-/30-percent shot/grit. The 100-percent shot mixture was the most susceptible to attack, with a composite blister rating of 2 and an average cutback of 1 in. (25.4 cm). The 70-/30-percent shot/grit and 100-percent grit mixtures were the best performers, having composite blister ratings of 4.6 and 5.3, respectively, and average cutback measurements of 0 and 0.25 in. (6.5 mm), respectively.

The zinc TSMC in constant immersion tests had a corrosion rating of 8 for the grit and shot/grit mixtures (no shot abrasive was tested for this coating). The blister ratings were 6.9 for grit, 10 for 70-/30-percent shot/grit, and 3 for 33-/67-percent shot/grit after 12 months. There was no cutback observed for the grit-blasted panel, 0.19 in. (4.8 mm) for the 70-/30-percent shot/grit mixture, and 0.38 in. (9.7 mm) for the 33-/67-percent shot/grit mixture.

These tests show that at 12 months of exposure, the aluminum TSMC is insensitive to the abrasive mixes used in these tests. On the other hand, the zinc TSMC performs better when a 100-percent grit or high-content grit mixture is used.

Effects of Application Parameters on Metallurgical Characteristics and Performance

Metallography

Most TSMC guides and specifications for wire-arc spray call for the distance between the tip of the gun to be within 6 to 8 in. (15 to 20 cm) and the angle of the gun to the work surface to be 90 degrees (optimum) and 45 degrees (maximum). The extremes of distance and deposition angle (45 degrees) are situations that are expected to be encountered when coating difficult-to-reach surfaces such as the inside flange surfaces of H-piles. In order to test whether the extremes of these ranges are detrimental to TSMC performance, tests were conducted to evaluate porosity, oxide content, adhesion, and corrosion performance. Table 13 shows the application parameters tested.

Table 14 shows the results of the metallographic examination. Some studies (*10*, *39*, *40*) imply that greater spray distances and more acute angles of incidence between the metal spray and surface lead to more porosity and oxides in the coating. In our studies, the pore size in the zinc and zinc/aluminum TSMC samples was slightly smaller at the 12-in. (30.5-cm) distance than at the 8-in. (20.3-cm) distance. The pore size for the zinc TSMC was larger at the 45-degree application angle than at the 90-degree application angle. The porosity distribution was a larger percentage of the coating volume at the 8-in. (20.3-cm) distance. The degree of interconnection between pores was also larger at the 8-in. (20.3-cm) distance.

TABLE 13 Test protocol for application parameter study

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

* Commercial purity wire; 1 cm = 2.54 in., 453.5 g = 1 lb.

TABLE 14 Effects of application parameters on TSMC metallurgy

ALLOY	PARAMETER 45/90 degrees 8 in. or 12 in. spacing	POROSITY				OXIDES			PHASES	SUBSTRATE INTERFACE	
		Max size in.	Distribution %	Geometry	Degree of interconnection	%	Max size in.	Geometry		Trapped Grit	Debond
Zinc	45 deg 8 in.	0.004	20	irregular	moderate	ND	N/A	N/A	1	ND	minor
		0.002	20	irregular	moderate	5	0.002	irregular	1	ND	major
	90 deg 8 in.	0.001	5	rounded	minor	ND	N/A	N/A	1	ND	moderate
		0.002	<5	irregular	moderate	<5	0.002	irregular	1	ND	moderate
	45 deg 12 in.	0.001	<5	irregular	minor	ND	N/A	N/A	1	ND	minor
		0.003	6	rounded	minor	<5	0.002	irregular	1	ND	major
	90 deg 12 in.	0.001	<5	rounded	minor	ND	N/A	N/A	1	ND	minor
		0.0003	<5	rounded	minor	ND	N/A	N/A	1	ND	minor
Aluminum	45 deg 8 in.	0.002	7	rounded	minor	ND	N/A	N/A	1	ND	minor
		0.002	5	rounded	moderate	<5	0.007	elongated	1	ND	minor
	90 deg 8 in.	0.001	5	rounded	minor	ND	N/A	N/A	1	ND	minor
		0.001	<5	rounded	minor	30	0.006	irregular	1	ND	minor
	45 deg 12 in.	0.001	<5	rounded	minor	10	0.005	irregular	1	ND	moderate
		0.001	<5	irregular	minor	5	0.002	irregular	1	ND	minor
	90 deg 12 in.	0.001	<5	irregular	minor	30	0.007	irregular	1	ND	moderate
		0.003	7	rounded	minor	ND	N/A	N/A	1	ND	minor
Zn/Al	45 deg 8 in.	0.001	<5	irregular	minor	<5	0.007	irregular	2	ND	moderate
		0.003	5	irregular	moderate	ND	N/A	N/A	2	ND	major
	90 deg 8 in.	0.003	6	irregular	moderate	ND	N/A	N/A	2	ND	moderate
		0.002	<5	rounded	minor	ND	N/A	N/A	2	ND	major
	45 deg 12 in.	0.001	<5	rounded	minor	ND	N/A	N/A	2	ND	major
		0.001	<5	rounded	minor	<5	0.007	elongated	2	ND	minor
	90 deg 12 in.	0.001	<5	rounded	minor	ND	N/A	N/A	2	ND	minor
		0.002	<5	rounded	minor	ND	N/A	N/A	2	ND	minor

NOTE: 1 in. = 2.54 cm, ND = not detected, N/A = not applicable, deg = degrees, Zn/Al = zinc/aluminum.

Adhesion

Figure 23 shows the average tensile adhesion strength values measured for each of the application parameters. The adhesion of aluminum is seen to decrease at the 12-in. (30.5-cm) distance from the value at 8 in. (20.3 cm), but is not affected by the angle (45 or 90 degrees). The adhesion of zinc and zinc/aluminum appear to be unaffected by application angle and gun-to-surface distance within the parameters tested.

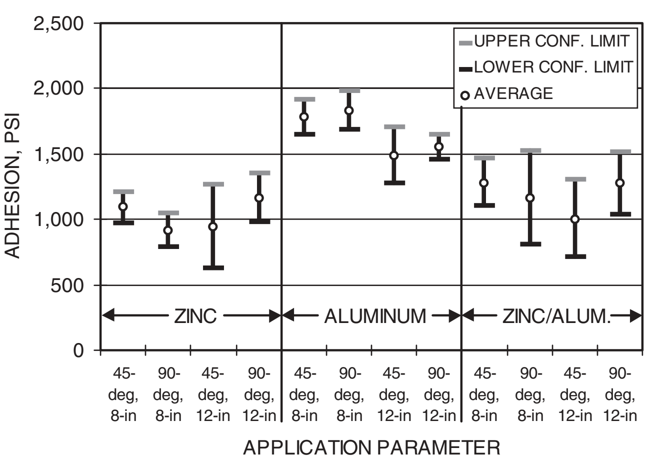


Figure 23. Average adhesion strengths and confidence limits for the application parameters tested (1 psi = 6.89 KPa).

Recent research by the U.S. Army Corps of Engineers concluded that distance affected the variation in porosity and oxide levels of zinc and zinc/aluminum, but none of the parameters affected the variation in oxide and porosity of aluminum (*39*). That report recommended the following optimum angles and distances:

TSMC	Angle (degrees)	Distance
Zinc	90	6 in. (15.2 cm)
Aluminum	90	6–11 in. (15.2–27.9 cm)
Zinc/Aluminum	90	6–10 in. (15.2–25.4 cm)

Corrosion Tests Comparing Application Parameters

The aluminum TSMC in constant immersion displayed a corrosion rating and composite blister rating of 10 for all of the application parameter variables. No cutback was observed on any of the test panels in this test. In the cyclic immersion tests, the aluminum had an overall corrosion rating of 9, a blister rating of 10, and displayed no measurable cutback for all of the application parameters.

The zinc coating in the constant immersion tests displayed corrosion ratings of 9 at 45 degrees, 8 in. (20.3 cm); 8 at

90 degrees, 8 in. (20.3 cm); 7 at 45 degrees, 12 in. (30.5 cm); and 8.5 at 90 degrees, 12 in. (30.5 cm). The composite blister rating was 10 for all application parameters except 45 degrees, 12 in. (30.5 cm), where it was 6.5. The cutback was 0.19 in. (4.8 mm) at both 45 degrees, 8 in. (20.3 cm), and at 90 degrees, 12 in. (30.5 cm), and it was 0.38 in. (9.7 mm) at 45 degrees, 12 in. (30.5 cm). The zinc TSMC in the cyclic immersion tests displayed an overall corrosion rating of 10 for all of the application parameters. The blister rating was 10 for the 90-degree angle at both spacings, but fell to 4.6 at 45 degrees, 8 in. (20.3 cm), and 5.2 at 45 degrees, 12 in. (30.5 cm). No measurable cutback was observed at any of the application parameters.

The zinc/aluminum TSMC in the constant immersion tests had an overall corrosion rating of 10 for all application parameters tested, and no cutback was observed. In the cyclic immersion tests, the zinc/aluminum coating displayed an overall corrosion rating of 10 for all parameters. The composite blister rating was 5.2 at 45 degrees, 8 in. (20.3 cm); 4.6 at 90 degrees, 8 in. (20.3 cm), and 45 degrees, 12 in. (30.5 cm), and 3.9 at 90 degrees, 12 in. (30.5 cm). There was no measurable cutback at any of the application parameters.

The results at 12 months of exposure time suggest that the aluminum and zinc/aluminum TSMCs are insensitive to the application parameters tested, but that the zinc TSMC is sensitive to shallow angles from gun to work surface.

Effect of Carbon Steel Hardness

The effects of small differences in hardness caused by different steel alloys were addressed by measuring the surface profile and adhesion of TSMCs on ASTM A36 and ASTM A572 Grade 50 steel panels abrasive blasted in the same manner. The tensile strength of ASTM A36 steel can range from 58 to 80 ksi (400 to 550 MPa), and the tensile strength of ASTM A572 Grade 50 steel is specified as 65 ksi (450 MPa). Because this means that there can be overlap in the hardness between the two materials, we measured the hardness of the samples and found a Rockwell B (R_B) hardness of 90.8 for the A36 material and 75 for the Grade 50 material. Figure 24 shows the surface profiles of the A36 and Grade 50 steel samples as measured with Testex tape. The profiles appear to be the same for both alloys.

Adhesion

Figure 25 shows the adhesion strength of aluminum and zinc TSMCs on grit-blasted A36 and Grade 50 steel panels. The adhesion of the zinc TSMC was essentially the same on the A36 and Grade 50 panels. There is a considerable variation in the aluminum adhesion strength; however, this wide variation was observed on both aluminum and zinc TSMC panels. No discernable difference was observed in the adhesion of the zinc or aluminum TSMCs on A36 and Grade 50 samples prepared by grit, shot, or the mixtures tested.

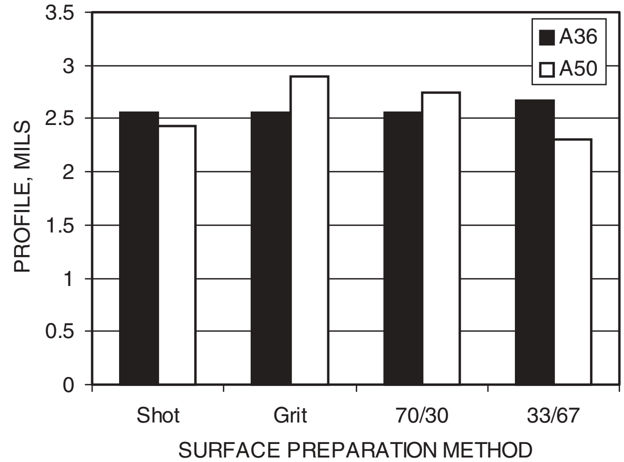


Figure 24. Surface profile of A36 and A50 steel samples using Testex tape (1 mil = 25.4 μm).

Corrosion Tests Comparing Steel Hardness

In the constant immersion tests, the overall corrosion ratings of both alloys were similar, differing by less that 1 unit for all of the abrasive mixes used. The blister ratings were 6.8 for A36 steel, 8.7 for Grade 50 steel over a 100-percent shot/prepared surface, and 10 for both steel alloys on 100-percent grit-prepared surfaces. For a 70-/30-percent shot/grit-prepared surface, the blister ratings were 10 for A36 steel and 8.4 for Grade 50 steel. Cutback was less than 0.05 in. (1.3 mm) for all panels except the Grade 50 on a 100-percent grit surface, where it was 0.11 in. (2.8 mm).

In the cyclic immersion tests, the overall corrosion ratings were within 1 unit for both alloys and abrasive mixes, except the 70-/30-percent shot/grit mixture, where the A36 steel had

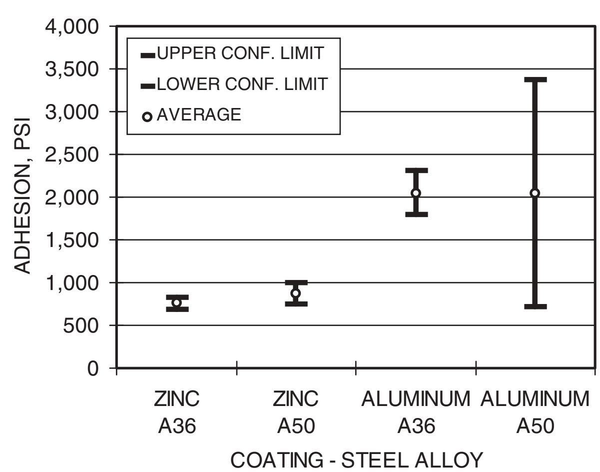


Figure 25. Tensile adhesion of zinc and aluminum TSMCs on A36 and A50 grit-blasted steel panels (1 psi = 6.89 KPa).

a rating of 9.6, and the Grade 50 steel had a rating of 8.3. The composite blister ratings were all within 1 unit for each steel alloy and abrasive mix tested. The shot-prepared panels had the lowest blister ratings, 7.7 (Grade 50) and 7.9 (A36). The other panels had blister ratings between 9 and 10. The cutbacks for the shot-prepared surface were 0.06 in. (1.5 mm) for A36 and 0.36 in. (9.1 mm) for Grade 50. The cutbacks for the grit-prepared surfaces were 0 for A36 and 0.02 in. (0.51 mm) for Grade 50. The cutbacks for the 70-/30-percent shot/grit-prepared surfaces were 0.2 in. (0.51 mm) for A36 and 0.03 in. (0.76 mm) for Grade 50. The cutbacks for the 33-/67-percent shot/grit-prepared surfaces were 0 for A36 and 0.02 in. (0.51 mm) for Grade 50.

The corrosion test data indicate that, with the exception of cutback at defects in cyclic immersion on shot-prepared surfaces, the substrate hardness does not affect the performance of the TSMC.

HSLA Steel versus Carbon Steel

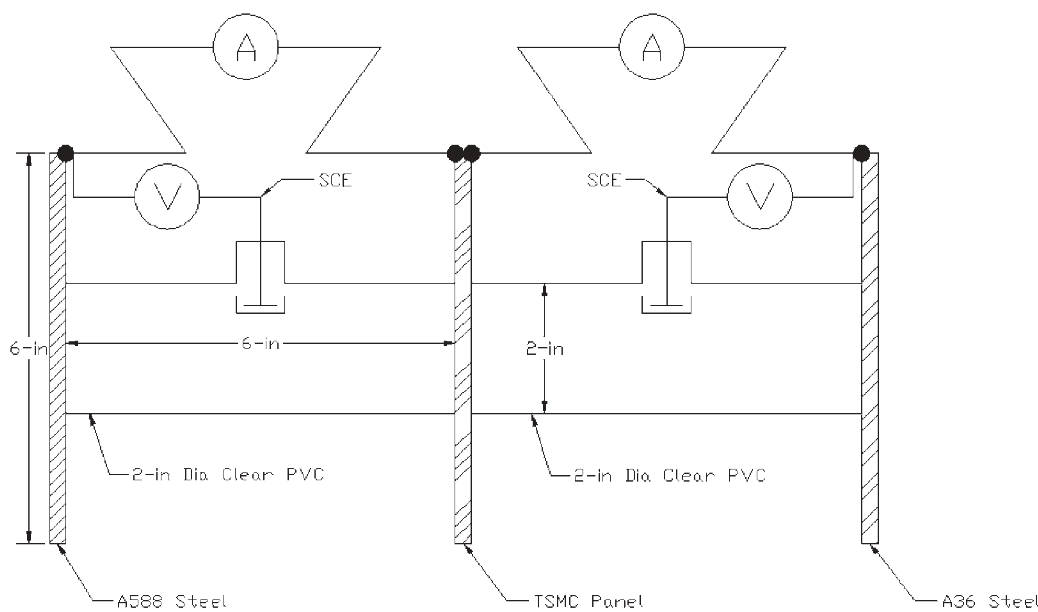
HSLA steels, such as ASTM A588, are designed to have better strength and atmospheric corrosion resistance than conventional carbon steel. The corrosion resistance of HSLA steels is due to small quantities of alloying elements such as chromium, nickel, manganese, copper, and molybdenum in the steel. Weathering steels, a type of HSLA steel, are sometimes used as steel pilings because of their strength and corrosion resistance. The low alloy content of the steel might make it slightly nobler than carbon steel (*41*). This testing was designed to determine what effect, if any, that has on the performance of TSMCs allied to the HSLA steel.

Galvanic Behavior

To determine the overall ability of aluminum and zinc to provide sacrificial protection to Grades A36 and A588 steels, testing was conducted to measure current flow versus time in several aqueous environments. Sacrificial protection is provided by the TSMC to the steel substrate onto which it is applied. Intimate contact between the TSMC and the steel occurs during the application process, providing an electrical pathway for sacrificial protection, but it is impossible to measure the protection current being provided to the substrate. However, by simulating such an exposure using temporary connections between a TSMC sample and a bare steel panel, a measure of the protective current provided by the TSMC was performed.

A panel coated with aluminum TSMC and a panel coated with zinc TSMC, each with equal areas exposed in an electrochemical test apparatus, were used for testing. In tests, the coated panel was coupled to freshly blasted Grade 36 and Grade 588 steel panels through individual wire connections. Provisions were made to periodically monitor current flow between the TSMC panel and bare panels to determine if sacrificial protection was being provided. Visual evaluations were also conducted to verify the mitigation of steel substrate corrosion mitigated and the presence of TSMC corrosion. Figure 26 shows a sketch of this test setup.

By their very nature, aluminum and zinc TSMCs are not uniform and contain voids, pores, and other areas where electrical contact to the substrate and/or surrounding aluminum or zinc particles may be compromised. As such, the electrical current measurements are subject to variation, and time-based activation of the TSMC may occur unlike the behavior of an aluminum or zinc anode connected to a steel structure. However, these measurements can be indicative of the presence



NOTE: A = ammeter, V = voltmeter, SCE = saturated calomel electrode.

Figure 26. Electrochemical sacrificial protection test cell (1 in. = 2.54 cm).

and relative level of sacrificial protection being provided. Figures 27 through 30 show plots of current versus time for aluminum and zinc TSMCs to A36 and A588 steel, using electrolytes of 25, 500, 1,000, and 5,000 ohm-cm.

Sacrificial current flow monitoring has demonstrated that after 2 to 5 days in tests, a measurable sacrificial current is generated by both TSMC materials to protect the A36 and A588 bare steel panels. Current flow to these samples is marginally reduced for A588 steel compared with A36 steel, suggesting that this more corrosion-resistant alloy requires less sacrificial protection.

Current flow is also shown to be inversely proportional to solution resistivity (i.e., low resistivity = higher current flow). This is as expected, because a higher resistivity electrolyte is typically considered less corrosive (without the presence of other factors).

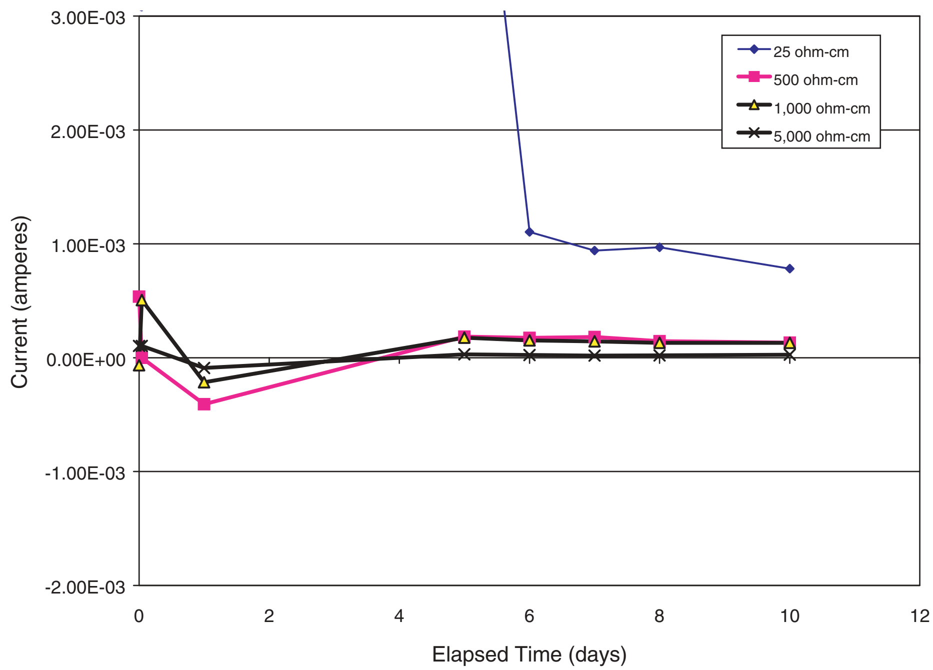


Figure 27. Galvanic current, zinc TSMC versus A36 steel.

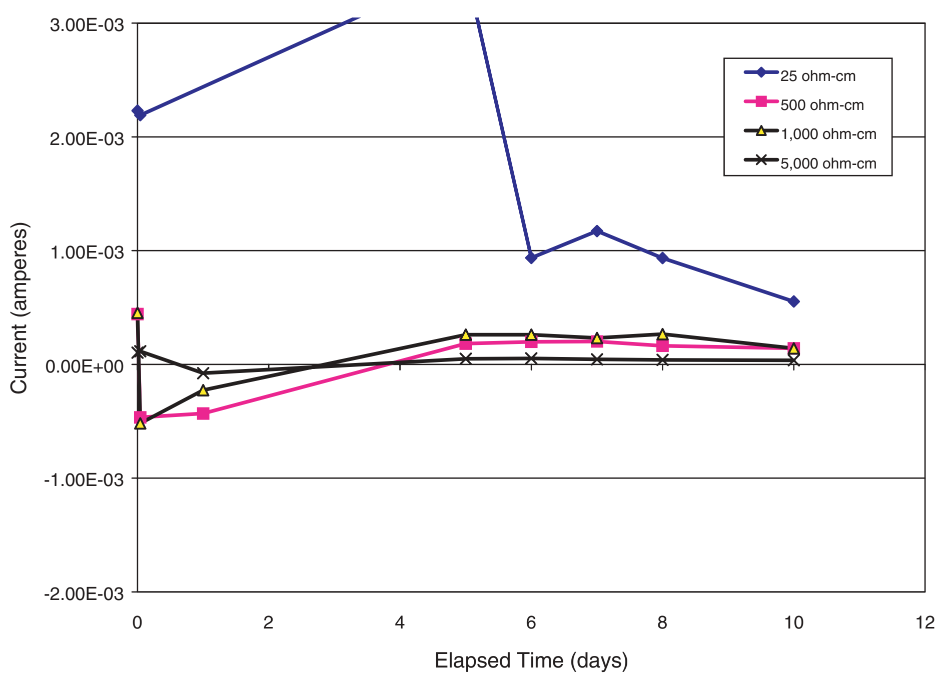


Figure 28. Galvanic current, zinc TSMC versus A588 steel.

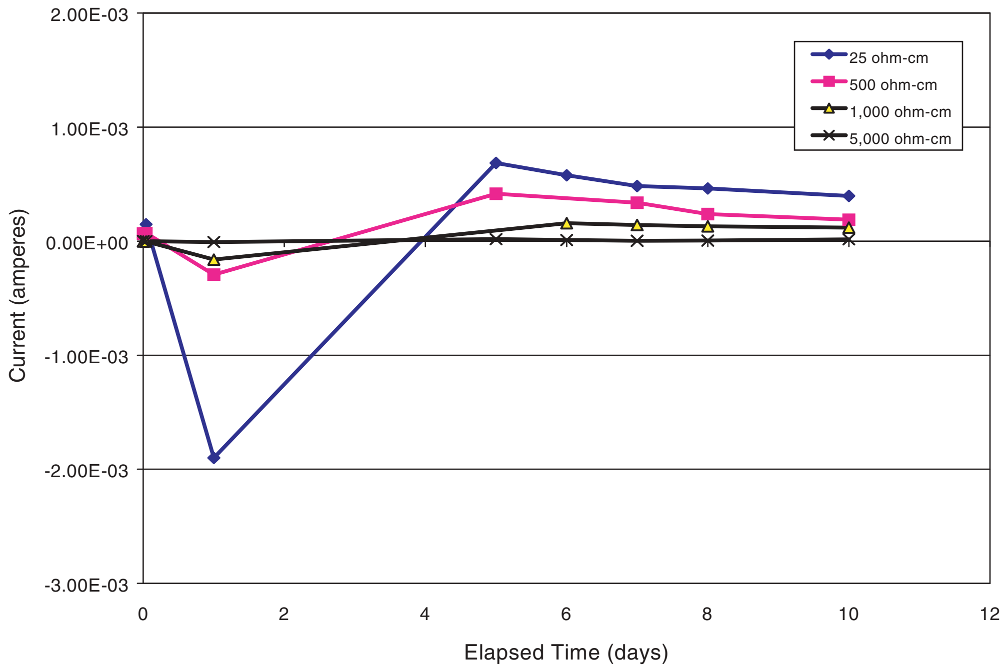


Figure 29. Galvanic current, aluminum TSMC versus A36 steel.

In addition to electrical measurements, periodic visual evaluations were made without disrupting exposure. After approximately 1 week of exposure, samples in seawater and lower-conductivity electrolytes began to show calcareous deposits on the bare steel surfaces. Calcareous deposits are a by-product of cathodic protection. The formation of calcareous deposits occurs at the cathode of a protected substrate (by either sacrificial or impressed current cathodic protection). The formation of these deposits suggests that some degree of cathodic protection is being provided.

Long-Term Marine Atmospheric Exposure Analysis

In a past Federal Highway Administration project ("Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges," Contract DTFH61-92-C-00091), Corrpro evaluated TSMC for corrosion protection of steel at its Sea Isle City, New Jersey, marine atmospheric exposure facilities. Although this project is completed, the panels have been continued in testing. The site

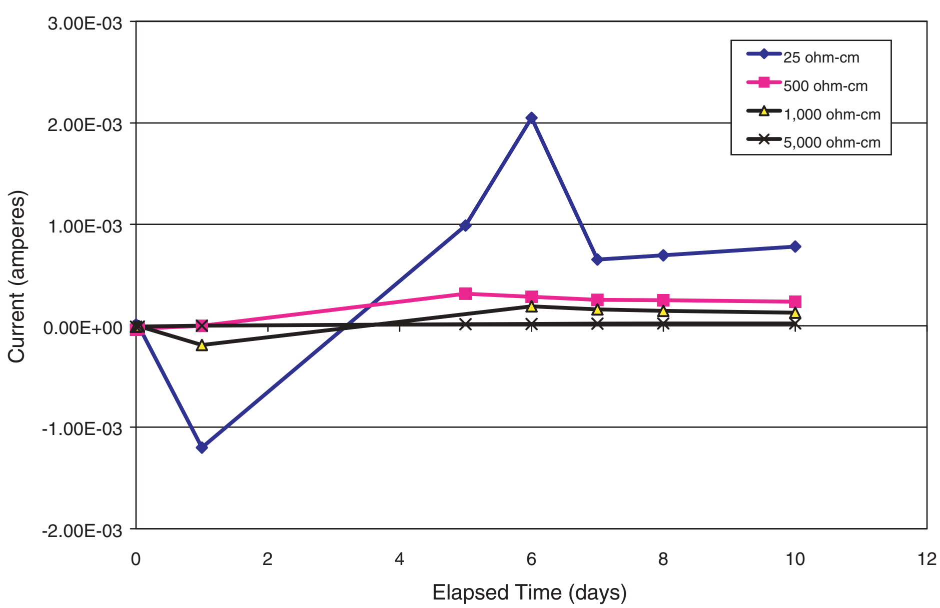


Figure 30. Galvanic current, aluminum TSMC versus A588 steel.

is located approximately 100 yards from the Atlantic Ocean to the east and bordered by Ludlum's Bay to the west. In 1989, several panels of A36 and A588 steel with aluminum, zinc, and zinc/aluminum (85 : 15 wt%) thermally sprayed coatings were exposed at this test site. The panels were prepared by grit blasting with G16 steel grit to an SSPC-SP-10 finish and 4-mil (102-µm) profile. The TSMCs were applied by the flame spray wire technique. A vinyl chloride/vinylidene chloride copolymer was used to seal half the panels. These samples have been exposed to a harsh, natural marine environment for a period of 13 years. Evaluation of these samples is beneficial in determining the long-term atmospheric performance of a TSMC over low-alloy and weathering steel.

The general condition of the TSMC samples did show minimal signs of deterioration. Panels coated with organic coatings (epoxy powder, electrostatic spray polyester, electrostatic spray epoxy powder with polyurethane, and acrylic topcoats), and also exposed for 13 years, showed severe deterioration. Figure 31 shows a photo of all TSMC and liquid-coating systems exposed as part of this previous program.

Thickness measurements were taken on each of the zinc, aluminum, and zinc/aluminum panels. Some corrosion of the TSMC had occurred and was evidenced by the white corrosion products on the panel surface. A slight thickening of the coating was measured, which is due to corrosion products. However, with the exception of the aluminum TSMC samples, no substrate corrosion was observed on these samples. Some substrate corrosion (red rust) occurred on two aluminum TSMC A36 panels (without sealer) at a scribe and at the edges of the welded channels indicating possible inadequate galvanic protection ability at exposed substrate defects. Localized corrosion (red rust) was also found on the back of two aluminum TSMC A588 panels (without sealer), which is due to a crevice between the panel and wood support. The sealers appeared to be eroded on the aluminum panels, but they are generally intact on the zinc and zinc/aluminum panels.

The conclusion to these tests is that the TSMCs perform similarly on both carbon steel and HSLA steel substrates.

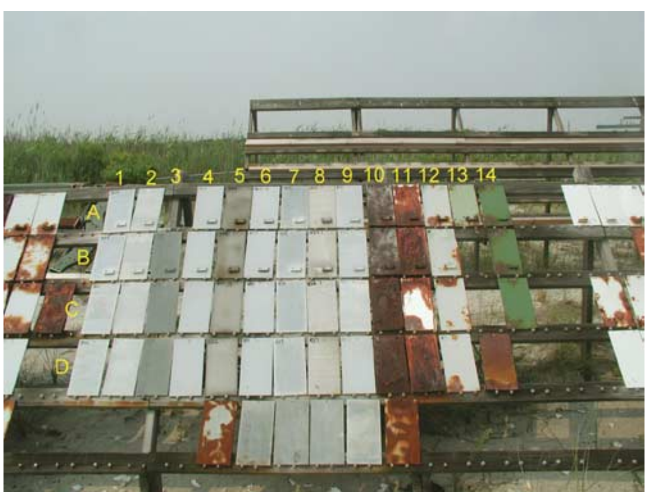


Figure 31. TSMC and paint systems, 13 years marine atmospheric exposure. (Panels shown in Columns 1, 3, and 5 are not sealed. Panels in Columns 1 and 2 have a zinc TSMC. Panels in Columns 3 and 4 have a zinc/aluminum TSMC, and panels in Columns 5 and 6 have an aluminum TSMC. Panels in Columns 2, 4, and 6 are sealed. Panels in Columns 7, 8, and 9 are powder-spray coated. Panels in Columns 10 to 14 are coated with organic materials. Panels in Rows A and B have a Grade 36 steel substrate. Panels in Rows C and D have a Grade A588 substrate.)

Edge Geometry Effects

Sheared, saw-cut, and flame-cut edges are common occurrences in sheet piles. Edge retention analysis was performed on cut sections of the complex panels prepared for corrosion testing (see Figure 5). Prior to the TSMC application, the edges of these samples were altered using a bench-top shop grinder. Some edges were chamfered (approximately 45 degrees), some were rounded (approximately semicircular), and some were made flat (approximately 90 degrees from panel face).

The chamfered and rounded edges simulate the "relief on an edge" used to promote coating adhesion and coverage. The flat edge provides a "sharp" edge, which has historically shown worse performance. These different edges were used to determine if the TSMCs are susceptible to edge retention issues, like liquid systems, and if sharp edges reduce corrosion protection.

Edge retention/characterization was performed by microscopic analysis. Sections of untested panels were cut, exposing the cross section of one of the four edges. This section was then mounted in an epoxy resin and polished using successively finer abrasives to evaluate TSMC thickness and microstructure. Visual metallography was used to examine these samples and compare them with flat sections of the same panel, with the following observations.

Aluminum TSMC

The use of a relieved edge (i.e., rounded or chamfered) appeared to promote adhesion of the TSMC as evidenced by more uniform coverage. Figure 32 shows aluminum TSMC applied to a chamfered edge. The aluminum TSMC adheres well along the chamfer and provides complete coverage. However, at the end of the chamfer (performed on approximately $^{1}/_{2}$ the width of the edge) no TSMC is present.

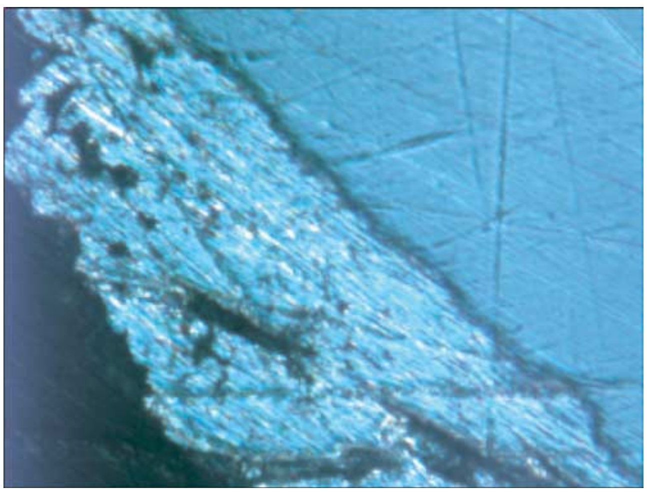
Figure 33 shows similar results for aluminum TSMC applied to a rounded edge, although to a lesser degree. The semi-circular treatment here covers most of the edge width and the TSMC appears to adhere more readily to this surface. The exception is where the edge and face of the panel meet, where a reduction in thickness is observed. Figure 34 shows the ground flat edge for the aluminum TSMC panels. This figure shows that at sharp corners there is notable thinning of the aluminum TSMC. The TSMC was also observed to have thin spots and voids along the flat edge.

Zinc TSMC

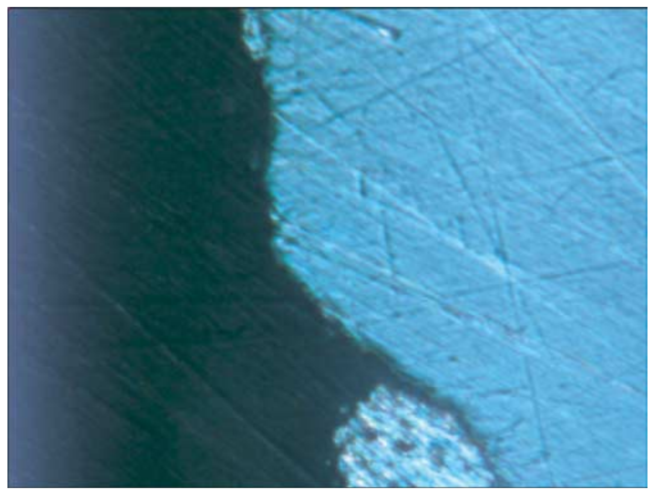
On a relieved (chamfered) edge, the zinc TSMC was observed to have a consistent thickness (see Figure 35). However, at the end of the chamfer a notable thinning was observed. The end of the chamfer can create a sharp corner, as this is where the relieved and flat edges meet. The observed reduction in the zinc TSMC is consistent with the observations on the chamfered edge of the aluminum TSMC.

Figure 36 shows the rounded edge for the zinc TSMC panels. This figure shows that the zinc TSMC has no visible thinning or voids when applied on this type of edge. This was also the best edge (with respect to TSMC integrity and retention) for aluminum.

Figure 37 shows the flat edge for the zinc TSMC panels. This figure shows that although the zinc TSMC could be applied consistently, there was a gap between the substrate and the thermally sprayed coating. The clean edge with which this coating disbonded, combined with the lack of visible

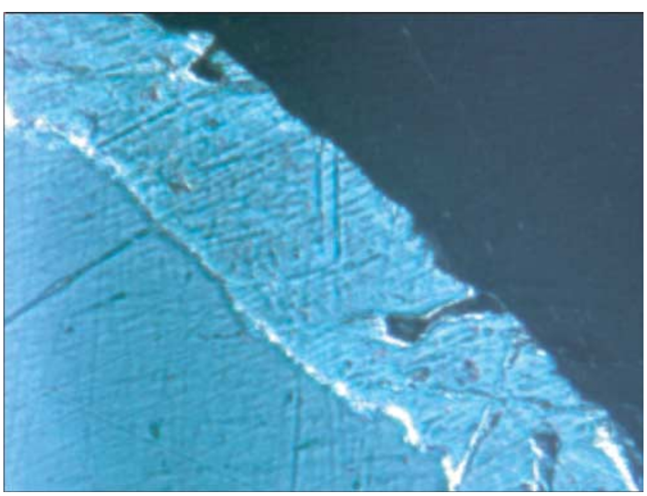


Aluminum on Chamfer

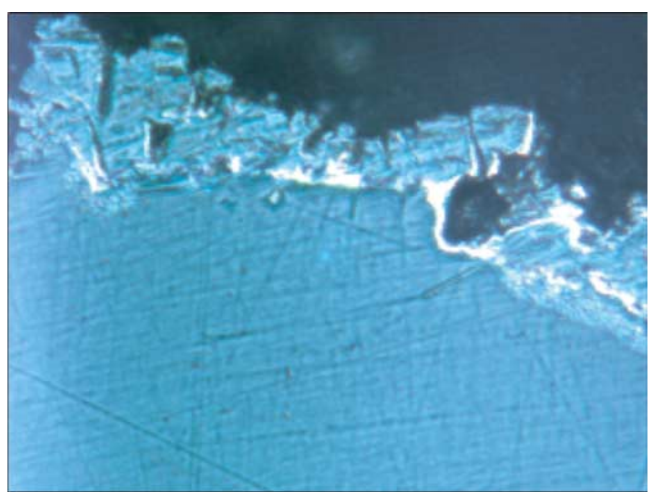


No Aluminum at End of Chamfer

Figure 32. Aluminum TSMC photomicrographs, chamfered edge.

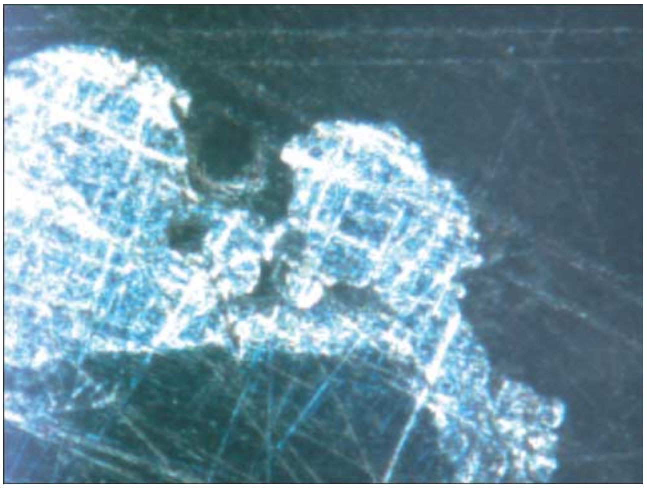


Aluminum on Rounded

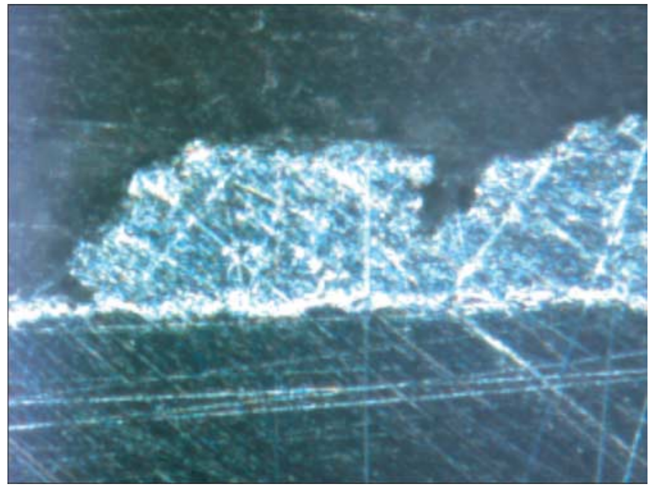


Thin/Porous Aluminum at End

Figure 33. Aluminum TSMC photomicrographs, rounded edge.

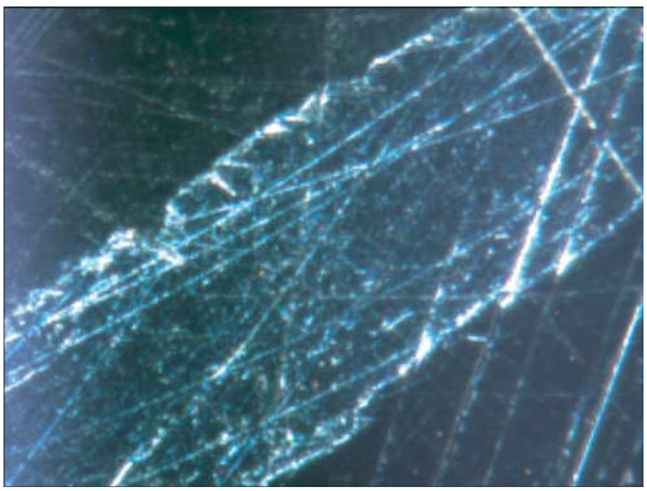


Thinning Aluminum at Sharp Corner

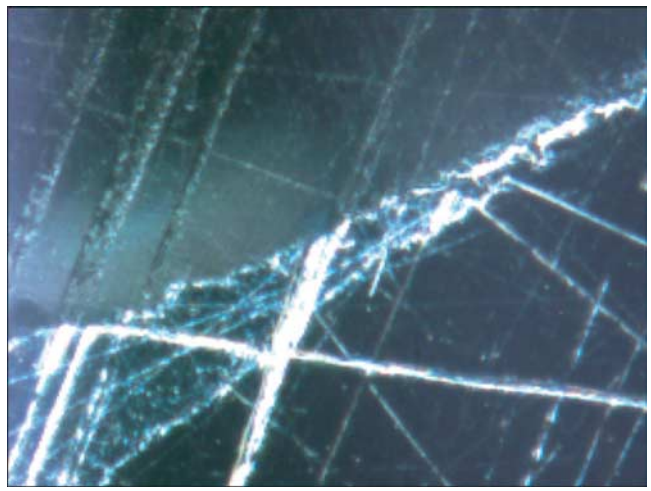


Incomplete Coverage of Flat Edge

Figure 34. Aluminum TSMC photomicrographs, flat edge.

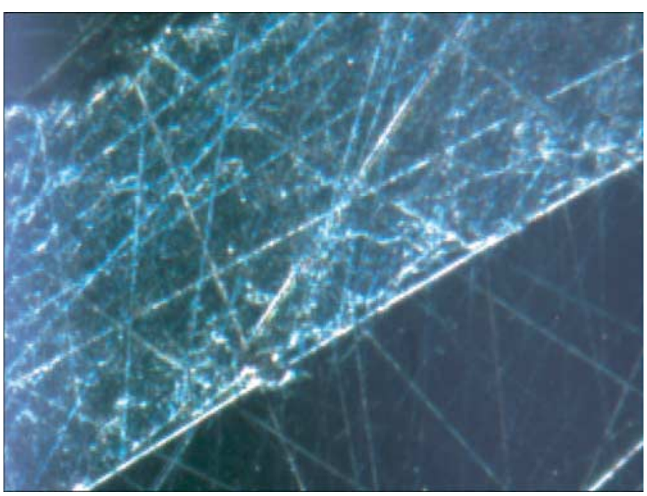


Zinc on Chamfer

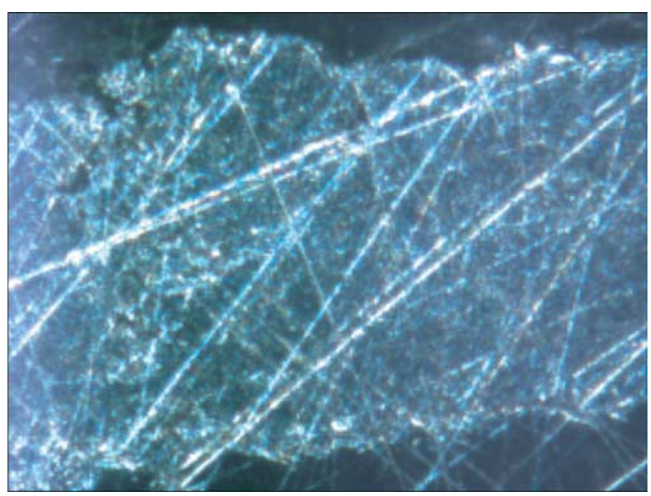


Thinning Zinc and End of Chamfer

Figure 35. Zinc TSMC photomicrographs, chamfered edge.



Zinc on Rounded Edge



Zinc at Apex of Rounded Edge

Figure 36. Zinc TSMC photomicrographs, rounded edge.

contamination at the interface, suggests that the zinc TSMC has poor adhesion over this type of edge. This disbondment probably occurred during application.

On the basis of the conditions observed for both TSMC materials, the optimum edge for coating application would be achieved by rounding. A chamfered edge can help improve coating retention, but the edges can still be affected by thinning and/or lack of coating adhesion as observed above.

Corrosion Tests Comparing Edge Geometry

No differences in corrosion performance caused by edge geometry were observed after 12 months of testing.

Coating Defects

Several samples (with and without chloride contamination) received a 3.8-cm- (1.5-in.-) diameter intentional holiday prior to testing. These were used to test the "throwing power" of the TSMC materials. Following 6 months of constant immersion exposure, minimal deterioration of these TSMC materials has been observed. Some corrosion of the holiday area has occurred on most samples, suggesting that such large defects are not fully protected by the exposed TSMC surface area.

Similar to the constant immersion samples above, minimal deterioration of the TSMC on the cyclic immersion samples has been observed. Some corrosion of the holiday area has occurred on most samples, suggesting that such large defects are not fully protected by the exposed TSMC surface area under conditions of cyclic immersion and drying.

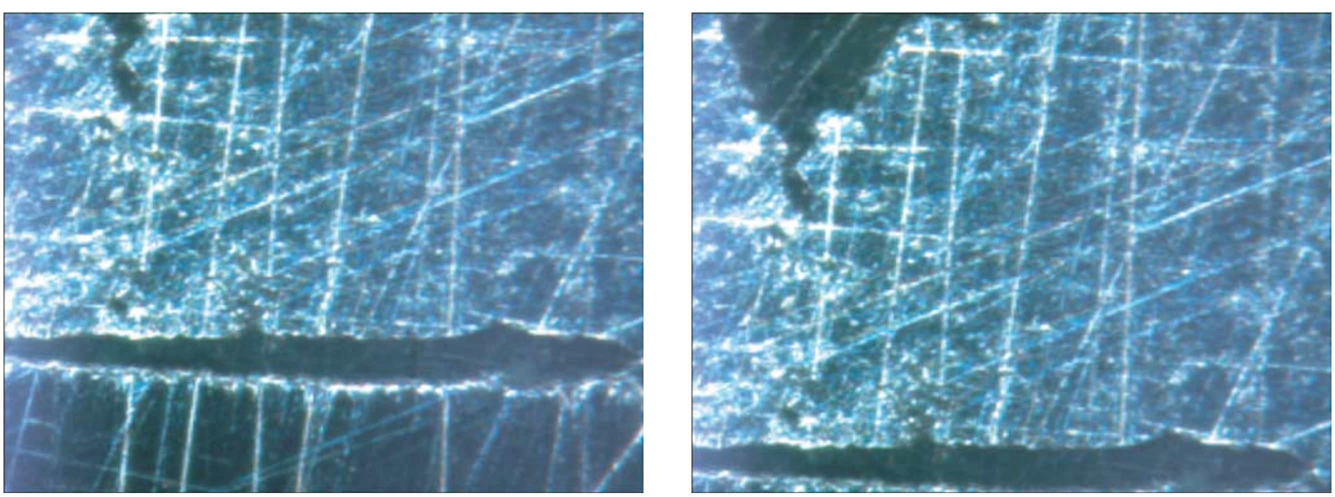
Surface Contamination

Surface contamination can decrease the performance of a coating system, liquid, or TSMC. However, some coatings are more tolerant of contamination, and their performance is not as significantly reduced. The U.S. Navy recommends a chloride contamination limit of 3 $\mu g/cm^2$, and both higher and lower limits are found elsewhere for immersion service (*42*). The U.S. Army Corps of Engineers guide for thermal spray coating recommends a level of chloride contamination less than 7 $\mu g/cm^2$. Experience suggests that performance degradation generally begins at chloride levels above 5 $\mu g/cm^2$ and significantly affects coating performance at 10 $\mu g/cm^2$.

Some panels were purposefully contaminated using a sodium chloride solution to achieve chloride levels of 5 and 10 $\mu g/cm^2$ to determine if the aluminum and zinc TSMCs are significantly affected. To contaminate the surface of the test samples, A36 steel panels that had been abrasive blasted using 100-percent steel grit were immersed in a sodium chloride solution made using deionized water. To verify the contamination level, chloride measurements were made using 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 exposed to the steel substrate and massaged to dissolve the available chloride ions into solution. The extraction fluid is then removed, and a titration is performed to determine the presence of chloride ions. The 5-$\mu g/cm^2$ panels had actual chloride levels of 5 to 7 $\mu g/cm^2$ and the 10-$\mu g/cm^2$ panels had actual chloride levels of 9 to 11 $\mu g/cm^2$.

Adhesion

Figure 38 shows the results of the tensile adhesion tests on the contaminated panels compared with the measure-



Zinc on Flat Edge, TSMC and Substrate *Zinc on Edge, TSMC Only*

Figure 37. Zinc TSMC photomicrographs, flat edge.

ments on uncontaminated panels. The data indicate that the adhesion of the zinc TSMC is insensitive to chloride contamination at the levels tested. On the other hand, the aluminum TSMC shows a definite decrease in adhesion values at both levels of contamination tested.

Corrosion Tests Comparing Surface Contamination

The zinc TSMC in constant immersion tests exhibited a lower corrosion rating at the 10-μg/cm^2 chloride level than at the 5-μg/cm^2 level. The ratings at 5-μg/cm^2 of chloride were 9.6 with a holiday and 9.2 without a holiday. The ratings at 10 μg/cm^2 were 8 without a holiday and 7.7 with a holiday. The composite blister ratings were actually higher for the higher level of contamination: the values at 5 μg/cm^2 were 6.9 with a holiday and 5.1 without a holiday. At 10 μg/cm^2, the ratings were 8.7 with a holiday and 8.4 without a holiday. The corrosion ratings were independent of contamination levels, having a value of 10 across the board. In cyclic immersion tests, the zinc TSMC had a corrosion rating of 10 across the board. The composite blister ratings were 7.2 at 5 μg/cm^2 with a holiday, 5.2 at 5 μg/cm^2 without a holiday, 4.8 at 10 μg/cm^2 with a holiday, and 4.5 at 10 μg/cm^2 without a holiday. No significant cutback was observed under any condition in this particular test.

The aluminum TSMC in constant immersion tests did not exhibit a trend in the corrosion ratings with contamination level. The ratings at the 5-μg/cm^2 level were 8.2 with a holiday and 7.3 without a holiday. The ratings at 10 μg/cm^2 were 8 with a holiday and 6.7 without a holiday. The composite blister ratings were independent of contamination levels, having a value of 10 across the board. Negligible cutback was observed on all panels. In cyclic immersion tests, the aluminum TSMC had corrosion ratings of 9.3 at 5 μg/cm^2 with a holiday, 7.7 at 5 μg/cm^2 without a holiday, and 9 at 10 μg/cm^2 with or without a holiday. The composite blister ratings for aluminum TSMC were 10 at 5 μg/cm^2 with a holiday, 8.7 at 5 μg/cm^2 without a holiday, 8.6 at 10 μg/cm^2 with a holiday, and 10 at 10 μg/cm^2 without a holiday. No significant cutback was observed under any condition in this particular test.

In general, the zinc TSMC appeared to perform better than the aluminum coating with regard to overall corrosion rating, but worse than the aluminum with respect to blister rating. The performance of the TSMC materials in constant immersion varied depending on the metric being evaluated. The presence of holidays in the coating did not appear to affect performance, with holiday samples often having improved performance compared with the scribed samples. Negligible cutback was observed for all test samples. Overall, the aluminum TSMC appears to be more tolerant of surface contamination. In general, application of a TSMC over a contaminated substrate should be avoided. Figures 39 and 40 show typical panels (5 μg/cm^2 chloride) with circular holidays and scribes after 6 months of exposure to cyclic seawater immersion.

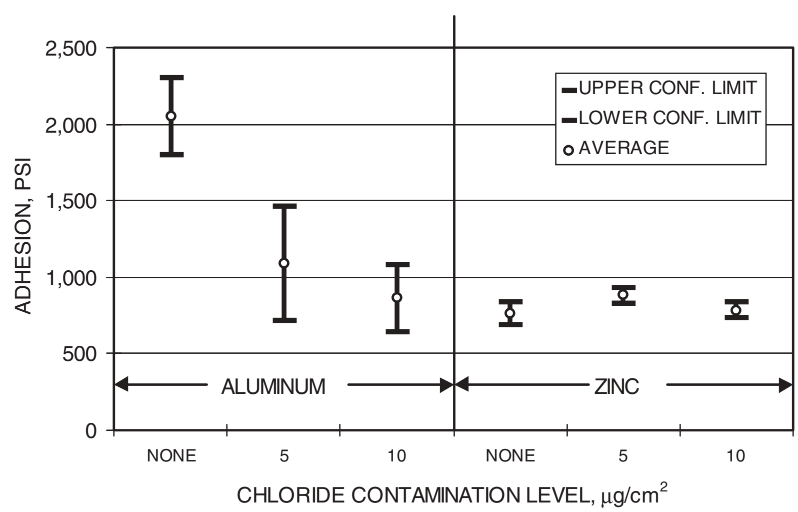


Figure 38. Average tensile adhesion and confidence limits for zinc and aluminum TSMCs on chloride-contaminated substrates (1 psi = 6.89 KPa).

Figure 39. Cyclic (alternate) immersion panels with circular holidays after 6 months in test (zinc TSMC on left and aluminum TSMC on right).

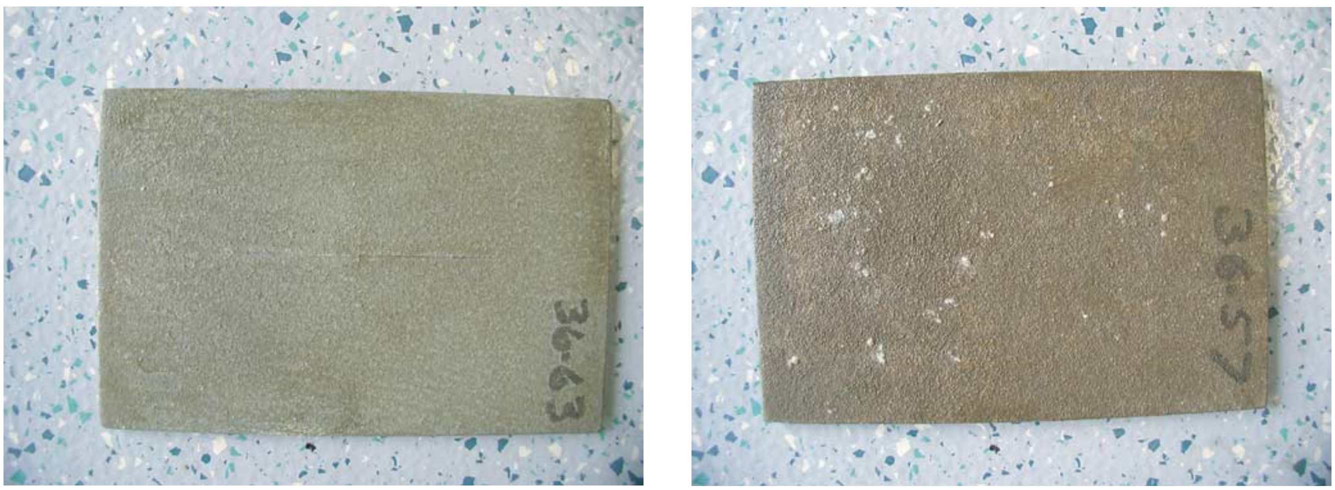


Figure 40. Cyclic (alternate) immersion panels with scribes after 6 months test (zinc TSMC on left and aluminum TSMC on right).

CHAPTER 3

INTERPRETATION, APPRAISAL, APPLICATION

The research study provided several important facts concerning surface preparation and application of TSMCs. Many of these confirmed existing guidelines, but others suggested future research that might lead to improvements in TSMC performance.

INTERPRETATION AND APPRAISAL

Surface Preparation

The use of 100-percent grit provides better adhesion than does 100-percent shot. Using a 100-percent grit abrasive also provides better adhesion than either of the shot/grit mixtures tested in this study. Shot/grit mixtures did provide better adhesion than 100-percent shot and might provide adequate corrosion performance. Shot/grit mixtures are sometimes used to improve equipment life because the shot is not as aggressive toward the blasting equipment. However, these findings show that, in order to improve coating adhesion, shot or shot/grit mixtures can be used for initial cleaning, and 100-percent grit should be used for final surface preparation.

The test results also show that not all 100-percent grit-prepared surfaces are the same and that improvements in coating adhesion can be achieved with improved angularity in the surface profile. This can be achieved through the use of fine angular grit. Measuring angularity can be performed in the field using a profilometer; however, interpretation of the data can be a problem. This study found correlation between profilometer measurements using a field-friendly instrument of R_{PC} (peak count) and R_Q (root mean square deviation) and adhesion; however, other research in the literature has not. Research is suggested to study the role of grit size and shape on surface profile and coating performance. Better definition of the values of R_{PC} and R_Q should be researched. Meanwhile, an indirect method of ensuring an angular profile is suggested using grit classified as very angular, angular, and subangular with respect to an American Geological Society grading system.

Zinc TSMC should be considered for areas where salt contamination is present because of its relative insensitivity to salts. Where aluminum must be used, the surface preparation should include provisions for thorough washing of the surface to remove chlorides.

Application

The study found no differences among surface profile, adhesion, and performance of coatings applied over steel grades with differing hardness. Areas with extreme differences in hardness, such as flame-cut edges, however, still require special attention in order to achieve satisfactory coating performance. The study also found no differences in the performance of TSMCs when they were applied to carbon steel and HSLA steel.

Even if surface preparation and coating application have been done properly, TSMC deterioration can occur at sharp edges and defects. The study confirmed that removing the sharpness of edges by slight curvature or grinding provides better coating coverage and adhesion. Although TSMCs are capable of protecting the substrate at narrow defects because of their ability to provide cathodic protection to the steel, larger defects present a problem. Coating defects larger than relatively narrow scratches should be repaired.

LONG-TERM IMPLEMENTATION PLAN

The ultimate goal of this program is to have a guide to TSMCs adopted by AASHTO. The keys to effective implementation are (1) identification of the user community, (2) reports demonstrating and advocating the technical and cost benefits of this work, and (3) effective report and data distribution.

The probable user community for the project is large. At a minimum, it extends to architects/engineers involved in bridge design, ferry terminal design, and DOT, FHWA, and transportation-authority engineers at headquarters, regional, or divisional levels. The user community also includes industry consultants and equipment manufacturers.

The biggest impediment to implementation will be the higher cost of the TSMC materials in comparison with more traditional coatings. People will, at first, only see the increased material and application cost. The user community has to understand that the cost benefits of TSMC materials outweigh the increased initial costs. They also need to understand that the cost of the coating materials and application are not as significant as costs such as mobilization, containment, waste removal, and temporary removal of the structure from service for any repair work. Studies have shown that TSMCs do not have to be replaced as often as liquid-applied coating. This can make them more economical to use. This research includes

- Research conducted by the U.S. Army Corps of Engineers;
- Research conducted by Rosbrook et al., Bhursari and Mitchener, Bland, Kain and Young, Kuroda and Takemoto, Tsourous, Kogler et al., and the Platt Brothers and Company (*11, 14, 43–48*);
- The observations of the coatings at the North Carolina DOT test facility at Ocracoke Island, North Carolina, reported in this study (discussed in Chapter 2); and
- The test panels in continuous exposure at Corrpro's Sea Isle City, New Jersey, test facility, reported on in this study (discussed in Chapter 2).

It is recommended that the guide to TSMCs and associated articles on the benefits of TSMCs be presented in periodicals such as *Roads and Bridges, Journal of Protective Coatings and Linings, Materials Performance,* and at the TRB annual conference. It is further recommended that the Tri-Society (AWS/NACE/SSPC) Thermal Spray Committee on Corrosion Protection of Steel be addressed to assist in the dissemination of the guide.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The results of the laboratory testing indicate the conclusions listed below.

1. The Effect of Sealers

1.1. The use of sealers has no detrimental effect on TSMCs and might actually improve the adhesion properties as measured by the tensile adhesion, U-bend, and impact tests.

1.2. Sealers appear to improve the performance of zinc TSMC, but do not appear to improve the performance of aluminum TSMC in the corrosion tests to date.

1.3. Based on the falling weight impact tests, the use of a sealer improves the impact resistance of the TSMC.

2. The Effect of Abrasive Mixes

2.1. Based on tensile adhesion and disbondment tests, 100-percent grit abrasive results in significantly better adhesion than does 100-percent shot. Also, 100-percent grit provides better adhesion than do either of the two shot/grit mixtures tested in this study; however, the shot/grit ratios used might provide acceptable performance based on the corrosion tests completed to date. At this point, the TSMC Guide should specify the use of 100-percent grit as the optimum surface preparation finish.

2.2. The zinc TSMC showed better corrosion performance with 100-percent grit and the 70-/30-percent shot/grit mixture than with 100-percent shot or the 33-/67-percent shot/grit mixture.

2.3. The aluminum TSMC appeared to be insensitive to the abrasive mixes tested in this study based on the 12-month corrosion tests.

3. Angularity Measurements

3.1. A simple field-friendly measurement technique for angularity was found in this study. Measurements using a surface profile gauge that measures R_{PC} and R_Q showed that high values of R_{PC} and low values of R_Q provided higher tensile adhesion than low R_{PC} and high R_Q values. Further work is recommended to determine the optimum values of R_{PC} and R_Q.

3.2. Until the critical values of R_{PC} and R_Q can be defined, angularity should be defined by a surface comparator chart such as the chart showing abrasive grit shapes that was published in the *Journal of Protective Coatings and Linings* in 1994 (*38*). Acceptable grit shapes, as determined under 25-power magnification and the standard chart, should be "very angular," "angular," and "subangular."

4. Application Parameters

4.1. Increased gun-to-surface distance decreases the adhesion of aluminum, but does not affect the adhesion of the zinc or zinc/aluminum coatings. The angle of the gun to the work surface did not affect the adhesion of any of the TSMCs tested at the angles used in this study.

4.2. The corrosion tests indicate that aluminum TSMC is insensitive to the application parameters tested in this study.

4.3. The corrosion tests indicate that the zinc TSMC is sensitive to the gun-to-workpiece angle, showing lower performance at an angle of 45 degrees.

5. Steel Hardness

5.1. Similar surface profiles (as measured by depth) and adhesion values for aluminum and zinc TSMCs were observed on the A36 and Grade 50 steel panels.

5.2. Both zinc and aluminum thermally sprayed coatings applied to the A36 and Grade 50 steels are performing similarly to date.

6. Carbon Steel and HSLA Steel

Aluminum, zinc, and zinc/aluminum thermally sprayed coatings applied over carbon steel and HSLA steel showed no differences in performance in previously conducted studies and in galvanic studies conducted in this research.

7. Edge Geometry

7.1. A smoother edge promotes more uniform coating coverage at the edge.
7.2. No differences in corrosion performance caused by edge geometry have been observed to date.

8. Defects

Small narrow defects in the TSMC where the substrate has been exposed are protected by the galvanic behavior of the TSMC. However, the TSMC cannot provide complete cathodic protection to larger holidays.

9. Chloride Contamination

9.1. Aluminum TSMC is sensitive to chloride contamination on the metal surface, showing loss of adhesion at even the lowest level of contamination used (5 µg/cm^2). On the basis of the adhesion results, zinc TSMC was insensitive to chloride contamination up to the 10 µg/cm^2 used in this study.
9.2. Aluminum is more tolerant to chloride contamination than zinc TSMC in corrosion tests, showing better overall corrosion performance, but it has more tendency to blister.
9.3. The presence of defects has not affected the performance of the coatings on contaminated panels to date.

SUGGESTED RESEARCH

1. Initiate a study to examine the effects of grit angularity on R_{PC}, R_Q, adhesion, and performance of TSMCs; to define acceptable limits of angularity; and to establish a standard for angularity.
2. Continue to monitor the test panels currently in immersion and cyclic immersion testing at Corrpro's Ocean City facility. The testing should be continued until a clear difference is observed between the panels prepared by different processes, or for at least 5 years. A report should be prepared at the end of that period, and changes should be made to the guide to TSMCs as appropriate.

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APPENDIX A

LIST AND DESCRIPTION OF EXISTING TSMC SPECIFICATIONS

Testing Specifications for Metallizing Steel Structures

STANDARD	TITLE	SCOPE	DATE	COMMENTS
ASTM C 633	*Standard Test Method for Adhesive or Cohesive Strength of Flame-Sprayed Coatings*	Consists of coating one face of a substrate fixture and bonding this coating to the face of a loading fixture. This assembly of coating and fixtures is subjected to a tensile load normal to the plane of the coating.	Reapproved in 1993	
ASTM D 4417	*Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel*	Discusses techniques to measure the profile of abrasive blast cleaned surfaces in the laboratory, field, or fabricating shop. Three methods are discussed: visual comparison, fine pointed probe, and reverse image	Last revised in 1993	
ASTM D 4541	*Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*	Evaluates adhesion by application of a concentric load and counter load to a single surface.	Last revised in 1995	
ASTM D 4285	*Standard Test Method for Indicating Oil or Water in Compressed Air*	Used to determine the presence of oil or water in compressed air used for abrasive blast cleaning and coating application.	Reapproved in 1993	Other types of contamination may require additional analytical techniques for detection.
ASTM E 1920	*Standard Guide for Metallographic Preparation of Thermal Sprayed Coatings*	This guide provides general recommendations for sectioning, cleaning, mounting, grinding, and polishing to reveal the microstructural features of thermal sprayed coatings and the substrate when examined microscopically.	Last revised in 1997	This standard also references ASTM E 3 *Practice of Preparation of Metallographic Specimens.*
ASTM F 1978-99	*Standard Test Method for Measuring Abrasion Resistance of Metallic Thermal Spray Coatings by Using the Taber™ Abraser*	This test method quantifies the abrasion resistance of thermal spray metallic coatings on flat metallic surfaces. This test uses the Taber™ abraser which causes wear to the coating surface by rolling and rubbing. Wear is quantified as cumulative mass loss.	1999	Developed by ASTM Subcommittee F04.15.
ISO 14918	*Thermal Spraying – Approval Testing of Thermal Sprayers*	This standard provides procedural instructions for approval testing of thermal sprayers. It defines essential requirements, test conditions and acceptance and certification requirements.	October 1, 1998	
ISO 14922-1	*Thermal Spraying – Quality Requirements of Thermally Sprayed Structures*	Four parts discuss the quality requirements for thermal spraying for application by the manufacturers using the thermal spraying process for coating new parts, for repair and for maintenance.	June 15, 1999	
NACE Standard RP0287-95	*Standard Recommended Practice, Field Measurement of Surface Profile of Abrasive Blast Cleaned Steel Surfaces Using a Replica Tape*	Provides a procedure to measure the surface profile of abrasive blast cleaned steel. A tape is utilized to replicate the surface profile.	Originally prepared in 1987 and reaffirmed in 1991 and 1995	Limited to the surface profile defined in the standard (1.5 to 4.5 mils).
SSPC-PA 2	*Measurement of Dry Paint Thickness with Magnetic Gages*	This standard describes the procedures to measure the thickness of a dry film using commercially available magnetic gages. The procedures for calibration and measurements are described for pull-off gages and constant pressure probe gages.	November 1, 1982; editorial changes August 1, 1991	

Materials/Equipment Specifications for Metallizing Steel Structures

STANDARD	TITLE	SCOPE	DATE	COMMENTS
ASTM A 690	*Standard Specification for High-Strength Low-Alloy Steel H-Piles and Sheet Piling for Use in Marine Environments*	This specification covers high-strength low-alloy steel H-piles and sheet piling of structural quality for use in the construction of dock walls, sea walls, bulkheads, excavations and like applications in marine environments.	Last revised in 1994	
ASTM B 833	*Specification for Zinc Wire for Thermal Spraying (Metallizing)*	This specification covers zinc wire used in depositing zinc coatings by oxy-fuel and electric arc thermal spray.	1997	Developed by ASTM Sub-committee B02.04.
MIL-W-6712C	*Military Specification: Wire; Metallizing*	Specifies wire for use in deposition of metallic coatings by flame-spray.	Last amended May 21, 1987	
MIL-M-80141C	*Metallizing Outfits, Powder-Guns and Accessories*		April 30, 1987	Canceled without replacement, November 20, 1998.
MIL-P-83348/1	*Powders, Plasma Spray, Nickel Aluminum Powder Type I, Composition G, Class 2*		October 25, 1984	Canceled without replacement December 27, 1990.
AWS A3.0	*Welding Terms and Definitions Including Terms for Brazing, Soldering, Thermal Spraying and Thermal Cutting*	Provides a glossary of terms used in the welding industry.	May 23, 1994	ANSI approved.

Application and Surface Preparation Specifications for Metallizing Steel Structures

STANDARD	TITLE	SCOPE	DATE	COMMENTS
ANSI/AWS C2.23-XX	*Guide for Corrosion Protection of Steel with Metallic Thermal Spray Coatings of Aluminum, Zinc, Their Alloys and Composites*	Specifies required equipment, application procedures and in-process quality control checkpoints. This paper discusses procedures and equipment for abrasive blasting, coating application and sealer application.	Working Draft #2, February 25, 1999	SSPC/NACE/AWS Tri-Society Thermal Spray Committee for the Corrosion Protection of Steel. Last known C2B Tri-Society meeting was in April, 1999.
BPS 677	*Metallic Coatings — Protection of Iron and Steel Against Corrosion — Metal Spraying of Zinc and Aluminum*		Approved in 1990	This standard is not approved by ANSI or DoD.
ISO 2063	*Metallic Coatings – Protection of Iron and Steel Against Corrosion – Metal Spraying of Zinc, Aluminum and Alloys of these Materials*	This international standard defines the characteristic properties and specifies methods of test of coatings obtained by the spraying of zinc and aluminum and alloys based on these metals for the general purposes of corrosion protection.		
ISO 14920	*Thermal Spraying – Spraying and Fusing of Self-Fluxing Alloys*	This standard covers thermal spraying of self fluxing alloys that are simultaneously or subsequently fused to create a homogeneous diffusion bonded coating.	February 1, 1999	
MIL-STD-2138A(SH)	*Metal Sprayed Coatings for Corrosion Protection Aboard Naval Ships (Metric)*	Specifies requirements for the use of metal sprayed aluminum coatings on naval ships.	Last notice of change August 29, 1994	Due to excessive weight and hazards, zinc was eliminated as a metal sprayed coating material.
SSPC CS 23.00	*Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc and their Alloys and Composites for the Corrosion Protection of Steel*	Covers the requirements for thermal spray metallic coatings on steel substrates.	June 1, 1991	Serves as a guide for preparing specifications for thermal spray applications.
SSPC SP-1	*Solvent Cleaning*	This specification covers the requirements for the solvent cleaning of steel surfaces.	November 1, 1982	
SSPC SP-5/NACE No. 1	*White-Metal Blast Cleaning*	A white metal blast cleaned surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter.	September 15, 1994	
SSPC SP-10/NACE No. 2	*Near-White Blast Cleaning*	A near-white blast cleaned surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter, except for staining. Staining shall be limited to no more than 5% of each unit area of surface.	September 15, 1994	
SSPC Vis 1-89	*Visual Standard for Abrasive Blast Cleaned Steel*	Provides standard reference photographs illustrating four unpainted steel surfaces cleaned to white metal, near-white metal, commercial blast and brush-off blast finishes.		Conforms with ASTM D 2200.

Foreign Standards for Metallizing Steel Structures

STANDARD	TITLE	SCOPE	DATE	COMMENTS
JIS H 8300	*Zinc Spray Coating on Iron or Steel*	This Japanese Industrial Standard specifies zinc spray coating on iron or steel products with the object of prevention of corrosion. The standard discusses quality, testing and inspection.		Japanese Industrial Standard
JIS H 8301	*1971 Aluminum Spray Coating on Iron or Steel*	This Japanese Industrial Standard specifies aluminum spray coating on iron or steel products with the objects of prevention of corrosion and high temperature oxidation. The standard discusses quality, testing and inspection.		Japanese Industrial Standard
EN 22063	*Metallic and Other Inorganic Coatings – Thermal Spraying – Zinc, Aluminum and Their Alloys*	12 pages provide information on thermal spraying of aluminum, zinc and their alloys. The standard discusses surface preparation, coating metal, thermal spraying and sealers. Adhesion test methods are located in an appendix.	1994	Has the status of a British Standard; supersedes BS 2569.
BS 5493	*Protective Coating of Iron and Steel Structures against Corrosion. Handling, Transport, Storage and Erection*	114 pages provide a guide on how to specify a chosen protective system, how to ensure its correct application and how to maintain it. Does not include specific recommendations for ships, vehicles, offshore platforms, specialized chemical equipment, cladding materials, plastic coatings, cement mortar linings or weathering steels.		British Standard
SS-EN 1395	*Thermal Spraying – Acceptance Inspection of Thermal Spraying Equipment*	This European standard specifies requirements for the acceptance inspection of thermal spraying equipment including plasma, arc and flame spraying plants used to produce high-quality sprayed coatings. The purpose of acceptance inspection as part of a quality assurance system for spraying equipment serves to provide proof that the equipment is suitable for producing sprayed coatings of uniform quality in particular to satisfy the requirements of this standard.	March 1996	Swedish Standard
SS-EN 1274	*Thermal Spraying – Powders – Composition – Technical Supply Conditions*	This standard covers powders, which are currently applicable in thermal spraying on the basis of the physical and chemical properties. Properties and property determination of powders for thermal spraying include: • Sampling and sample splitting, • Chemical composition, • Particle size range, • Particle size distribution, • Manufacturing process and particle shape, • Apparent density, • Flow properties, • Microstructure, and • Determination of phases.	June 1996	Swedish Standard

Safety Standards for Metallizing Steel Structures

STANDARD	TITLE	SCOPE	DATE	COMMENTS
SSPC PA-3	*A Guide to Safety in Coating Application*	This guide defines methods and practices which are most practical in maintaining safety during application of protective coatings on steel structures. Complete coverage of all aspects is not presented. The objective of this guide is to itemize basic actions. Section titles include coatings, solvents, airless sprayers, ladders, scaffolding, rigging, personnel protection, respirators, ventilation, and barricades.	November 1, 1982; editorial changes July 1, 1995	
AWS TS1	*Recommended Safe Practices for Thermal Spraying*	AWS *Thermal Spraying: Practice, Theory and Application*. Chapter 11 of this book discusses the potential hazards associated with thermal spraying.	May, 1993	
OSHA 29 CFR 1910	*Occupational Safety and Health Standards*	Part 1910 contains several subparts that discuss safety issues regarding hazardous materials, welding, cutting and brazing, electrical and toxic and hazardous substances, to name a few.		

APPENDIX B

LIST AND DESCRIPTION OF EXISTING TSMC GUIDES

Surface Preparation

STANDARD	BLAST PROFILE	BLAST FINISH	BLAST ABRASIVE
ANSI/AWS C2.23-XX	SSPC SP-5/NACE No.1 (marine and immersion); SSPC SP-10/NACE No. 2 (other)	2.5-mil angular IAW ASTM 4417 (Method B - profile depth gauge or Method C - replica tape or both)	Clean, dry and sharp angular abrasive
Draft #2 ANSI/AWS C2.18-XX SSPC CS 23.00A-XX NACE TPC #XA	SSPC SP-10	2.0- to 4.0-mil anchor tooth profile for TSMC thickness of 12 mils or less; measured with replica tape	Clean, sharp, angular abrasive of suitable mesh size; steel grit, mineral slag or aluminum oxide
EN 22063	Surface is to have a white metallic appearance and uniform texture	According to specifications agreed upon by relevant parties	Hematitic chilled iron grit, aluminum oxide grit or other (grit size of 0.5 to 1.5 mm)
ISO 2063	Surface is to have a white metallic appearance and uniform texture	Surface shall be verified with a reference surface	Hematitic chilled cast iron grit, aluminum oxide grit or other (grit size of 0.5 to 1.5 mm)
JIS H 8300 JIS H 8301	None specified	None specified	None specified
MIL-STD-2138A(SH)	SSPC SP-5	2.0- to 3.0-mil profile IAW ASTM 4417 (Method B or C)	Aluminum oxide (16 to 30 mesh) or angular chilled iron (25 to 40 mesh)
U.S. Army COE Manual EM 1110-2-3401	SSPC SP-5	2.0- to 3.0-mil profile, depending on TSMC material and thickness	Hard, dense, angular blast media such as aluminum oxide, iron oxide and angular steel grit

TSMC Application

STANDARD	HOLDING PERIOD	ENVIRONMENTAL CONDITIONS	COATING THICKNESS	SPRAY PARAMETERS
ANSI/AWS C2.23-XX	Typically within 6 hours of blasting, depending on environmental conditions	5°F above dew point	Ref. AWS C2.18 below	To be validated at each crew change with a bend test
Draft #2 ANSI/AWS C2.18-XX SSPC CS 23.00A-XX NACE TPC #XA	Typically within 6 hours of blasting, depending on environmental conditions	9°F above dew point	For 10- to 20-year life in salt water immersion: Zinc – 14 to 16 mils Aluminum – 10 to 12 mils Zinc/Aluminum – 14 to 16 mils	Several perpendicular overlapping passes
EN 22063	Typically within 4 hours of blasting, depending on environmental conditions	5°F above dew point	Varies Zinc – 2 to 10 mils Aluminum – 4 to 12 mils Zinc/Aluminum – 2 to 8 mils	None specified
ISO 2063	Shall not exceed 2 to 12 hours, depending on environmental conditions	5°F above dew point	Varies Zinc – 6 to 14 mils Aluminum – 4 to 10 mils Zinc/Aluminum – at least 6 mils	2-ft square block pattern
JIS H 8300 JIS H 8301	None specified	None specified	Varies Zinc – up to 12 mils Aluminum – up to 16 mils	None specified
MIL-STD-2138A(SH)	Spraying must be started and completed within 4 and 6 hours, respectively	10°F dew point spread	10 to 15 mils	Angle of spray stream shall be close to 90° and never less than 45°
U.S. Army COE Manual EM 1110-2-3401	Within 4 hours of blasting	At least 5°F above the dew point	Aluminum – 10 mils for seawater Zinc/Aluminum – 6 to 16 mils for fresh water	Block pattern measuring 24 in. on a side

TSMC QA Procedures

STANDARD	FINISH	POROSITY	BEND TEST	BOND TEST
ANSI/AWS C2.23-XX	Uniform without blisters, cracks, loose particles, or exposed steel when viewed at 10X	Measurements may be used to qualify process and parameters	Mentioned, but not defined	ASTM D4541 – 1 test per 500 ft^2 Zinc - >500 psi Aluminum - >1,000 psi 85/15 Zn/Al - >700 psi Al/Al_2O_3 - >1,000 psi
Draft #2 ANSI/AWS C2.18-XX SSPC CS 23.00A-XX NACE TPC #XA	No degraded TSC	Used for qualifying spraying parameters; not normally used for process control	Bend coupons and a mandrel with a suitable diameter (0.5 in. for TSC thickness of 7 to 12 mils)	ASTM C 633
EN 22063	Uniform without blisters or bare patches and free from non-adhering metal and defects	Not specified	None specified	Grid test and tensile test
ISO 2063	Uniform without blisters, bare patches, non-adhering metal and defects	Not specified	None specified	Grid test, adhesive tape and/or tensile test
JIS H 8300 JIS H 8301	Free from blisters, cracks and other harmful defects	Zinc – not specified Aluminum – IAW JIS H 8663	None specified	Zinc – IAW JIS H 8661 Aluminum – IAW JIS H 8663
MIL-STD-2138A(SH)	Uniform appearance with surface defects limited to small nodules not greater than 0.025 in. in height. The coating shall not contain blisters, cracks, chips, loosely adhering particles, oil, internal contaminants or pits exposing the undercoat or substrate	Not specified	No disbonding, delamination, or gross cracking shall occur due to bending	Minimum bond strength of 1,500 psi and an average bond strength of 2,000 psi
U.S. Army COE Manual EM 1110-2-3401	Smooth with no blisters, cracks, chips, loosely adhering particles, oil, pits exposing the substrate and nodules	Not specified	No cracks or minor cracking with no lifting of the coating	Not specified

Sealers and Topcoats

STANDARD	WHEN TO SEAL	RECOMMENDED MATERIALS
ANSI/AWS C2.23-XX	Acidic or alkaline environments, direct chemical attack, decorative finish is required, abrasion resistance is required, splash or immersion service is intended	None specified
Draft #2 ANSI/AWS C2.18-XX SSPC CS 23.00A-XX NACE TPC #XA	Recommended	Wash primers (0.3 to 0.5 mils) or sealers (1.5 mils)
EN 22063	Not specified	Natural sealing (by oxidation), chemical conversion (phosphating, reactive painting, etc.) or application of a paint system
ISO 2063	Aggressive environments, such as industrial or marine	PVB primers or paints with a single vinyl component; paints based on chlorinated rubber or epoxy systems
JIS H 8300 JIS H 8301	Not specified	None specified
MIL-STD-2138A(SH)	Not specified	High temperature: heat resistant aluminum paint IAW TT-P-28 or equivalent seal coat Low temperature: MIL-P-24441 Polyester powder
U.S. Army COE Manual EM 1110-2-3401	Recommended to fill porosity	Coal tar epoxy, vinyl

Maintenance and Repair

STANDARD	SURFACE PREP	TSC/SEALER APPLICATION	TOUCH-UP
ANSI/AWS C2.23-XX	Not specified	Inspect and maintain on a periodic basis, before maintenance repair and recoating is required	Not specified
Draft #2 ANSI/AWS C2.18-XX SSPC CS 23.00A-XX NACE TPC #XA	Solvent clean; scrape off loosely adherent paint; hand brush, abrasive brush blast, power tool and abrasive blast; feather and lightly abrade	As specified	Spray can degreasing and spray can painting may be used for temporary repairs
EN 22063	Not specified	Not specified	Not specified
ISO 2063	Not specified	Not specified	Not specified
JIS H 8300 JIS H 8301	Not specified	Not specified	Not specified
MIL-STD-2138A(SH)	Solvent clean; scrape, brush, blast, abrade – depending on level of damage	As specified	Paint coating may be replaced when TSC facilities are unavailable
U.S. Army COE Manual EM 1110-2-3401	SSPC SP-10	Same as original application	Repair with TSC, sealer, and paint as required

APPENDIX C

LITERATURE REVIEW REFERENCES AND SUMMARIES*

No.	References	Comments
1	R. Avery, "Application of Thermal Sprayed Coatings in a Shop Environment – Some Practical Considerations," *SSPC International Conference*, 1995.	This paper discusses the advantages of thermal spray coatings in comparison with conventional air dry coatings systems. Some of these advantages include resistance to mechanical damage, provisions for barrier and sacrificial protection, low VOC emissions, and rapid turnaround. However, the author cautions that quality control, surface preparation, and operator training are necessary to provide superior long-term performance. Compared with air dry coatings, application of TSMCs is more cost competitive with respect to labor, material and schedule costs.
2	J. C. Bailey, "Corrosion Protection of Welded Steel Structures by Metal Spraying," *Metal Construction*, 1983.	This paper provides a general overview of the use of thermal spray coatings (zinc and aluminum) and sealers on steel. In waters where carbonate hardness is high, zinc is generally recommended. In waters where chloride content is high, aluminum is the recommended coating. In comparing combustion spraying versus electric arc spraying, the author states that the latter provides application at higher deposition rates, hotter particles and higher coating adhesion strengths. The author notes that since the corrosion product of zinc coatings is often readily removed, they benefit greatly from the use of a sealer. The corrosion products of aluminum coatings, on the other hand, are generally more corrosion resistant and adherent and, thus, benefit less so than zinc coatings from the application of a sealer. Recommended sealers include vinyl chloride/acetate copolymers, phenolic resins, silicone modified alkyds, silicone resins or polymers, and, for higher temperatures, aluminum pigmented silicone resins.
3	J. C. Bailey, F. C. Porter, and M. Round, "Metal Spraying of Zinc and Aluminum in the United Kingdom."	This paper discusses metal spraying of zinc and aluminum on bridges in the U.K. The authors conclude that zinc is preferable in alkaline conditions while aluminum is preferable in slightly acidic conditions and at high temperatures.
4	E. Bardal, "The Effect of Surface Preparation on the Adhesion of Arc and Flame-Sprayed Aluminum and Zinc Coatings to Mild Steel," Norwegian Institute of Technology, University of Trondheim, Trondheim, Norway.	This paper provides significant experimental data on the relationship between adhesion and surface profile: • Arc spraying of aluminum provides about 3x the bond strength to a steel substrate vs. flame spraying of zinc or aluminum, or arc spraying of zinc. Grit type also makes a large difference, with angular iron grit preferred over copper slag or silica sand. • This work was for low thickness coatings, 0.15 to 0.25 mm (9 mils). • Adhesion was found to increase with measured reflectivity, as compared to a standard light gray tile. This also correlated to a degree with improving from a Sa 2 to 2 to a Sa 3 standard of cleanliness. • The paper also shows that cleanliness is not the only factor. Adhesion values also increase with R_a x n where R_a is the center-line average of roughness times the number of peaks, and also with an electrochemically determined value of total surface area. R_a is defined by (1/L)* integral (o to L) of y dx. N is the number of peaks in the profile length. The electrochemical principal is based on the assumption that R_p is a material constant in a passivating solution, thus differences in R_p will be related to different surface areas in contact with the electrolyte. R_p values are compared on blasted steel substrates vs. polished surfaces of the same material.
5	V. Begon, J. Baudoin, and O. Dugne, "Optimization of the Characterization of Thermal Spray Coatings," *International Thermal Spray Conference*, 2000.	This paper discusses the metallographic process, describing it as the primary way to evaluate thermally sprayed coatings. The management and organization of a metallographic process is of prime importance to keep the process both repeatable and expedient. The paper defines a complete method for metallographic preparation based on a pragmatic approach.
6	Alfred D. Beitelman, "Evaluation of Surface Preparation and Application Parameters for Arc-Sprayed Metal Coatings," *USACERL Technical Report 99/40*, April 1999.	The U.S. Army Corps of Engineers uses 85-15 zinc aluminum alloy arc-sprayed coatings on hydraulic structures exposed to corrosive environments. Premature failure of these coatings has been attributed to poor surface preparation and application procedures. This study evaluated various materials used for metallizing, specifically the effects of surface preparation and application parameters on adhesion, cavitation, erosion, porosity, and oxide content.
7	Thomas Bernecki, "Final Report to U.S. Army-CERL: Evaluation of Two-Wire Electric Arc Systems," February 26, 1996.	This program evaluated the suitability of seven two-wire arc-spray systems to apply coatings of zinc, aluminum, 85-15 Zn-Al and 90-10 Al-Al_2O_3. The authors found that only three of the seven units tested were capable of continuously applying 85-15 Zn-Al. The average adhesion values, performed in accordance with ASTM D4541-93, for the combustion wire coatings of zinc, 85-15 Zn-Al, aluminum, and 90-10 Al-Al_20_3 were 200, 435, 200, and 400 psi, respectively. The authors discuss some potential factors that may affect adhesion: • Unlike combustion, wire arc has no open flame to remove moisture and preheat the surface of the substrate. This may be factor in applications involving structures in water. • ASTM C633 is based on the measurement of normal forces. The presence and magnitude of a surface profile may affect the accuracy of the measurement. Also the porosity at the surface could also affect measured adhesion values. • Power settings define initial particle size and velocity. Stand-off distance can affect final impact velocities. Low velocities and/or large particles can result in lower temperature on impact, thereby affecting the splatting characteristics of the coating.
8	M. Bhursari and R. Mitchener, "Ski-Lift Maintenance: Wire Arc Spray vs. Galvanizing," *SSPC International Conference*, 1998.	This paper reviews the use of wire arc spray zinc vs. galvanizing on ski lifts. The authors discuss a case study in which painted lifts required repainting every 3 years, hot dipped lifts showed signs of corrosion in fewer than 5 years and thermal sprayed ski lifts exhibited no corrosion after 5 years. It was estimated that the wire arc-spray zinc coating, depending upon the thickness, would have a life expectancy of 20 years with minimal maintenance. The authors concluded that thermal spray coatings were more resistant to abrasion and wear than thin galvanized coatings.
9	M. M. Bhusari and R. A. Sulit, "Standards for the Thermal Spray Industry," *International Thermal Spray Conference*, 2000.	This paper provides a brief compilation of information on thermal spray standards set by various professional societies, including American Society for Testing and Measurement (ASTM), American Welding Society, American Water Works Association (AWWA), International Association of Corrosion Engineers (NACE), and Society of Protective Coatings (SSPC). These efforts have the ultimate objective of making the coating system performance more reliable and predictive.

* References and Summaries not verified by TRB.

No.	References	Comments
10	J. Bland, "Corrosion Testing of Flame-Sprayed Coated Steel – 19 Year Report," American Welding Society, Miami 1974.	This report presents the results of a 19-year study of the corrosion protection afforded by wire-flame-sprayed aluminum and zinc coatings applied to low carbon steel. The program was initiated in July, 1950 by the Committee on Metallizing (now the Committee on Thermal Spraying) of the American Welding Society. The first panels were exposed in January, 1953. This report presents the results of an inspection of the flame-sprayed coated steel panels made after all panels had been exposed for 19 years. Aluminum-sprayed coatings 0.003 in. to 0.006 in. (0.08 mm to 0.15 mm) thick, both sealed and unsealed, gave complete base metal protection from corrosion in sea water and also in severe marine and industrial atmospheres. Where aluminum coatings showed damage such as chips or scrapes, corrosion did not progress, suggesting the occurrence of galvanic protection. The use of flame-sprayed aluminum and zinc coatings is recommended as a means to extend the life of such iron and steel structures as bridges, highway or street light poles, marine piers or pilings, ship hulls, storage tanks, industrial structures, etc. Corrosion is thereby combated, and the natural resources needed in the manufacture of iron and steel are conserved.
11	P. E. Bonner, "The Corrosion of Zinc, Zinc Alloy and Aluminum Coatings in the Atmosphere."	This paper discusses an exposure test of mild steel panels coated with wire-sprayed aluminum, powder-sprayed aluminum, wire-sprayed zinc, powder-sprayed zinc, hot-dipped aluminum, hot-dipped zinc, powder-sprayed 65 w/o Zn-35 w/o Al and electrodeposited 60 w/o Zn-40 w/o Fe. The five exposure sites used were located in rural, marine, and industrial environments. Metallographic examination revealed that the powder-sprayed coatings of aluminum and zinc were significantly more porous and less uniform than the wire-sprayed coatings. The powder-sprayed 65 w/o Zin-35 w/o Al coating was the least uniform of the sprayed-metal coatings, being of variable quality and somewhat discontinuous. After 6 months of exposure, the zinc-aluminum alloy coatings at all sites were in excellent condition and showed little corrosion product. Even after 2 years, only a few white areas of corrosion product were visible on some of the Zn-Al specimens. The paper goes on to discuss metallographic examinations of the coatings following these exposure tests. Pores were observed in the sprayed aluminum coatings where corrosion product was visible. A few pores were also observed in the sprayed zinc coatings, but with little or no corrosion product. Very few corrosion product filled pores were observed in the zinc-aluminum alloy coatings; however, some corrosion product was visible in some of the surface valleys when exposed to the more aggressive environments.
12	J. M. Brodar, "Blundering Towards Success with Metal Spray," *SSPC International Conference*, 1995.	This paper discusses case histories involving zinc thermal spray coatings. The author discusses advantages of TSMCs over paint type coatings, including no cure time; durability; no VOC; and a single coating method for immersion, atmospheric, and alternating wet and dry exposures. The author emphasizes the need for a high zinc-to-steel surface area ratio – in excess of 100,000:1 for freshwater immersion.
13	T. Call and R. A. Sulit, "Protecting the Nation's Infrastructure with Thermal-Sprayed Coatings," *AWS International Welding Exposition*.	This paper summarizes some metallizing applications for the maintenance and repair of the infrastructure and provides a general overview of metallizing technology. The authors provide data on aluminum and zinc spray rates and coverage of arc-spray machines, a comparison of vinyl and zinc metallized coating life cycle cost (LCC) to include maintenance interval, current cost and so forth, and applications. Thermal sprayed aluminum and zinc provide the long-term corrosion control coatings. However, its initial application is usually more expensive than painting or galvanizing if thermal spraying (metallizing) is not integrated into the design and fabrication phases of new construction and repair projects. Aluminum and zinc metallized coatings are tough enough to withstand fabrication, transportation, and assembly operations. The improved capabilities and productivity of metallizing equipment for aluminum and zinc spraying are a major factor in their current cost competitiveness. The net result is that the costs of metallizing, paint, and galvanizing are getting closer every day. Even though the initial application cost of metallizing may be higher, the life cycle cost (LCC) and average equivalent annual costs are lower than paint coating systems. Metallizing LCCs, when properly engineered into the construction schedule, are equal to or less than paint coating LCCs.
14	K. A. Chandler, *Marine and Offshore Corrosion*, 1985.	This book discusses corrosion and its control in marine environments. Topics discussed include forms of corrosion, material selection, coatings (paint and metallic), and steel pilings (although no discussion of metallic coatings on steel pilings).
15	W. Cochran, "Thermally Sprayed Aluminum Coatings on Steel," *Metal Progress*, December 1982.	This is a brief technical paper outlining the performance features of thermal spray applied aluminum coatings. Pertinent issues from this paper include the following: ∞ Coatings are applied to white metal substrates at 3–7 mils. Sealers are useful for cosmetic concerns, primarily to reduce dirt build-up. ∞ TSA coatings have been used in freshwater supply systems by a Texas utility for over 25 years.
16	Committee on Thermal Spray Coatings for Corrosion Control, "Metallized Coatings for Corrosion Control of Naval Ship Structures and Components, National Materials Advisory Board," National Academy of Sciences, Washington, D.C., Report NMAB-409, February 1983.	This is a comprehensive document which attempts primarily to review the U.S. Navy's approach to the use of metallizing for corrosion control on Navy ships. The report does provide several major conclusions that seem meaningful with respect to the subject contract. • TSA coatings are known to be excellent corrosion control coatings for below-deck applications. However these coatings perform inconsistently on the weather deck. This is attributed to the lack of consistent application and quality control, which is especially evident in the more harsh environments. • Long-term performance data for TSA materials are based on coatings applied using best practices with extensive QA. It is not clear that the same level of QA is achieved in production applications. The report notes that there are not good NDT techniques available for finding critical defects such as excessive porosity, bond-separation, local coating penetrations, and excessive oxide inclusions. This is where future research should focus. • Risk factors can be mitigated by the use of a good seal coat. These are especially good at mitigating porosity. • The report suggests that TS pure aluminum is the best material for marine use. • The report suggests that humidity and surface cleanliness during application are key and need to be carefully specified and controlled during material application. • While it is clearly understood that low bond strength of TSM reduces performance, high bond strength does not guarantee good performance. There is no demonstrated minimum acceptable bond strength to guarantee performance.
17	T. Cunningham, "Quality Control of Thermal Spray Coatings for Effective Long-Term Performance," *SSPC International Conference*, 1995.	This paper discusses the benefits of thermal spray coatings, as well as quality control parameters, surface preparation, and application technique. The author concluded that while TSMCs have relatively high initial applied costs, they can provide economical long-term protection because of their long service life. Ideal coating characteristics include low porosity, a smooth surface, closely controlled DFT, and good adhesion. Quality control measurements should examine surface profile, film thickness, coating adhesion, and porosity.

No.	References	Comments
18	T. Cunningham and R. Avery, "Thermal Spray Aluminum for Corrosion Protection: Some Practical Experience in the Offshore Industry," *SSPC International Conference*, 1998.	This paper describes specific experiences with TSA on offshore components: • Wellhead support structures – SP-5, 12 mils TSA; little mechanical damage and a few blisters after 5 years of exposure. • Riser pipe – 8 to 10 mils TSA plus 0.6 mil conventional sealer (aluminum pigmented silicone or thinned epoxy; concern for overspray contamination in the weld bead). • Flotation chambers – Large structures (63 ft long) were coated with TSA applied by an automated process. • Sealers – traditionally either vinyl or aluminum pigmented silicone. Silicone exhibits superior performance, but is intended to be heat cured and is difficult to see.
19	T. Cunningham and R. Avery, "Sealer Coatings for Thermal Sprayed Aluminum in the Offshore Industry," *Materials Performance*, January 2000.	This paper summarizes findings on the performance of sealers on thermal spray coatings in offshore environments. Two thermal spray coating sealers are commonly used: aluminum-pigmented silicone (for high temperature applications) and vinyl etch primer. While the performance of the silicone sealer is reportedly better than that of vinyl, the aluminum silicone sealer is virtually invisible and requires heat cure. The lack of visibility causes difficulties for sprayers and inspectors. Epoxy sealers are available in any color, but there is occasionally an adverse reaction to the visual appearance of a thin sealer. The authors recommend that the two-pack epoxy be thinned, suggesting that more than half of the applied materials should be thinner.
20	K. DuPlissie, "Lessons Learned of the I-95 Thermal Spray Project in Connecticut," Fifth World Congress on Coating Systems for Bridges and Steel Structures, 1997.	The Research Division of the Connecticut Department of Transportation, sponsored by the FHWA, completed an 8-year project to evaluate the performance of zinc-based coatings for abrasive blast-cleaned structural steel. This study concluded that • In order for the coating to adhere to a steel surface, an anchor tooth (jagged) surface profile is necessary. • Performance of a bend test is important because 1. It enables adjustment of equipment to proper settings and proper techniques. 2. It allows the inspectors to test the blast and the coating prior to the actual application.
21	E. Escalante, W. P. Iverson, W. F. Gerhold, B. T. Sanderson, and R. L. Alumbaugh, "Corrosion and Protection of Steel Piles in a Natural Seawater Environment," Institution for Materials Research, National Bureau of Standards, June, 1977.	This paper discusses the results for the first 8 years of a long-term evaluation of various coating and cathodic protection systems. These systems include nonmetallic coatings, metallic pigmented coatings, nonmetallic coatings on metal-filled coatings, nonmetallic coatings on metallic coatings, metallic coatings and cathodic protection on bare and coated piles. With 25 systems tested, the following conclusions were made: • Above the high-water line was the most corrosive zone on bare steel samples, on the order of 8 to 12 mils per year; some pitting was visible above and below the mudline. • Coal tar epoxy coatings exhibited severe damage below the water line due to sand impingement; general attack and some undercutting were visible in the atmospheric zone; undercutting resistance was improved in the tidal zone, but general attack was still visible; coatings were susceptible to mechanical damage during installation. • Electrochemical measurements indicated that phenolic mastic and polyester glass flake exhibited good resistance to deterioration; the phenolic mastic was good over the entire surface of the pile after 6 years of exposure – little pitting in the erosion zone, maximum corrosion rate of 0.15 mpy just below the mean high-water line, moderate undercutting in the atmospheric zone with a maximum penetration of 1 in., some coating failure at the flange edge; the polyester glass flake, with an average coating thickness of 32 mils, exhibited minor pitting, little coating breakdown, difficult to remove coating by sandblasting, minor deterioration at the flange edges in the erosion zone, little damage in the atmospheric or splash zones, and undercutting of up to 1 in. in the atmospheric zone. • Polyvinylidene chloride, when compared with phenolic mastic and polyester glass flake, exhibited a significantly higher degree of deterioration – corrosion rate of 5 mpy in the erosion zone, average corrosion rate of 2.4 mpy over entire pile, considerable deterioration in the atmospheric zone, undercutting of up to 0.3 in. in the tidal zone and 2 in. below the mudline. • Aluminum pigmented coal tar epoxy exhibited high electrical resistivity, very little deterioration, some coating damage in the erosion zone with a corrosion rate of less than 0.1 mpy, minor pitting over most of the pile, less than 1.2 in. of undercutting and some rust staining in the atmospheric zone, 0.1 in. of undercutting in the tidal zone, no undercutting or coating deterioration below the mudline; the aluminum pigmented coal tar epoxy system with a 30% thinner coating thickness exhibited more damage overall, little deterioration at the flange but some deterioration and pitting 2 to 3 in. from the edge, average corrosion rate of 0.2 mpy over the entire pile, undercutting of 1.5 in. in the atmospheric zone and as much as 2 in. below the mudline, and minor coating damage in the tidal zone. • Nonmetallic coatings on metal-filled coatings were also tested; coal tar epoxy over zinc rich organic primer performed well, exhibited an average corrosion rate of 0.2 mpy, severe coating damage with undercutting of almost 2 in. in the atmospheric zone, minor undercutting in the tidal zone, negligible damage below the mudline; epoxy polyamide over zinc rich inorganic primer exhibited good resistance with an average corrosion rate of less than 0.1 mpy, some deterioration in the erosion zone, negligible damage below the mudline, good undercutting resistance in all zones with less than 0.5 in. in the atmospheric zone, some blistering below the mudline; coal tar epoxy over zinc rich inorganic primer exhibited good resistance to deterioration, no metal loss near the flange, minor pitting, undercutting of 0.6 in. in the atmospheric zone, minor undercutting in the tidal zone, no measurable undercutting below the mudline; vinyl over zinc rich inorganic primer exhibited general attack over the pile length with more attack in the erosion zone, an average corrosion rate of 0.2 mpy, undercutting of less than 0.5 in. with some edge deterioration in the atmospheric zone, undercutting of less than 0.1 in. but extensive general deterioration in the tidal zone, undercutting of less than 0.1 in. below the mudline; vinyl mastic over zinc rich inorganic primer exhibited an average corrosion rate of less than 0.25 mpy, little attack and undercutting of less than 0.1 in. in the atmospheric zone, general deterioration with undercutting of less than 0.1 in. in the tidal zone, and undercutting of 0.2 in. with some blistering below the mudline. • Nonmetallic coatings on metallic coatings: vinyl sealer over flame-sprayed aluminum exhibited an average corrosion rate of less than 0.05 mpy, a small amount of metal loss in the erosion zone, practically insignificant pitting, excellent corrosion resistance in the atmospheric zone, visible general coating failure and immeasurable undercutting in the tidal zone, some coating deterioration below the mudline; polyvinylidene chloride over flame-sprayed zinc developed a nonconducting film over time which gradually improved the coating performance, exhibited an average corrosion rate of less than 0.1 mpy, little and uniform metal loss, minor scattered pitting, minor damage in a few areas in the atmospheric zone, significant blistering of the topcoat (but the zinc coating still provided protection) in the tidal zone; vinyl-red lead over flame-sprayed zinc exhibited the most deterioration of the three systems with the topcoat beginning to fail during the first year of exposure followed by the gradual deterioration of the zinc (the total coating thickness of this system was only 50% of that of the polyvinylidene chloride over zinc flame spray).

No.	References	Comments
		zone, no undercutting or coating deterioration below the mudline; the aluminum pigmented coal tar epoxy system with a 30% thinner coating thickness exhibited more damage overall, little deterioration at the flange but some deterioration and pitting 2 to 3 in. from the edge, average corrosion rate of 0.2 mpy over the entire pile, undercutting of 1.5 in. in the atmospheric zone and as much as 2 in. below the mudline, and minor coating damage in the tidal zone. • Nonmetallic coatings on metal-filled coatings were also tested; coal tar epoxy over zinc rich organic primer performed well, exhibited an average corrosion rate of 0.2 mpy, severe coating damage with undercutting of almost 2 in. in the atmospheric zone, minor undercutting in the tidal zone, negligible damage below the mudline; epoxy polyamide over zinc rich inorganic primer exhibited good resistance with an average corrosion rate of less than 0.1 mpy, some deterioration in the erosion zone, negligible damage below the mudline, good undercutting resistance in all zones with less than 0.5 in. in the atmospheric zone, some blistering below the mudline; coal tar epoxy over zinc rich inorganic primer exhibited good resistance to deterioration, no metal loss near the flange, minor pitting, undercutting of 0.6 in. in the atmospheric zone, minor undercutting in the tidal zone, no measurable undercutting below the mudline; vinyl over zinc rich inorganic primer exhibited general attack over the pile length with more attack in the erosion zone, an average corrosion rate of 0.2 mpy, undercutting of less than 0.5 in. with some edge deterioration in the atmospheric zone, undercutting of less than 0.1 in. but extensive general deterioration in the tidal zone, undercutting of less than 0.1 in. below the mudline; vinyl mastic over zinc rich inorganic primer exhibited an average corrosion rate of less than 0.25 mpy, little attack and undercutting of less than 0.1 in. in the atmospheric zone, general deterioration with undercutting of less than 0.1 in. in the tidal zone, and undercutting of 0.2 in. with some blistering below the mudline. • Nonmetallic coatings on metallic coatings: vinyl sealer over flame-sprayed aluminum exhibited an average corrosion rate of less than 0.05 mpy, a small amount of metal loss in the erosion zone, practically insignificant pitting, excellent corrosion resistance in the atmospheric zone, visible general coating failure and immeasurable undercutting in the tidal zone, some coating deterioration below the mudline; polyvinylidene chloride over flame-sprayed zinc developed a nonconducting film over time which gradually improved the coating performance, exhibited an average corrosion rate of less than 0.1 mpy, little and uniform metal loss, minor scattered pitting, minor damage in a few areas in the atmospheric zone, significant blistering of the topcoat (but the zinc coating still provided protection) in the tidal zone; vinyl-red lead over flame-sprayed zinc exhibited the most deterioration of the three systems with the topcoat beginning to fail during the first year of exposure followed by the gradual deterioration of the zinc (the total coating thickness of this system was only 50% of that of the polyvinylidene chloride over zinc flame spray). • Metallic coatings: hot-dipped galvanized steel pile exhibited a decreasing corrosion current for the first 3 years of exposure followed by a steadily increasing corrosion current (approaching that of bare steel) for the next 5 years, exhibited an average corrosion rate of 0.15 mpy, significant corrosion in the erosion zone, some corrosion in the atmospheric zone, coating failure in the form of pits above the high-water line, pitting and undercutting in the tidal zone, thin and no coating below the mudline; flame-sprayed aluminum exhibited a steadily increasing corrosion current (approaching that of bare steel as the aluminun deteriorated), exhibited some metal loss in the erosion zone, virtually no pitting, minor corrosion damage in the atmospheric and tidal zones, and extensive coating damage below the mudline. • Cathodically protected steel piles: electrochemical measurements indicated corrosion rates much lower than similar piles without cathodic protection; in general, the anodes located below the mudline provided more protection than similar anodes above the mudline.
22	Karl P. Fischer, William H. Thomason, Trevor Rosbrook, and Jay Murali, "Performance of Thermal Sprayed Aluminum Coatings in the Splash Zone and for Riser Service," NACE 1994.	This paper discusses the performance of thermal sprayed aluminum after 8 years of service on offshore TLP risers and tethers. The authors believe that a 30-year service life is achievable with a 200 micron TSA coating with the use of specific sealer systems. The authors concluded that a silicone sealer adequately fills the pores of the TSA coating and prevents the formation of blistering. After 8 years of service, the TSA coating on the Hutton TLP production risers and tethers was in good condition. The splash zone area was indistinguishable from the remainder of the inspected components.
23	K. P. Fischer, W. H. Thomason, J. E. Finnegan, "Electrochemical Performance of Flame-Sprayed Aluminum Coatings on Steel in Seawater," *Materials Performance*, September 1987.	This paper studies the electrochemical behavior of flame-sprayed aluminum (FSA) coating in natural seawater. The authors concluded that FSA generally performs well in both the submerged and splash zone exposure, primarily as a very strong barrier-type coating. The free corrosion potential of the FSA coating in strongly flowing seawater was –930 to –950 mV vs. Ag-AgCl at ambient temperature. The authors claim that the use of a silicone sealer paint on the FSA coating will increase the service life of the system. An FSA coating with silicon sealer paint will have some reduced anodic capabilities, yielding a current density output of 30 to 200 mA/m^2 in a potential range of –950 to –850 mV. For FSA coating without sealer, the current output can be up to 500 mA/m^2 in an initial exposure period. However, at a high constant current density, the aluminum coating will be consumed during a few months of exposure.
24	Brendan Fitzsimons, "Thermal Spray Metal Coatings for Corrosion Protection," *Corrosion Management*, December 1995/January 1996.	This article provides an introduction to the uses of thermal sprayed metal coatings as corrosion protection for steel, as an alternative to paint coatings. Arc spray, when compared with flame spray, has been shown to give faster output and superior adhesion. Flame spray may be favorable in areas that are difficult to access. Aluminum and aluminum alloys are used and an alloy with 5% magnesium is currently widely specified, although Fitzsimons is not convinced it provides the best protection offshore. Aluminum-5% magnesium is highly efficient for offshore platforms and ship topsides, where the anodic advantages of the metal are shown. Although experience has shown that sealers are of benefit on exposed aluminum coatings, areas not exposed to driving rain (e.g., undersides of platforms and bridges) may be better left unsealed to reduce the effect of "sweating" or condensation. Sprayed aluminum has been shown to be effective against corrosion under insulation, which might have become wet due to leakage of rainwater through the weather cover. Thermally sprayed aluminum works well on plant operating at elevated temperatures, coated with epoxy sealers for use up to 120°C and with a silicone aluminum sealer above that temperature. Fitzsimons also discusses the advantages and disadvantages (cathodic vs. anodic, cost, adhesion, etc.) of different coatings (aluminum, zinc, tin, lead, etc.).
25	M. Funahashi and W. T. Young, "Development of a New Sacrificial Cathodic Protection System for Steel Embedded in Concrete," Report FHWA-RD-96-171, FHWA, Washington, DC, May 1997.	This interim report studies aluminum and zinc alloys as anodes to cathodically protected steel embedded in concrete. Laboratory studies indicated that a series of aluminum-zinc-indium alloys outperformed both pure zinc and pure aluminum as anodes.

No.	References	Comments
26	P. O. Gartland and T. G. Eggen, "Cathodic and Anodic Properties of Thermal Sprayed Al- and Zn- Based Coatings in Seawater," Corrosion 1990, Paper Number 367.	This paper studies the performance of thermal spray (arc and flame spray) coatings of Al, AlMg, and ZnAl for 18 months in seawater. The arc-sprayed specimens exhibited better adhesion than the flame-sprayed specimens. The authors concluded the following: • Al and AlMg were acceptable barrier coatings in combination with a sacrificial anode system. ZnAl exhibited blistering at low potentials and high corrosion rates at higher potentials. • The use of a silicone sealer significantly improves the barrier properties of the thermal spray coatings. The corrosion rate at the free corrosion potential was reduced by a factor of two to three. At higher potentials, the corrosion rate is not affected. • Coating thickness and surface preparation had only a minor influence on coating properties.
27	N. D. Greene, R. P. Long, J. Badinter and P. R. Kambala, "Corrosion of Steel Piles," *Innovative Ideas for Controlling the Decaying Infrastructure*, NACE Paper No. 95017, 1995.	This paper discusses case histories of pile corrosion, as well as theoretical and experimental analyses. The authors concluded that pile corrosion is the result of macrocell activity along the pile surface. Different oxygen concentrations can lead to rapid localized corrosion.
28	Robert M. Kain and Walter T. Young, *Corrosion Testing in Natural Waters (Second Volume)*, ASTM Rep. No. STP 1300, 1997.	This publication contains papers presented at the Second Symposium on Corrosion Testing in Natural Waters in 1995 in Norfolk, Virginia. Some of the papers include: • Ashok Kumar, Vicki L. Van Blaricum, Alfred Beitelman, and Jeffrey H. Boy, "Twenty Year Field Study of the Performance of Coatings in Seawater." Steel H piles were coated with various coatings including coal tar epoxy, polyurethane and flame-sprayed zinc and aluminum. Electrochemical techniques (polarization resistance and Tafel plots) were periodically utilized. Long-term coating evaluation showed that flame-sprayed aluminum with a topcoat sealer performed best at the cooler temperatures in Massachusetts waters (Buzzards Bay, Cape Cod) and polyester glass flake performed best in Florida waters (La Costa Island) • R. E. Melchers, "Modeling of Marine Corrosion of Steel Specimens." This paper proposes a conceptual model for immersion corrosion, tidal corrosion, and atmospheric corrosion for steel under marine conditions. Diffusion and kinetic theory are utilized in the development of phenomenological modeling.
29	W. R. Kratochvil and E. Sampson, "High Output Arc Spraying – Wire and Equipment Selection," *SSPC International Conference*, 1998.	This paper discusses the deposition of two wire diameters (1/8" and 3/16"), three wire materials (Al, Zn/Al, and Zn) and two spray rates (rated at 300A and 450A). The authors concluded that 3/16" wire, when compared with 1/8", exhibits higher deposition rates and deposits over 60% more material for Al, 32% more for Zn/Al, and 34% more for Zn. The stiffness of the thicker wire affects operator comfort, range of motion, and fatigue levels.
30	S. Kuroda and M. Takemoto, "Ten Year Interim Report of Thermal Sprayed Zn, Al and Zn-Al Coatings Exposed to Marine Corrosion by Japan Association of Corrosion Control," *International Thermal Spray Conference*, 2000.	The thermal spray committee of the Japan Association of Corrosion Control (JACC) has been conducting a corrosion test of thermal sprayed zinc, aluminum, and zinc-aluminum at a coastal area since 1985. Arc-spray and flame-spray coatings were applied to steel piping at varied thicknesses and subjected to various post-spray treatments. No significant changes were observed in the coating systems after 5 years of exposure. After 7 years, zinc coatings with and without sealing exhibited degradation in the immersion zone. However, the aluminum and zinc-aluminum coatings still exhibited excellent corrosion resistance. The test is scheduled to continue until 2001.
31	F. L. LaQue, *Marine Corrosion Causes and Prevention*, 1975.	This book discusses the various mechanisms involved in marine corrosion. The author describes an experiment involving continuous and isolated specimens in seawater to demonstrate the effects of macrocell corrosion.
32	Eric S. Lieberman, Clive R. Clayton, and Herbert Herman, "Thermally-Sprayed Active Metal Coatings for Corrosion Protection in Marine Environments," *Final Report to Naval Sea Systems Command*, January 1984.	This paper evaluated flame and electric arc-sprayed coatings of zinc, aluminum, zinc-15 wt% aluminum and duplex layered coatings onto mild steel substrates. These systems were exposed to a variety of corrosive conditions in a 3.0 wt% sodium chloride solution and in natural sea water. The sprayed coatings were sealed with an epoxy polyamide to reduce surface porosity. Electrochemical, salt spray, immersion, and adhesion tests were utilized to evaluate the coating systems. The authors concluded that because of zinc's strong electrochemical activity, zinc does not afford as long-lasting protection as does aluminum. Zinc-15 wt% aluminum, although electrochemically similar to zinc, provides barrier protection similar to aluminum, while still maintaining zinc's degree of protection. The zinc-aluminum coatings exhibit strong corrosion protection, high adhesive strength, and a high coating density. A duplex-layered coating of aluminum sprayed onto zinc-coated steel proves to be effective in reducing crevice attack of the aluminum coating. Electric arc-sprayed deposits, when compared with flame-sprayed deposits, were less porous, exhibited higher adhesive strength and superior corrosion resistance. Studies on the microstructure of electric arc-sprayed coatings of different wire diameters revealed that as the wire diameter is decreased, a more dense coating will arise due to better atomization.
33	R. T. R. McGrann, J. Kim, J. R. Shandley, E. F. Rybicki, and N. G. Ingesten, "Characterization of Thermal Spray Coatings Used for Dimensional Restoration," *International Thermal Spray Conference*, 2000.	Thermal spray coatings are used for dimensional restoration of worn parts during aircraft overhaul. Residual stress, tensile bond strength, porosity, oxides, impurities, and hardness affect the performance of thermal sprayed parts. An understanding of the relation of these coating characteristics to process variables (material selection, spray process, spray angle, and coating thickness) is needed. The authors studied four nickel alloys applied by plasma spray and high velocity oxy-fuel (HVOF) using different spray angles and coating thickness ranges. The authors investigated how the thermal spray process variables affect the thermal spray characteristics.
34	C. G. Munger, *Corrosion Prevention by Protective Coatings*, NACE, 1984.	This book discusses the use of protective coatings for corrosion control. One specific case that the book references is the use of galvanizing and inorganic zinc in tidal seawater conditions. The galvanized test panels exhibited significant pinpoint rust, while the inorganic zinc-coated panels exhibited no visible corrosion after 2 years of exposure.
35	P. Ostojic and C. Berndt, "The Variability in Strength of Thermally Sprayed Coatings," National Thermal Spray Conference Proceedings, ASM International, September 1987, p. 175.	This paper shows the variation in tensile adhesion test data for TS coatings. The authors conclude that adhesion values based on the average of several tests are meaningless. The data seem to fit a standard Weibull distribution, and thus such an analysis needs to be conducted to adequately characterize this critical QA parameter.
36	Timothy D. Race, "Evaluation of Seven Sealer Systems for Metallized Zinc and Aluminum Coatings in Fresh and Salt Waters," *Final Report for HQUSACE*, September 1992.	This study evaluated seven sealer systems for zinc and aluminum metallized coatings in fresh and salt waters. Conclusions: • For zinc in fresh and salt waters, recommend epoxy and epoxy with wash primer. • For aluminum in fresh water, recommend pigmented urethane or white pigmented vinyl. • For aluminum in salt water, none of the tested sealers performed adequately.

No.	References	Comments
37	Tim Race, Vince Hock, and Al Beitelman, *Performance of Selected Metallized Coatings and Sealers on Lock and Dam Facilities*, August 1989.	This paper evaluates metallized coating and sealer systems for highly abrasive environments. Four thermal spray materials were evaluated, including aluminum-bronze (89Cu, 10Al, 1Fe), stainless steel (18Cr, 8Ni), zinc-aluminum (85Zn, 15Al), and pure zinc. The authors concluded that coatings anodic to mild steel, such as 85-15 zinc-aluminum and pure zinc, are possible alternatives to conventional paint coatings for use in highly abrasive environments. However, a performance evaluation is required to establish the service lives of these materials. They also concluded that coatings cathodic to mild steel, such as aluminum-bronze and stainless steel, are not recommended for such environments.
38	F. S. Rogers, "Benefits and Technology Developed to Arc Spray 3/16 Inch (4.8 mm) Diameter Wires Used for Corrosion Protection of Steel," *International Thermal Spray Conference*, 2000.	This paper provides an overview of the variables that determine spray rate with the twin wire arc-spray process. A U.S. patent for spraying wire larger than 3.2 mm (1/8 inch) has resulted in surprising improvements in deposit efficiency and spray rates. The authors also discuss some other design improvements, such as • a new innovative nozzle system that atomizes and distributes the spray into a desirable spray pattern, • a new patented electrical design mastered arc starting by automatically gapping the wire at the end of each spray cycle, and • wire straighteners that prevent kinks and bends.
39	F. S. Rogers and W. Gajcak, "Cost and Effectiveness of TSC Zinc, Zinc/Aluminum and Aluminum Using High Deposition Low Energy Arc Spray Machines," *SSPC International Conference*, 1997.	This paper discusses the advantages of 3/16" wire feedstock over 1/8". These advantages include higher spray rate at lower amperages, better deposit efficiency, higher quality, lower labor costs, lower material cost, lower equipment maintenance cost.
40	T. Rosbrook, W. H. Thomason, J. D. Byrd, "Flame Sprayed Aluminum Coatings Used on Subsea Components," *Materials Performance*, September 1989.	This article reviews the in-service performance of FSA on subsea components of the Hutton Tension Leg Platform in the North Sea. While some blistering was observed after 2 years in service, the rate of consumption was not excessive, and it was concluded that the coating would exceed the 20-year design life. The blisters were believed to be the result of inadequate sealing of the aluminum by the vinyl sealer. Although the silicone type sealer may not crosslink without a high temperature cure, it penetrates the porosity of the FSA and provides a good barrier to water penetration. The authors recommend the use of chilled iron grit (grade C17/24) to overcome the possibility of contamination from the use of aluminum oxide abrasives.
41	M. M. Salama and W. H. Thomason, "Evaluation of Aluminum Sprayed Coatings for Corrosion Protection of Offshore Structures," *Society of Petroleum Engineers*, 1984.	This paper discusses corrosion protection methods for offshore structural high-strength steel to avoid problems with fatigue and hydrogen embrittlement.
42	E. R. Sampson and P. Sahoo, "New Arc Wire Approvals for Aircraft Power Plant Overhaul," *International Thermal Spray Conference*, 2000.	The increasing use of arc-spray systems in the overhaul of aircraft engine components has created a demand for new wire approvals. This paper discusses some historical background of the arc-spray process, materials that are presently approved and those that have been submitted for approval. The paper discusses advances in arc-spray systems that make them suitable replacements for plasma spray and HVOF coatings.
43	Brian S. Schorr, Kevin J. Stein, and Arnold R. Marder, "Characterization of Thermal Spray Coatings," *Materials Characterization*, 1999.	This paper attempts to correlate analytical techniques to characterize the microstructures of thermal spray coatings to understand in-service properties. The authors focus on cermet thermal spray coatings and show the breakdown of carbides during spraying. This breakdown produces a mixture of oxides and various carbides. The authors also reference other papers that discuss metallographic preparation and routine analysis of thermal spray coatings to avoid erroneous porosity readings.
44	B. A. Shaw and P. J. Moran, "Characterization of the Corrosion Behavior of Zinc-Aluminum Thermal Spray Coatings," DTNSRDC/SME-84/107.	This testing was designed to illustrate the marine performance of various thermal spray alloys. Pure zinc and aluminum were control materials. The Zinc-Aluminum alloys of interest were intended to be of nominal 85/15 (weight %) zinc-aluminum. These alloys were sprayed from either a pre-alloyed 85/15 mixture or via feeding controlled amounts of each material (a pseudo-alloy) during the thermal application. Key points include: • The 85/15 wt.% ratio provides for 32 vol.% of aluminum in the alloy. • The porosity levels in the pure aluminum coatings range from 5 to 15% vs. 5% for the zinc. The lower melting point for the zinc allowed for more material "flow" before freezing on the steel substrates. This higher liquid-time tends to reduce the material porosity. • There is a drastic difference in the material microstructure between the pseudo-alloy and the pre-alloyed materials. The average material grain size is drastically smaller with the pre-alloyed material. It consists of a fine dispersion of zinc-rich and aluminum-rich areas as opposed to the larger, distinct areas of zinc and aluminum in the pseudo-alloy. • For the pseudo-alloy, there were wide variations in local material content and little true alloying in the matrix. Wight percentage variations ranged from 85% zinc/15% aluminum to 40% zinc/60% aluminum. • All of the coatings stilled showed areas of imbedded grit and voids extending to the substrate—details that must be minimized in any thermal spray application. • In seawater immersion, after 6 months, the panels with pure zinc had significantly less fouling than those coated with pure aluminum. • At 6 months of seawater immersion, the pseudo-alloy showed areas of inter-coat blistering, not at the coating-substrate interface. This appeared to be attributed to attack of the zinc material and protection of the aluminum material. This would be in accordance with the expected material passivation behavior. Chloride was found to have permeated to these sites. • For the pre-alloyed materials, the coatings started as whitish-silver materials and turned a charcoal gray. These coatings also exhibited flaking and blistering. Blisters as large as 5 mm were noted. Again, the blisters were within the coating, not at the substrate. Corrosion product was noted within the blisters. In atmospheric exposure, 2 of 15 panels showed some flaking of the thermal coating. With both exposure conditions, the attack does seem to occur along oxide layers. • For the electrochemical testing, materials were applied to both PTFE and 1018 steel substrates. There was little difference in material performance as a result of the substrate. For the aluminum, the Ecorr values stabilized at –800 mV ±50mV. For the zinc and the alloy materials, the potential was nominally in the range of –1.0 to –1.05 volts. All potentials are vs. SCE. Reported exposure periods are only 30 days. Anodic polarization data were obtained after 1-hour and 14-day immersion. After 14 days, the aluminum was found to be in a passive state. The zinc and zinc alloy materials were more active. Thus, at this time in the test, the aluminum would not be expected to provide much cathodic current vs. the zinc and zinc alloy materials.

No.	References	Comments
		• The report conclusions of note include the following: (1) the pseudo-alloy provided the best overall protection—on the basis of being able to provide current to bare steel areas at scribes, (2) the pre-alloyed 85:15 wire is not suitable for immersion service due to accelerated attack along the material oxide boundaries.
45	B. A. Shaw and P. J. Moran, "Characterization of the Corrosion Behavior of Zinc-Aluminum Thermal Spray Coatings," Corrosion 85, Paper No. 212.	This paper provides an evaluation of the corrosion behavior of zinc-15% aluminum pre-alloyed wire coating and zinc-aluminum pseudo alloy coating of approximately the same composition. This evaluation consisted of corrosion field exposures, electrochemical testing, and coating characterization (optical microscopy, scanning electron microscopy, electron probe microanalysis and X-ray diffraction). After 6 months of atmospheric and splash and spray exposure, the pseudo alloy coatings provided the better overall corrosion performance. Zinc-aluminum (and aluminum-zinc) coatings appear to be capable of combining the long-term protection provided by aluminum and the sacrificial protection provided by zinc. However, in order to obtain long-term protection, an alloy with a more coherent aluminum rich phase than the zinc-15% aluminum pre-alloyed wire and a more even distribution of phases than the pseudo alloy coating is needed.
46	H. D. Steffens and Dr. Ing, "Electrochemical Studies of Cathodic Protection Against Corrosion by Means of Sprayed Coatings."	This paper evaluates the electrochemical behavior of zinc and aluminum thermal spray coatings in seawater and sulfuric acid. Adhesion tests indicated that the adhesion of aluminum was twice that of zinc. The authors concluded that electric arc spraying, compared with flame spraying, of aluminum was more economically sound and led to better adhesion.
47	Robert A. Sulit, Ted Call, and Dave Hubert, *Arc-Sprayed Aluminum Composite Nonskid Coatings for AM-2 Landing Mats*, June 1993.	This paper discusses the use of *Duralcan* 90/10 aluminum composite nonskid coating for AM-2 Mats which are interlocking aluminum extrusions. The aluminum composite is composed of 90 vol% Al + 10 vol% Al_2O_3 (8 to 10 microns in diameter). The authors concluded that the Duralcan 90/10 nonskid coating, when compared with existing epoxy nonskid coating systems, exhibited superior wear resistance and a 30% less 20-year life cycle cost.
48	R. A. Sulit, F. West, and S. L. Kullerd, "Wire Sprayed Aluminum Coating Services in a SIMA Corrosion-Control Shop," *National Thermal Spray Conference*, September 1987.	This paper discusses the installation and operation of Corrosion-Control (CC) Shops in Navy Shore Intermediate Maintenance Activities (SIMAs) to deliver wire sprayed aluminum (WSA) coating services. The Navy-specified ambient temperature WSA coating system consists of an anchor tooth profile of 2 to 3 mils coated with 7 to 10 mils WSA, sealed with one thinned epoxy polyamide, two coats of epoxy polyamide barrier, and two coats of silicone alkyd topcoats for a total thickness of 16 to 20 mils.
49	Herbert E. Townsend, "Twenty Five Year Corrosion Tests of 55% Al-Zn Alloy Coated Steel Sheet," *Materials Performance*, April 1993.	This paper discusses the results from a long-term atmospheric corrosion test of steel sheets hot-dipped and coated with various aluminum-zinc alloy compositions. The author concluded that coatings composed of at least 44.6% aluminum exhibited a longer service life than conventional galvanizing.
50	Mark Trifel, "The Use of Metallic Protective Coatings in the Soviet Union," *News from the Field*.	This paper discusses the use of zinc and aluminum coatings on offshore (both fresh and salt water) pilings. Trifel concluded that thermal diffusion zinc coatings outperform thermal spray zinc coatings with respect to adhesion and service life. Thermal diffusion zinc coatings are applied by covering the tubes with zinc powder and increasing temperature to 680°F (360°C) for twelve hours. An average coating thickness of 4.7 mils (0.12 mm) is deposited on to the tubes. In splash zones, this coating has a service life greater than 17 years w/o sealer (25 to 30 years w/sealer). The author also concluded that aluminum coatings provide more corrosion resistance than zinc and are well suited for river water immersion. Electric arc metallizing produces more heat than flame spray and improves the adhesion of the lining.
51	A. Tsourous, "The Restoration of the Historic Trenton Non-Toll Bridge Using Field Applied Thermal Spray Coatings," *SSPC International Conference*, 1998.	This paper discusses the use of thermal spray zinc coating on an existing bridge superstructure. The project specified an SP-10 surface preparation and a minimum DFT of 8 mils. Deposition efficiency was approximately 75%. The material cost was \$0.80 per ft^2 and direct labor cost was approximately \$4.32 per ft^2. The author concluded that while application costs typically exceed those of traditional high-performance coating systems, metallizing's life cycle cost far outperforms most of these systems.
52	D. J. Varacalle and D. P. Zeek, "Corrosion Resistance of Zinc and Zinc/Aluminum Alloy Coatings," *SSPC International Conference*, 1998.	This paper studies twin wire electric arc spraying of 1/8" diameter Zn and 85:15 wt% Zn-Al wire and the suitability of such systems for anticorrosion applications. In general, the 85:15 wt% Zn-Al coating, when compared with Zn, exhibited higher bond strength, higher hardness, and higher deposition efficiency. The Zn coating exhibited higher corrosion resistance (salt spray) and higher density.
53	J. Wigren, "Grit-Blasting as Surface Preparation Before Plasma Spraying," *National Thermal Spray Conference Proceedings*, ASM International, September 1987, p. 99.	This is a general paper with several interesting conclusions: • The paper focuses on TSA adhesion as a function of surface roughness parameters. • The research shows that excessive blasting and particle embedment are concerns. • The paper concludes that the as-coated adhesion does not correlate with adhesion in service—as is the case with most coatings.
	American Welding Society References	
54	*Thermal Spray Manual*, 1996.	180-page training manual discusses the results of a National Shipbuilding Research Program performed by Puget Sound Naval Shipyard. Covers the fundamentals of thermal spraying: sequencing the job, processes, safety, and so forth.
55	*Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and their Alloys and Composites*, 1993.	30 pages provide a guide to select, plan, and control thermal sprayed coatings over steel. Discusses quality control checkpoints, maintenance and repair, job control records, and operator certification.
56	*Guide for Thermal Spray Operator Qualification*, 1992.	9 pages discuss recommended thermal spray operator qualification procedures.
57	*Thermal Spraying: Practice, Theory and Application*, 1985.	181 pages discuss thermal spraying and selection of suitable processes. Emphasis on practical shop and field procedures.
	Other References	
58	Metals Handbook - Desk Edition, ASM International, Materials Park, Ohio.	
59	NACE International Publication 1G194, "Splash Zone Maintenance Systems for Marine Steel Structures," NACE International, Houston, TX, 1994.	
60	SSPC *Volume I Good Painting Practice*, Fourth Edition, Chapter 4.4 Thermal-Spray (Metallized) Coatings for Steel, SSPS: The Protective Coatings Society, Pittsburgh, PA.	

APPENDIX D

BIBLIOGRAPHY*

	REFERENCES	COMMENTS
1	John R. Birchfield, "Stainless Steel Metallized Superheater Tubes," *Welding Design and Fabrication*, October 1985.	This paper is a case study of the use of D-gun (JETKOTE) spraying of 316 stainless steel to increase the corrosion resistance of tube assemblies.
2	M. S. J. Hashmi, C. Pappalettere, and F. Ventola, "Residual Stresses in Structures Coated by a High Velocity Oxy-Fuel Technique," *Journal of Materials Processing Technology*, 1998.	This paper discusses the use of the hole-drilling strain-gauge method to measure residual stresses that can develop in the coating. The authors concluded that the HVOF thermal spray process yields residual tensile stresses that can decrease the fatigue life of the component.
3	Robert R. Irving, "JET KOTE: A Supersonic Coating Method Ready to Take on 'D-Gun'," June 1984.	This paper discusses Thermal Dynamics' JET KOTE system and Union Carbide's D(detonation)-gun system. The JET KOTE system is a supersonic coating device capable of reaching temperatures of 5,500°F and exhaust velocities of 4,500 fps. The author discusses the advantages and disadvantages of JET KOTE, D-gun, and plasma. The JET KOTE system reportedly gives harder coatings than those produced by D-gun and plasma spray.
4	Robert A. Kogler, J. Peter Ault, and Christopher L. Farschon, "Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges," Federal Highway Administration Report FHWA-RD-96-058, January, 1997.	Abstract: The recently promulgated environmental regulations concerning volatile organic compounds (VOC) and certain hazardous heavy metals have had a great impact on the bridge painting industry. As a response to these regulations, many of the major coating manufacturers now offer "environmentally acceptable" alternative coating systems to replace those traditionally used on bridge structures. The Federal Highway Administration sponsored a 7-year study to determine the relative corrosion control performance of these newly available coating systems. A battery of accelerated laboratory tests was performed on candidate coating materials with a maximum VOC content of 340 g/L (2.8 lbs./gal). Accelerated tests included cyclic salt fog/natural marine exposure, cyclic brine immersion/natural marine exposure, and natural marine exposure testing. Natural exposure test panels were exposed and evaluated for a total of 6.5 years. The most promising coating systems were selected for long-term field evaluation based on accelerated test performance. The long-term exposure testing was conducted for 5 years in three marine locations. Panels were exposed on two bridges, one in New Jersey and one in southern Louisiana. The third long-term exposure location was in Sea Isle City, New Jersey. Thirteen coating systems were included for long-term exposure testing. These included 2 high-VOC controls and 11 test systems having a VOC level of 340 g/L (2.8 lbs./gal) or less. Five of the test systems contained high-solids primers, two of the test systems contained waterborne primers, one system was based on a powder, and three systems were metallizing. The best performing systems were the three metallized coatings. These were initially less aesthetic than coating systems with high-gloss topcoats, but they displayed near-perfect corrosion performance after 5 to 6.5 year exposure periods. Of the traditional liquid applied coating systems, those incorporating inorganic zinc primers performed the best over near-white blasted and power-tool cleaned surfaces. High-solids epoxy coatings had a tendency to undercut at intentional scribes and rust worse than coatings with zinc-rich primers over less than ideal surface preparations. Current bridge painting methodologies and corrosiveness of various bridge substructures were investigated. Various bridge maintenance painting options were evaluated on a life-cycle cost basis using data developed in the program. The analysis points to the potential advantages of long-term durable coatings such as metallizing and alternative painting practices such as zone painting.
5	P. A. Kulu and T. A. Khalling, "Flame Spray Coatings on Powder Metallurgy Materials," 1987.	This paper discusses the method of application and properties of fused coatings on powder metallurgy materials.
6	S. Lathabai, M. Ottmüller, and I. Fernandez, "Solid Particle Erosion Behavior of Thermal Sprayed Ceramic, Metallic and Polymer Coatings," *Wear*, 1998.	This paper studies the role of particle properties, such as hardness and shape in slurry and airborne erosion, on thermal sprayed coatings. The authors concluded that hard, angular particles cause more severe damage than softer, more rounded particles. Coating properties, such as hardness, do not exhibit a correlation with erosion rates. However, coating microstructure and defect population influence erosion mechanisms.
7	Clifford F. Lewis, "Processing Makes the Difference in Thermal Spray Coatings," *Materials Engineering*, August 1988.	This paper discusses various methods to apply thermal spray coatings. Methods discussed include Union Carbide's D-gun and Stoody Deloro Stellite, Inc.'s JET KOTE II hypervelocity oxy-fuel (HVOF) system and plasma spray. One of the benefits of JET KOTE II is the ability to control oxide content with the choice of fuel.
8	"Thermal Spraying with Zinc and Zinc/Aluminum Alloy Wire," *Metallize*, The Platt Brothers and Company.	The Platt Brothers & Company is a manufacturer of zinc and zinc alloyed wire used in the thermal spray process. Platt publishes *Metallize*, a quarterly newsletter to promote the advantages of zinc thermal spraying. This particular issue discussed comparative studies of various thermally sprayed materials at dams and canals. The newsletter, in these applications, obviously concluded that thermal spray zinc and zinc alloys exhibited superior performance when compared with conventional paint coatings, coal tar enamel, emulsion and epoxy, aluminum-bronze coatings, and stainless steel coatings. In one case, a service life between 100 and 200 years was estimated for the zinc thermal spray coating.
9	K. V. Rao, "Characteristics of Coatings Produced Using a New High Velocity Thermal Spray Technique," October, 1985.	This paper discusses the JET KOTE thermal spray technique when it was new. JET KOTE relies on continuous internal combustion of oxygen and a fuel to produce a high velocity exhaust jet stream. The author focuses on four JET KOTE coatings: WC-12%Co, WC-17%Co, TRIBALOY® alloy T-800, and HASTELLOY® alloy C.
10	Ronald W. Smith and Richard Knight, "Thermal Spraying I: Powder Consolidation – from Coating to Forming," *JOM*, August 1995.	This article discusses thermal spray processes and characteristics. The authors present a range of thermal spray processes and the materials systems that are able to be produced.

	REFERENCES	COMMENTS
11	Ronald W. Smith and Richard Knight, "Thermal Spraying II: Recent Advances in Thermal Spray Forming," *JOM*, April 1996.	This article discusses the economics and reliability concerns over material structure, uniformity, and materials properties associated with thermal spray formings.
12	Yu N. Tyurin, A. D. Pogrebnjak, "Advances in the Development of Detonation Technologies and Equipment for Coating Deposition," *Surface and Coating Technologies*, 1999.	This paper discusses new devices and methods for plasma detonation deposition of coatings which give a permanent delivery of gases and powders into the combustion chamber. The authors focus on α-Fe_2O_3 and WC(88%)-Co(12%) coatings. It was concluded that while plasma detonation technology may be used in various applications, an increased concentration of the γ-phase and other metastable phases in the Al_2O_3 coating reduce its micro-hardness, wear resistance, and corrosion resistance while, at the same time, improving its density and adhesion to the substrate. Thus, care must be taken to control the parameters to produce the desired coating characteristics.
13	D. J. Varacalle, Jr., D. P. Zeek, G. S. Cox, D. Benson, K. W. Couch, E. Sampson, and V. Zanchuck, "Twin Wire Arc for Infrastructure," *J. Therm. Spray Technol., Vol 7 (No.4)*, December 1998.	Accelerated corrosion testing was performed to evaluate arc sprayed 85:15 wt% Zn-Al and 70:30 wt% Zn-Al coatings. Experiments were performed to evaluate coating performance as a function of process conditions (nozzle diameter, spray distance, current, etc.).
14	D. J. Varacalle, Jr., D. P. Zeek, V. Zanchuck, E. Sampson, K. W. Couch, D. M. Benson, and G. S. Cox, "Zinc and Aluminum Coatings Fabricated with the Twin-Wire Electric Arc Spray Process," *SSPC International Conference*, 1997.	This paper discusses the suitability of zinc and aluminum coatings, applied by a twin-wire arc process, for corrosion protection. The authors performed a sequential regression analysis to establish a relationship between process parameters (orifice diameter, gun pressure, current, and spray distance), coating microstructural attributes, and corrosion performance. This analysis generally indicated that corrosion resistance increased with increasing porosity and lower oxide content. However, the authors concluded that, based on confirmation testing, the combination of lower porosity and lower oxide content mitigates corrosion.
15	"Preparing Flame-cut Edges for Thermal Spray," *Journal of Protective Coatings and Linings*, Problem Solving Forum, May 2002, pp. 17–18	Question and answer article. Responses are uniform in recommending that flame cut edges be ground to remove the hardened layer formed from flame cutting. Unless this is done, the hardened layer (having a hardness of Rc 50 or more) will prevent adequate profile from being formed.
16	H. X. Zhao, H. Goto, M. Matsumura, T. Takahashi, M. Yamamoto, "Slurry Erosion of Plasma-Sprayed Ceramic Coatings," *Surface and Coatings Technology*, 1999.	This paper investigates the effects of slurry erosion on ceramic coatings under different plasma spray conditions. The authors concluded that ceramic coatings, such as Al_2O_3 and Cr_2O_3, generally exhibit improved wear resistance, but become significantly weakened under normal impact conditions. Also, slurry resistance varied with different plasma spray methods. Methods (using a "jet-in-slit type apparatus) were used to assess the slurry erosion properties quantitatively and qualitatively.
	National Association of Corrosion Engineers (NACE) International References	
17	*Classic Papers and Reviews on Anode Resistance Fundamentals and Applications*, 1986.	This book provides a compilation of technical papers on anode resistance. These papers discuss fundamentals of anode resistance and specific applications including ships and offshore platforms.
18	*Innovative Ideas for Controlling the Decaying Infrastructure*, 1995.	This book provides a compilation of papers presented at the NACE symposium held in Orlando, Florida in March 1995. These papers discuss case histories and innovative and cost-effective ideas for resolving corrosion problems in marine environments.

* Bibliography not verified by TRB.

THERMALLY SPRAYED METAL COATING GUIDE

CONTENTS

1 INTRODUCTION

The U.S. Army Corps of Engineers and a consortium of three technical societies (AWS [American Welding Society], NACE [National Association of Corrosion Engineers] International, and SSPC [The Society for Protective Coatings]) have developed metallizing guides. They are *Thermal Spraying: New Construction and Maintenance* (U.S. Army Corps of Engineers, Washington, D.C., January 29, 1999) and "Guide for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel" (ANSI/AWS C2.18A-XX, SSPC CS 23.00A-XX, and NACE International TPX #XA), which is currently under development. These guides provide detailed information about metallizing in general. The objective of this guide is to compile existing information about metallizing into a form directed toward steel piling designers and users. The guide is intended to focus on the specialized needs of steel pilings:

- The presence of edges and crevices,
- Geometric shapes,
- Different exposure zones and interactions between zones,
- Abrasion/erosion factors, and
- The effect of mechanical damage to coating.

This guide covers the procedures for the application and use of thermally sprayed metal coatings (TSMCs) for corrosion control applications on piles used in highway construction. Surface preparation, materials selection, test methods, and field repair are also discussed. The guide provides the information necessary for a user to select, specify, and apply a metallized coating for steel piles in freshwater, brackish water, or seawater environments. This guide contains

- Information needed to successfully apply thermally sprayed metal technology to the corrosion protection of steel piles used in highway construction.
- A brief description of metallizing and the various methods of applying metallic coatings to steel, emphasizing the most appropriate means of both shop and field application of metallic coatings to steel piles. This guide discusses only wire-arc and wire-flame spray techniques because these are the most effective techniques for coating steel piles.
- Descriptions of appropriate TSMCs, their life expectancies under various exposure conditions, methods of application, and any specific advantages and disadvantages.
- A discussion of coating selection.
- A listing of specifications and existing documents useful in the selection and application of TSMCs.
- Applicator, equipment, and inspector qualifications and certifications.
- Surface preparation methods and equipment.
- Application methods, equipment, and tolerances.
- A review of sealer coatings and a generic specification.
- Inspection and quality control (QC) requirements.
- A review of the effects of mechanical damage and maintenance and repair methods.
- Safety and environmental considerations.
- Glossary/definitions of terms and abbreviations.

2 SAFETY AND ENVIRONMENTAL

2.1 Introduction

Surface preparation, thermal spraying, and sealing and painting operations expose workers to numerous potential health and safety hazards. Common health and safety hazards associated with the industry include (a) electric shock; (b) flammable and explosive solvents, gases, and fine particulate dusts and fumes; (c) confined space entry; (d) fall hazards; (e) exposure to high- intensity noise, ultraviolet light, and toxic materials; and (f) high-velocity particle impingement.

While this guide does not purport to address all of the safety issues regarding TSMCs and their application, some of the more important safety concerns associated with the process are discussed below. It is recommended that all personnel involved with the thermal spray process be familiar with safe working practices and safety regulations in current standards and guides. These standards and guides include, but are not limited to, documents from the American National Standards Institute (ANSI), the American Welding Society (AWS), the Coast Guard Academy (CGA), the military, the National Association of Corrosion Engineers (NACE), the National Fire Protection Association (NFPA), the Occupational Safety and Health Administration (OSHA), and the Society for Protective Coatings (SSPC). Also refer to the U.S. Army Corps of Engineers's Manual, *Safety—Safety and Health Requirements*, EM 385-1-1, Washington, D.C., November 3, 2003. Some of these standards are listed in Section 10 of this guide.

2.2 Blast Cleaning

2.2.1 Equipment Maintenance and Use

Maintain abrasive blast machines and equipment in accordance with the manufacturers' recommendations. Tag and remove from service worn or damaged components pending replacement or repair.

2.2.1.1 Hose connections. Use hoses and hose connections that do not allow electrostatic discharge. Use hose couplings and nozzles designed to prevent accidental disconnection. Use a "deadman" control device that automatically shuts off the flow of air and abrasive when the hose is dropped. Inspect hoses and fittings used for abrasive blasting frequently to ensure the timely replacement of worn parts and equipment.

2.2.1.2 Hose use. Blast hoses shall be kept as straight as possible. Use a large radius of curvature for any bends so as to avoid excessive friction and wear. Store hoses in cool dry areas to avoid accelerated degradation. Never point the blast nozzle at the body parts of any person. Relieve air pressure in the blast tank and system before working on the system. Use a "tag-out" labeling system during system maintenance.

2.2.1.3 Ventilation. Provide mechanical ventilation in blasting operations that are not performed in the open or in a properly designed and ventilated room.

2.2.2 Personal Protective Equipment

Wear respiratory protective devices—helmets, hand shields, eye protection (face shields or goggles), and appropriate protective clothing—during all blasting operations. For blasting in the open, use a mechanical filter respirator in conjunction with face shields and dust hoods. Alternatively, an air-line respirator may be used. For blasting in confined or enclosed spaces, a continuous flow air-line respirator, a full-face piece or helmet, and dust hood are required.

2.2.2.1 Respirators. The guidelines listed below should be followed when using respirators.

- Compressed air should meet at least the requirements of the specification for Type 1, Grade D breathing air as described in CGA G 7.1 "Commodity Specification for Air."
- Respiratory protection shall be in accordance with ANSI Z88.2.
- All respiratory devices shall comply with the U.S. Bureau of Mines and the National Institute for Occupational Safety and Health (NIOSH). Respirators selected from those currently approved and certified by NIOSH/Mine Safety and Health Administration (MSHA) Section 134 should be used.
- Use NIOSH-certified Type CE respirator and Type CE hood (air-line-supplied air hood with faceplate and devices to protect the wearer's eyes, face, chin, neck, shoulders, and upper body from rebounding abrasive blasting media).
- Note: Personnel using/wearing respirators require "fit-testing" before they can legally work under these conditions. Also, beards can affect the efficacy of respirators.

2.2.2.2 Eye and body protection. The guidelines listed below should be followed when using eye and body protection.

- Head protection shall be in accordance with ANSI Z89.1. Face shields or helmets shall be equipped with dust hoods to protect the eyes, face, chin, and neck.
- Personnel in or near blasting operations should wear helmets, handshields, faceshields, or goggles conforming to ANSI Z87.1 and eye protection conforming to ANSI Z89.1.
- Appropriate protective clothing shall be worn during spray operations. Clothing should be strapped tightly around wrists and ankles to prevent contact with abrasive dust. Open shirt collars and unbuttoned pocket flaps are unacceptable. High-top shoes should be worn and cuff-less trousers should cover the tops.
- Blasting operators should wear heavy canvas or leather gloves and an apron or coveralls. Approved safety shoes should be worn to protect against foot injury.

2.2.2.3 Hearing protection. Noise levels generated during blasting and thermal spray operations can cause temporary or permanent hearing loss, damage, and fatigue.

- Wear approved earmuffs and properly fitted approved earplugs when thermal spray operators and personnel are in the immediate vicinity of thermal spray operations to reduce the high-intensity noise levels to acceptable conditions.
- All personnel in the vicinity of blasting operations shall be provided with hearing protection if the noise exposure exceeds the limitations established by OSHA in paragraph 1910.95, "Occupational Noise Exposure".

2.2.3 Cleaning with Compressed Air

Cleaning with compressed air should be restricted to systems where the air pressure has been reduced to 204 kPa (30 psi) or less. Cleaning operators should wear safety goggles or a face shield, hearing protection, and appropriate body covering. Compressed air or pressurized gas nozzles should never be pointed at other personnel or at exposed skin.

2.2.4 Cleaning with Solvents

The guidelines listed below should be followed when cleaning with solvents.

- The material safety data sheet (MSDS) for each solvent used must be readily available and should be consulted for specific solvent information, handling, and storage and disposal procedures, in addition to those listed here.
- Flammable liquids with a closed-cup test flash point below 100°F (38°C) should not be used for cleaning purposes.
- Sources of ignition should not be permitted in the vicinity of solvent cleaning if there is any indication of combustible gas or vapor present.
- Measurements should be made to ensure that solvent vapors are not present during thermal spray operations, especially in confined spaces. Representative air samples should be collected from the breathing zone of workers involved in the cleaning process to determine the specific solvent vapor concentrations.
- Worker exposures should be controlled to levels below the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit, as indicated in CFR 29 Part 1910, Section 1000.

2.3 Thermal Spraying

2.3.1 Safety Issues

Airborne metal dusts and fumes, finely divided solids, or other particulate accumulations should be treated as explosive materials. Proper ventilation, good housekeeping, and safe working practices should be maintained to prevent the possibility of fire and explosion. Thermal spray equipment should never be pointed at personnel or flammable materials. Thermal spraying should not be performed in areas where paper, wood, oily rags, or cleaning solvents are present. Electrically conductive safety shoes should be worn in any work area where an explosion is a concern. During thermal spray operations, including the preparation and finishing processes, employees should wear approved protective coveralls or aprons, hand protection, eye protection, ear protection, and respiratory protection.

SAFETY PRECAUTION: The fine aluminum and zinc particulates (metal dust and fume) produced during thermal spraying may be an extreme explosion hazard. Special precaution should be taken during wire-arc spraying due to the higher amounts of metal dust and fume produced that accompany higher spray rates, especially if multiple wire-arc spray units are being used in the same work area. **Do not use water to extinguish aluminum or zinc fires. Use dry sand or a Class D extinguisher.**

2.3.2 Personal Protective Equipment

The general requirements for the protection of personnel involved with thermal spraying are the same as those specified for welders in ANSI/AWS Z49.1, "Safety in Welding and Cutting." Helmets, hand shields, eye protection (face shields or goggles), hearing protection, respirators, and appropriate protective clothing shall be worn during all spraying operations.

2.3.2.1 Eye and skin protection. All thermal spray processes introduce particulates and fumes into the air that may irritate and damage the eyes or skin. The processes also emit hazardous ultraviolet (UV), infrared (IR) and intense visible light radiation.

- Eye and face protection must be worn to protect against particulate impingement. Hoods or face shields conforming to ANSI Z87.1 and ANSI Z89.1 with filter lenses should be worn to protect the face and eyes. Various shades of lens filters are recommended based on the type of thermal spray process being used:

  – For wire-flame spray, use lens shades 2 to 4.
  – For wire-arc spray, use lens shades 9 to12.
  – Shades 3 to 6 can be used for wire-arc spray if the gun is equipped with an arc shield. The shield encloses the arc and reduces the operator's exposure to the high-intensity light radiation.

- Other workers in the vicinity of the thermal spray applicator should also use proper eye protection.
- Flame-resistant clothing should be worn to protect the skin. Clothing should be strapped tightly around the wrists and ankles to prevent contact with sprayed materials. Open shirt collars and unbuttoned pocket flaps are unacceptable. High-top shoes should be worn, and cuff-less trousers should cover the shoe tops. Protection against radiation from the spray process is detailed in ANSI/AWS Z49.1.
- Aluminized clothing may be used with the following precautions:

  – IR and UV radiation are not to be reflected onto unprotected skin.
  – Provide suitable protection against electric shock.

2.3.2.2 Hearing protection. Thermal spray produces very high noise levels (up to 130 dBA) that can rapidly cause permanent hearing loss.

- Thermal spray operators and other workers in the vicinity of the thermal spray operation should wear approved hearing protection at all times.
- Protection against the effects of noise exposure should be provided in accordance with the requirements of EM 385-1-1, Section 5, "Personal Protective and Safety Equipment," Subsection 05.C, "Hearing Protection and Noise Control," and CFR 29 Part 1910, Section 95.
- Insert earplugs should be used during wire or powder flame spray. Insert earplugs should be worn as a minimum protection during wire-arc spraying. Insert earplugs and approved earmuffs are recommended for use with wire-arc, plasma, and high-velocity oxygen fuel

(HVOF) spray. Table 1 lists the minimum recommended hearing protection devices for various thermal spray application methods.

2.3.2.3 Respiratory protection. Thermal spray generates toxic dusts and fumes. Thermal spray operators and personnel in the general vicinity of the spraying operation should wear appropriate approved respirators. Overexposure to zinc fume is known to produce flu-like symptoms, often called “metal fume fever.”

- An approved mechanical filter type respirator shall be used when spraying nontoxic materials with dust and metal-fume exposure. When spraying in confined spaces, an air-line respirator shall be used. When spraying highly toxic materials, the air-line respirator shall be equipped with an emergency auxiliary cylinder of respirable air. Respiratory protection shall be in accordance with ANSI Z88.2.
- All respiratory devices used shall comply with the U.S. Bureau of Mines and the National Institute for Occupational Safety and Health (NIOSH).

2.3.3 Wire-Arc Spray

2.3.3.1 Electrical shock prevention. High DC voltages and amperages (currents) inherent to the wire-arc spray process pose severe electrical hazards. The operator shall be thoroughly trained in the safe operation of the wire-arc spray equipment prior to its use.

- The manufacturer’s safe operating procedures should always be followed.
- Ground protection for equipment and cords should be present, in good condition, and tested regularly for correct operation.
- Electrical outlets should have ground fault circuit interrupters (GFCIs) in addition to appropriate over-current protection (e.g., fuses and circuit breakers). Electrical circuit grounds and GFCIs should be tested before work begins and tagged, reported, and not used if found to be faulty.
- Switches and receptacles should have proper covers.
- Buttons, lights, plugs, and cables shall be in compliance with ANSI/NFPA 70, “National Electrical Code.” Periodic inspections of cables, insulation, and hoses shall be performed. Damaged components shall be tagged, removed from service, and immediately repaired or replaced.
- Cords should be approved for outdoor or wet or damp locations. The cords should be hard usage or extra hard usage as specified in ANSI/NFPA 70 “National Electrical Code.” Cords should not be spliced.
- Arc guns and power supplies should be cleaned frequently, as per the manufacturer’s recommendations, to remove build-ups of metallic dusts, which may cause short circuits.

TABLE 1 Typical noise levels and hearing protection requirements

Thermal Spray Process	Noise Level, dB(A)	Minimum Recommended Protection
Wire-flame spraying	114	Earplugs
Wire-arc	111–116	Earplugs and earmuffs

2.3.4 Flame Spray

2.3.4.1 Gas cylinder safety. To ensure gas cylinder safety, the guidelines listed below should be followed.

- Compressed gas cylinders should be handled in accordance with ANSI Z49.1 and with CGA P-1.
- Only special oxidation-resistant lubricants should be used with oxygen equipment; grease or oil should not be used.
- Manifolds, pressure-reducing regulators, flow meters, hoses, and hose connections should be installed in accordance with ANSI Z49.1.
- A protective shield should be used to shield glass tube flowmeters from the spray gun.
- Pressure connecting nuts should be tight, but not overly tight. Fittings that cannot be sealed without excessive force should be tagged and replaced.
- Compressed air for thermal spraying or blasting operations should only be used at pressures recommended by the equipment manufacturers. The air-line should be free from oil and moisture.
- Compressed air, oxygen, or fuel gas should never be used to clean clothing.
- Cylinders should be handled, stored, and secured in accordance with established regulations and safe working practices.
- Hoses used with flammable gases shall be fitted with approved "flash-back" arrestors to prevent any flame burning back along the hoses from reaching the cylinders.

2.3.4.2 Flame spray safety. To ensure flame spray safety, the guidelines listed below should be followed.

- Flame spray equipment should always be maintained and operated according to the manufacturer's instructions. Thermal spray operators should be trained and familiar with their equipment before starting an operation.
- Valves should be properly sealed and lubricated.
- Friction lighters, pilot lights, or arc ignition methods of lighting flame spray guns should be used.
- If the flame spray gun backfires, it should be extinguished immediately. Re-ignition of a gun that has backfired or blown out should not be attempted until the cause of the trouble has been determined and remedied.
- Flame spray guns or hoses should not be hung on regulators or cylinder valves. Gas pressure should be released from the hoses after the equipment is shut down or when equipment will be left unattended.
- Lubricating oil should not be allowed to enter the gas mixing chambers when cleaning flame spray guns.
- Do not light wire-flame and rod guns without wire or rod in the nozzle as flames may burn back into the gun, causing operator injury and equipment damage.

2.3.5 Ventilation

Thermal spraying should only be performed by operators using appropriate respiratory protection and in locations with adequate ventilation.

- Local exhaust or general ventilation systems should be used to control toxic fumes, gases, or dusts in any operations not performed in the open. Thermal spraying in an enclosed space should be performed with general mechanical ventilation, air-line respirators, or local exhaust ventilation sufficient to reduce the fumes to safe limits specified by ACGIH-02.
- Personnel exposures should be controlled to the safe levels recommended by ACGIH-02 or prescribed by CFR 29 Part 1910, whichever is the more stringent.
- Air sampling should be performed before entry of personnel into a confined space, during confined-space entry that involves contaminant-generating operations such as flame spraying, and in areas where ventilation is inadequate to ensure that air contaminants will not accumulate.
- Engineering controls (enclosures and/or hoods with ducted, mechanical ventilation of sufficient volume to remove contaminants from the work space) are the most desired methods of preventing job-related illness resulting from breathing air contaminated with harmful dusts, mists, fumes, vapors, and/or gases.
- Treat airborne metal dusts, finely divided solids, or their accumulations, as explosives. Use adequate ventilation in the thermal spray work area and collect overspray to minimize the danger of dust explosions and fires. In shop environments, wet, bag, and dry filter-cartridge type collectors may be used to collect the fine overspray particles, thus minimizing the explosion and fire hazard and release of controlled and/or hazardous materials. Keep bag- and filter-cartridge collector units at least 50 ft (15 m) away from the spraying area to preclude ignition from the flame or heat of the thermal spray process.
- Thermally sprayed aluminum and zinc powders, nominally 40 to 110 µm (0.0016 to 0.0044 in.) in diameter, are not a combustion or explosive hazard when handled and used in accordance with a powder manufacturer's instructions. Refer to the Aluminum Association's recommendations for the safe storage and handling of aluminum powders.
- All fans, pipes, dust arrestors, and motors should be properly grounded. Ground to piping that carries fuel gases or oxygen should not be used. Ventilating fans should be kept running when cleaning out spray booths, pipes, etc., to prevent the accumulation of dust or fumes in the system. Aluminum and magnesium dusts present an explosive hazard that requires special attention. Adequate wet collector systems should be used with either of these metals. Care should be exercised, since these metallic dusts may generate hydrogen gas on contact with water. These systems should be designed to prevent hydrogen accumulation. Frequent, scheduled, cleanout operations should be performed to reduce residues. Residues should be handled and disposed of in accordance with OSHA and EPA regulations.

2.4 Housekeeping

2.4.1 Thermal Spraying Area

Remove paper, wood, oily rags, cleaning solvents, sealers, and paints from the thermal spraying area.

2.4.2 Shop and Field Work Areas

Good housekeeping in the shop and field work areas should always be maintained to ensure proper storage of hazardous materials and to avoid accumulation of combustible or potentially explosive materials and metal dusts, and particular attention should be given to inspecting for dust build-ups on beams, rafters, booth tops, and in floor cracks.

2.5 Sealers and Topcoats

2.5.1 Solvents

Solvents used for cleaning or to apply sealers or topcoats (e.g., acetone, xylene, or alcohol) emit vapors that are harmful and can be fatal.

- Use only with adequate ventilation or proper respiratory protection and other protective clothing as needed.
- Avoid breathing solvent vapors and skin contact with solvents.
- Most solvents are also flammable liquids. All solvent tanks must have lids and be covered when not in use. Take proper safety precautions.
- Keep all solvents and flammable materials at least 50 ft (15.2 m) away from welding, oxyfuel cutting and heating, and thermal spraying operations.

2.5.2 Spray Application

Sealers and paint coats are typically applied by spray application. Spray application is a high-production rate process that may rapidly introduce very large quantities of toxic solvents and vapors into the air.

- Airless spray systems operate at very high pressures. Very high fluid pressures can result in penetration of the skin on contact with exposed flesh.
- Tip guards and trigger locks should be used on all airless spray guns. The operator should never point the spray gun at any part of the body.
- Pressure remains in the system even after the pump is turned off and can only be relieved by discharging or "blow-down" through the gun.

2.6 Material Safety Data Sheets (MSDSs)

The contractor should maintain current MSDSs for all materials used on the job. These materials include cleaning solvents, compressed gases, thermal spray wires or powders, sealers, thinners, and paints or any other materials required to have an MSDS as specified in CFR 29 Part 1910, Section 1200. The MSDSs should be readily available to all personnel on the job site in a clearly labeled folder.

2.7 Environmental

2.7.1 Regulations

Federal, state, and local regulations may be applicable with regard to containment, storage, and disposal of blasting debris and metallizing emissions. This may include partial or complete containment of the work site for surface preparation and thermal spraying and the collection and safe disposal of used blasting media and thermal spray overspray. Ensure compliance with the purchaser's requirements and all pertinent government agency requirements and regulations for air-quality and hazardous-materials control.

2.7.2 Handling Debris

The applicator and the purchaser should coordinate the specific requirements, responsibilities, and actions for the containment, storage, collection, removal, and disposal of the debris produced by the TSMC operations.

2.7.3 Lead in Coating

The removal of old coating containing lead requires special treatment. Further information is available in Chapter 11 of the U.S. Army Corps of Engineers Engineering and Design Manual, *Painting: New Construction and Maintenance*, EM 1110-2-3400, Washington, D.C., April 30, 1995.

3 COATING MATERIALS AND SELECTION

3.1 Alloy Selection

TSMCs are used for the protection of the exposed surfaces of iron and steel components used in various corrosive environments. Long-term protection in excess of 20 years in both industrial and marine exposures has been documented. Zinc, aluminum, and zinc/aluminum alloy coatings provide sacrificial corrosion protection to a steel substrate, even when areas of the substrate are exposed to the corrosive environment. The relatively low corrosion rates of these coatings, in combination with the sacrificial corrosion protection that they offer, make them suitable for use in such harsh environments.

Zinc has a higher electrochemical activity than aluminum has and thereby provides a higher level of cathodic protection to a steel substrate than does aluminum. Aluminum, with its lower electrochemical activity and adherent oxide film formation, provides a lower level of cathodic protection to a steel substrate. Electrical conductivity and pH contribute to the corrosivity in immersion environments. Due to the relatively high electrical conductivity of natural seawater, aluminum is the recommended thermal spray coating material for this environment. The higher galvanic interaction of zinc with the steel corresponds to a higher consumption rate in seawater immersion. In a freshwater environment, where the electrical conductivity is lower, zinc or 85 : 15 weight percent (wt%) zinc/aluminum alloy coating will provide a better balance between cathodic protection and barrier protection and is the recommended thermal spray coating material.

3.1.1 Types of Exposure and Suitable Alloys

Foreknowledge of the environmental stresses to which the protective coating system will be exposed is critical for the proper selection of the coating system. This is true of both paint and thermally sprayed coating systems. Exposure environments typically encompass one or more of the following environmental stresses: extremes of temperature, high levels of humidity, complete or partial or intermittent immersion, extremes of pH, solvent exposure, wet/dry cycling, thermal cycling, ultraviolet exposure, impact and abrasion, cavitation/erosion, and special exposures. The service environment is the single most important consideration in the selection of a coating system. Table 2 provides a summary of thermal spray metal coatings selection recommendations. Table 2 lists several environmental categories. It should be recognized that, particularly in atmospheric environments, a single category might not represent a particular environment. Moisture, wind direction, solar radiation, and local pollution effects (e.g., groundwater runoff discharge pipes and industrial drainage) can create microclimates that will affect the performance of materials and coatings. These conditions must be recognized in the selection of the proper coating.

3.1.1.1 Atmospheric high humidity. High humidity is often accompanied by condensation, which is considered to approximate the severity of freshwater immersion. An 85 : 15 wt% zinc/aluminum wire-arc spray coating to a thickness of 12 mils (305 µm) is the recommended thermal spray system for high-humidity environments. Typically, high-performance paint

TABLE 2 Thermally sprayed metal coating selection guide for 20- to 40-year life

Environment	Coating	Thickness mils [μm]	Sealer*
Atmospheric			
Rural	Zinc or zinc-aluminum	6–8 [150–200]	No
Industrial	Zinc or zinc-aluminum	12–15 [305–380]	Yes
Marine	Aluminum or zinc-aluminum	12–15 [305–380]	No
Immersion			
Freshwater	Zinc-aluminum	12–15 [305–380]	Yes
Brackish Water	Aluminum	12–15 [305–380]	No
Seawater	Aluminum	12–15 [305–380]	No
Alternate Wet-Dry			
Freshwater	Zinc-aluminum	10–12 [250–305]	Yes
Seawater	Aluminum	12–15 [305–380]	Yes
Abrasion	Zinc-aluminum	14–16 [355–405]	Yes
Condensation	Zinc or zinc-aluminum	10–12 [250–305]	Yes

* See Section 6, "Sealer Selection and Application," for further information.

systems, such as the epoxy and vinyl systems, are specified for high-humidity applications. Because paint systems are generally less costly to apply, they are more likely to be used for these types of exposures. However, the 85 : 15 wt% zinc/aluminum thermal spray system should have a longer service life than paint coatings for this application.

3.1.1.2 Wet/dry cycling. A zone of alternating wet and dry is generally the most corrosive zone due to macrocell corrosion. This type of exposure is found in splash zones and tidal zones. Most TSMC systems will provide adequate protection under such conditions. Sealing and topcoating of the TSMC is generally recommended for such exposures.

3.1.1.3 Immersion. Immersion exposures range from immersion in deionized water to immersion in natural waters, including freshwater and seawater. Ionic content and pH contribute to the corrosivity of immersion environments. Typical sealers and topcoats are vinyl paints and coal tar epoxy coatings. Several epoxy and vinyl systems are appropriate for various immersion exposures depending on whether the water is fresh or salt and the degree of impact and abrasion. Epoxy systems are preferred for saltwater exposures, whereas the vinyl systems are generally preferred for freshwater exposures, especially where the level of impact and abrasion is significant.

- **Seawater.** Wire-arc sprayed aluminum to a coating thickness of 10 mils (250 μm) is recommended for seawater immersion. Aluminum thermal spray has been used extensively by the offshore oil industry to protect immersed and splash zone platform components from corrosion. Aluminum thermal spray is thought to perform better in seawater immersion without an organic sealer and paint topcoat, and some specifications, such as U.S. Army COE CEGS-09971, recommend not using a sealer in seawater immersion. Wire-arc sprayed aluminum is the recommended thermal spray system for this application.

- **Freshwater.** Wire-arc sprayed 85 : 15 wt% zinc/aluminum to a coating thickness of 12 mils (300 µm) is recommended for freshwater immersion. These systems can be used either with or without sealers and topcoats. The 85 : 15 wt% zinc/aluminum system combines the superior corrosion resistance of zinc and the improved impact and abrasion resistance of aluminum. Seal coats and paint topcoats may be used to add a further degree of protection to the TSMC systems used in freshwater immersion, but their use is not considered an absolute necessity.

3.1.1.4 Ultraviolet exposure. Resistance to ultraviolet (UV) radiation–induced degradation is an important aspect of coating performance. All thermally sprayed coatings are essentially unaffected by UV radiation. Organic sealers and topcoats used over TSMCs will be affected the same way as any other paint materials of the same type. Organic paint coatings are affected by UV radiation to varying degrees. Depending on the coating resin and pigmentation types, UV degradation may result in loss of gloss, color fading, film embrittlement, and chalking. Certain paints, including silicone and aliphatic polyurethane coatings, may exhibit superior UV resistance. Some coatings, including most epoxies and alkyds, have fairly poor UV resistance. The properties of a specific coating must be considered when selecting a coating that must have UV light resistance.

3.1.1.5 Impact and abrasion. Impact and abrasion are significant environmental stresses for any coating system. Abrasion is primarily a wear-induced failure caused by contact of a solid material with the coating. Examples include foot and vehicular traffic on floor coatings, ropes attached to mooring bitts, sand particles suspended in water, and floating ice. When objects of significant mass and velocity move in a direction normal to the surface as opposed to parallel, as in the case of abrasion, the stress is considered to be an impact. Abrasion damage occurs over a period of time, whereas impact damage is typically immediate and discrete. Many coating properties are important to the resistance of impact and abrasion including adhesion to the substrate, cohesion within the coating layers, toughness, ductility, and hardness. Thermally sprayed coatings of zinc, aluminum, and their alloys are very impact resistant. Zinc metallizing has only fair abrasion resistance in immersion applications because the coating forms a weakly adherent layer of zinc oxide. This layer is readily abraded, which exposes more zinc, which in turn oxidizes and is abraded; 85 : 15 wt% zinc/aluminum is more impact/abrasion resistant than pure zinc or pure aluminum.

3.2 Concerns Related to Performance of the TSMC

3.2.1 Limits on Surface Preparation

Coating selection may be limited by the degree or type of surface preparation that can be achieved on a particular structure or structural component. Because of physical configuration or proximity to other sensitive equipment or machinery, it may not always be possible to abrasive blast a steel substrate. In such cases, other types of surface preparation, such as hand tool or power tool cleaning, may be necessary, which, in turn, may place limits on the type of coatings that may be used. In some cases, it may be necessary to remove the old coating by means other than abrasive blasting, such as power tools, high-pressure water jetting, or chemical strippers. These surface preparation methods do not impart the surface profile that is needed for some types of coatings to perform well. In the case of thermally sprayed coatings, a high degree of surface preparation is essential. This kind of preparation can only be achieved by abrasive blasting using a good-quality, properly sized angular blast media. Thermal spraying should never be selected for applications in which it is not possible to provide the highest quality surface preparation.

3.2.2 *Ease of Application*

Coating selection may also be limited by the ability of the applicator to access the surfaces to be coated. This is usually the result of the physical configuration or design of the structure. Items of limited access such as back-to-back angles, cavities, blind holes, and crevices may be difficult, if not impossible, to coat. Most items that can be coated by paint spray application may also be coated by thermal spray. Both methods require about the same amount of access area for hoses, maneuvering, and standoff distance. As a rule of thumb, if access to the surface allows proper blast cleaning, then thermal spray application is feasible. TSMCs perform best when sprayed in a direction normal (i.e., 90 degrees) to the surface and within a particular range of standoff distances from the substrate. Application at angles of less than 45 degrees to the vertical is not recommended. Maximum and minimum standoff distances depend on the material being applied, the manufacturer, and the type of thermal spray equipment used. If the standoff distance and spray angle cannot be maintained within the specified range, hand application of a paint coating may be necessary.

3.2.3 *Regulatory Requirements*

The use of paint coatings is regulated in terms of the types and amounts of solvents or volatile organic compounds (VOCs) they contain. Certain types of solvents, such as water and acetone, are exempt from these regulations because they do not contribute to the formation of photochemical pollution or smog in the lower atmosphere. Regulations vary by geographic location and by industry. Different rules apply for architectural and industrial maintenance painting, marine painting, and miscellaneous metal parts painting. The specifier should consult with local and state officials to determine which rules, if any, affect the proposed coating work. There are no VOC emissions associated with the use of TSMCs, and their use is not regulated by any such rule. TSMCs offer an excellent VOC-compliant alternative to paint coatings for many applications. However, the sealers and topcoats recommended for thermal spray systems are not exempt from VOC-type regulations. The thermal spray coatings will often perform just as well without the sealers and topcoats, which can therefore be omitted for reasons of compliance with air pollution regulations. It should also be noted that there are typically low-VOC paint coating alternatives for most applications. The relative merits of these products should be weighed against those of the zero-VOC TSMC systems.

Thermal spraying of metals produces airborne metal dusts and fumes. Finely divided solids or other particulate accumulations are an explosion hazard. Fine metal particles might damage some types of equipment, such as electronics and bearings. Metal fumes can pose a health hazard (e.g., "metal fume fever"). Proper containment and ventilation may be required in order to reduce these risks. See Section 2 for a discussion of appropriate safety and environmental concerns.

3.2.4 Field Conditions

The conditions under which the coating work will be performed are another important consideration in coating selection. Certain atmospheric conditions, including high levels of humidity and condensation, precipitation, high winds, and extreme cold or heat, place severe limitations on any type of coating work.

3.2.4.1 Moisture. Moisture on the surface should always be avoided to the greatest extent possible. Certain types of paint are more tolerant of small amounts of water on the surface than others and should be specified for work where such conditions cannot be avoided. Thermally sprayed coatings should never be applied if moisture is present on the surface.

3.2.4.2 High winds. High winds may affect the types of surface preparation and coating application methods that are practical for a given job. High winds will tend to carry surface preparation debris and paint overspray over longer distances. This problem can be avoided by using methods other than open abrasive blasting and spray application of paints.

3.2.4.3 High atmospheric temperatures. For sealers and finish coats, the pot life of multi-component catalyzed coatings such as epoxies can be greatly reduced by high atmospheric temperatures. High ambient air and surface temperatures can also adversely affect paint application and the subsequent performance of the coating; for example, vinyl paints are prone to dry spray at high temperatures. Most paints should not be applied below a certain minimum temperature because they will not cure or dry. Most epoxy paints should not be applied when the ambient and substrate temperatures are below 50°F (10°C); however, there are some specialized epoxy coatings that can be applied at temperatures as low as 20°F (−7°C). Latex coatings should never be applied when temperatures are expected to fall below 50°F (10°C) during application and drying. Vinyl paints can be applied at quite low temperatures compared with most paints. Vinyl application at 32°F (0°C) can be performed with relative ease. There are generally no upper or lower ambient or surface temperature limits on the application of TSMCs, although there are practical limits at which personnel can properly perform their tasks.

3.2.5 Maintainability

The future maintainability of a coating system should be considered by the specifier. Some protective coatings are easier to maintain than others. The specifier should also be cognizant of how maintenance painting is normally achieved, whether by contractor or with in-house labor. In-house labor is usually sufficient for low-technology processes requiring minimal training and equipment. For example, “touch-up” painting with brushes or rollers of paints exposed to the atmosphere is readily accomplished with in-house labor. More sophisticated, dedicated, in-house paint crews can carry out more complicated work including abrasive blasting and spray application of paints for immersion service. TSMC and maintenance, because of their specialized nature and relatively high equipment costs, are ordinarily best accomplished by outside contractors. TSMCs are more difficult to repair than are most paint coatings. The ease of spot repair of TSMCs approximates that of the vinyl paint systems. As with the vinyls, special care must be taken to properly feather the edges of the blast-repaired areas without causing the adjacent coating to disbond or lift from the surface. Because of the difficulty of effecting appropriate repairs, TSMC systems, like the vinyls, are generally kept in service until total recoating is needed.

3.3 Cost

3.3.1 Cost Considerations

Coating systems are cost-effective only to the extent that they provide the requisite corrosion protection. Cost should be considered only after the identification of coating materials that will perform in the exposure environment. Given that a number of alternative coating systems may perform in a given application, the next consideration is the cost of the coating job. Ideally, protective coating systems will be selected based on life-cycle cost rather than simple installed cost. However, given the realities of budgets, this approach is not always practical. Therefore, coating systems are sometimes selected on the basis of first or installed cost. Because TSMC systems are almost always more expensive to install than paint systems for a given application, they are often passed over, when, in fact, they can have significantly lower life-cycle costs than paint systems. Additional information on the cost of TSMCs and how to perform cost calculations is provided below.

3.3.2 Cost Analysis

3.3.2.1 Cost of materials and application. The cost of a TSMC system in terms of materials and application is higher than the cost of conventional liquid-applied coatings; however, the major cost of a coatings project is not the materials and application. The dominant factor in coating rework is not material and application cost, but rather it is the cost of taking the facility out of service, contractor mobilization, environmental constraints (e.g., containment and disposal), and monitoring. In most complex coating rework, the actual cost of materials and application is less than 20 percent of the total process. Thus, if one is able to gain a three-fold life extension by using TSMC, the process can pay for itself.

3.3.2.2 Life-cycle cost. Whenever possible, coating selection should be based on life-cycle cost. In reality, the engineer must balance competing needs and may not always be able to specify the least expensive coating on a life-cycle cost basis. Because of their somewhat higher first cost, TSMCs are often overlooked. To calculate life-cycle costs, the installed cost of the coating system and its expected service life must be known. Life-cycle costs for coating systems are readily compared by calculating the average equivalent annual cost (AEAC) or present worth (*PW*) for each system under consideration.

The present worth can be calculated using the following relationship:

$$PW = F + \frac{M(1+r_1)^{P_1}}{(1+r)^{P_1}} + \frac{M(1+r_1)^{P_2}}{(1+r)^{P_2}} + \cdots + \frac{M(1+r_1)^{P_n}}{(1+r)^{P_n}}$$

where

F = cost of initial coating system,
M = cost of maintenance in year P_n,
r = interest rate,
r_1 = inflation rate,
n = number of maintenance actions required to achieve life of structure,
P_1 = number of years to first maintenance,

P_2 = number of years to second maintenance, and
P_n = number of years to last maintenance.

(For more information, refer to E. L. Grant, W. G. Irerson, and R. S. Leavenworth, *Principles of Engineering Economy*, 7th ed., John Wiley & Sons, New York, 1982 and *ASM Handbook, Volume 13—Corrosion*, 9th ed., ASM International, Materials Park, OH, 1987, pp. 369–374).

3.3.2.3 Installed cost. The basic installed cost of a TSMC system is calculated by adding the costs of surface preparation, materials, consumables, and thermal spray application. The cost of surface preparation is well known. The cost of time, materials, and consumables may be calculated using the elements:

(1) **Surface area to be coated (*SA*).**

$$SA = \text{length} \times \text{width}$$

(2) **Volume (*V*) of coating material needed to coat the area.**

$$V = SA \times \text{coating thickness}$$

(3) **Weight of the material to be deposited (W_d).** The density (*D*) of the applied coating will be less than that of the feedstock material. A good assumption is that the applied coating will be about 90 percent of the density of the feedstock material. Densities are as follows: aluminum—0.10 lb/in.^{3} (2.70 g/cm^3), zinc—26 lb/in.^{3} (7.13 g/cm^3), and 85 : 15 wt% zinc/aluminum wire—0.207 lb/in.^{3} (5.87 g/cm^3).

$$W_d = V \times 0.9D$$

(4) **Weight (*W*) of material used.** Deposition efficiencies (*DE*) of zinc, aluminum, and 85 : 15 wt% zinc/aluminum, applied by wire-arc spray, are estimated to be 60 to 65 percent, 70 to 75 percent, and 70 to 75 percent, respectively.

$$W = W_d / DE$$

(5) **Spray time (*T*).** Spray rates (*SR*s) for wire-arc sprayed materials vary depending on wire diameter and current settings. Table 5 (in Section 5) provides typical spray rates for materials and wire sizes.

$$T = W / SR$$

(6) **Electricity or oxygen and fuel gas consumption (*C*).** Typical consumption rates (*CR*s) for electricity, fuel gas, and oxygen are available from equipment manufacturers.

$$C = CR \text{ x } T$$

(7) **Cost of materials (*CM*).**

$$CM = W \times \text{cost per unit weight}$$

(8) **Cost of application (*CA*).**

$$CA = T \times \text{unit labor cost}$$

(9) **Cost of consumables (*CC*).**

$$CC = T \times \text{unit cost of consumable}$$

(10) **Total cost (*TC*) of the TSMC.**

$$TC = CM + CA + CC.$$

3.3.2.4 Factors that increase cost. Factors that increase the cost of thermal spray and other coating jobs include the cost of containment, inspection, rigging, mobilization, waste storage and disposal, and worker health and safety. These can have a significant effect on coating cost and might be independent of the type of coating system being considered. They should be considered when comparing annual cost or *PW* of different systems.

3.3.2.5 Cost-effectiveness of TSMCs. In 1997**,** the Federal Highway Administration (FHWA) compared the performance of a number of coating systems, including paints and thermal spray. Coating life expectancies were estimated based on their performance in an aggressive marine atmospheric exposure and a mildly corrosive environment. Installed and life-cycle costs were calculated for each coating system for each exposure. Average equivalent annual costs were calculated based on a 60-year structure life. For the more severe marine atmospheric exposure, TSMCs of aluminum, zinc, and 85:15 wt% zinc/aluminum alloy were the most cost-effective coatings. For the less severe mildly corrosive atmospheric exposure, thermal spray was no more or less cost-effective than other coating options. Report FHWA-RD-96-058 provides the details of the study. For example, the costs used were the following:

Item	Costs per square foot		
	Zinc/Aluminum @ 6 mils	Epoxy Mastic/ Polyurethane	Annual Escalation Rate, %
Surface preparation (labor + material), SSPC-SP 10	$ 1.25	$ 0.60	3.94
Coating application (labor)	$ 2.50	$ 0.30	4.00
Coating material	$ 1.50	$ 0.42	1.91
Containment and air filtration system	$ 2.00	$ 2.00	3.00
Rigging	$ 0.50	$ 0.50	3.00
Mobilization	$ 0.50	$ 0.50	3.00
Hazardous waste storage and disposal	$ 2.50	$ 2.50	6.00
Worker health and safety	$ 2.00	$ 2.00	4.00

While the surface preparation, coating material, and application costs were initially higher for the zinc/aluminum TSMC, the savings came in the number of times the coating must be applied. The TSMC requires two applications within the 60-year life of the structure (one initial coat and one maintenance recoat), whereas the epoxy/polyurethane requires eight coats within the 60-year life of the structure (one initial coat and seven maintenance recoats). This worked out to a total present value for the epoxy mastic/polyurethane system of $21.37/ft^2 ($1.99/m^2) compared with $18.38/ft^2 ($1.71/m^2) for the zinc/aluminum TSMC.

3.4 Design

Proper design can improve the performance of coatings by removing some features that tax the coatings' ability to protect the structure. NACE International Recommended Practice RP0178, "Fabrication Details, Surface Finish Requirements, and Proper Design Considerations for Tanks and Vessels To Be Lined for Immersion Service," while it addresses tanks, has some pertinent recommendations that are applicable to piles. These include the following:

- Avoid dissimilar metals in direct contact with each other. Examples to be avoided are aluminum or stainless steel fasteners connected directly to steel without dielectric bushings and washers and aluminum conduit and straps connected directly to steel without dielectric insulation.
- Where welding is used, use a continuous weld bead. Remove weld spatter and weld metal irregularities that could interfere with obtaining an adequate coating film thickness.
- Edges should be beveled or rounded to break up sharp corners. Optimally, edges should have a minimum radius of 1/8 in. (3 mm) and preferably 1/4 in. (6 mm).
- Allow drainage in the case of horizontal members by installing drain holes or orienting the member such that it does not hold water. Make the drain hole large enough to reduce the likelihood of becoming clogged.
- Avoid lap joints (faying surfaces) where possible because these do not permit coating of the surfaces within the joint. If unavoidable, seal weld lap joints.
- Avoid pockets where the abrasive blast equipment cannot effectively clean and thermal spray cannot effectively coat the surface.
- Avoid back-to-back angles because the interior facing surfaces cannot be cleaned and protected. Alternately use a T-section or other shape that allows open access to all surfaces. Seal weld back-to-back angles if they must be used.
- Ensure that all corrosion-prone surfaces are accessible for applying TSMCs both during initial fabrication and during the lifetime of the structure.

3.5 Areas Requiring Special Treatment

3.5.1 Portions Below the Mudline

The TSMCs discussed in this guide are generally applicable to areas above the water, in tidal and splash zones, and below the waterline. Figure 1 shows typical corrosion losses with low-alloy and carbon steel. Significant corrosion occurs in the splash, tidal, and immersion zones and in the zone a few feet below the mudline, with relatively little corrosion deeper into the mud. This is because there is little oxygen below the mudline to support aggressive

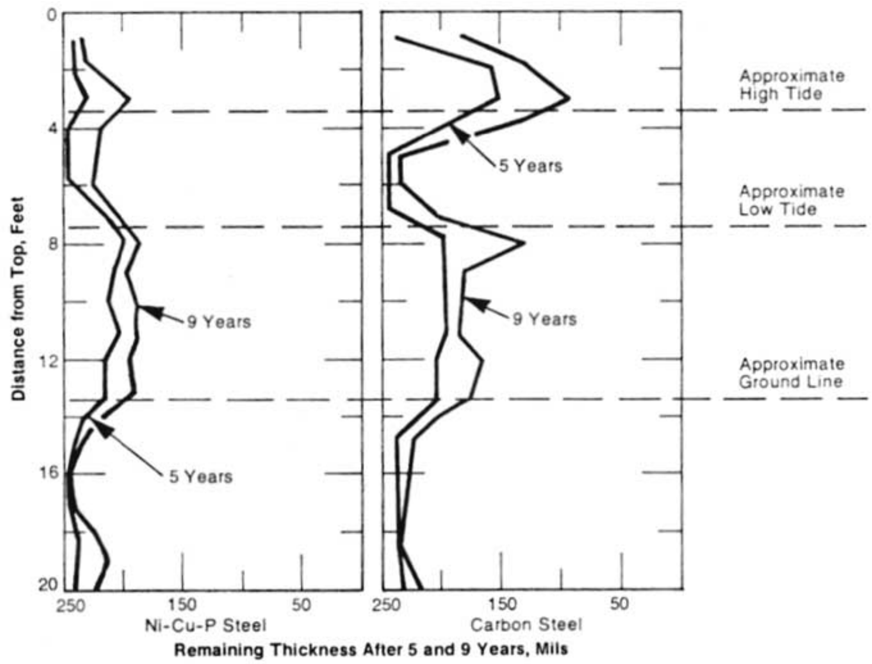

Figure 1. Corrosion of sheeting piling at various locations (Source: AASHTO Highway Structures Design Book, Vol. 1, 1986, p. 10.49).

corrosion. The application of a TSMC below the mudline is not necessary; however, coating a few feet below the mudline will allow for changes in bottom elevation with time and situations in which the piles are not driven to their intended depth. However, if this is considered, it should be kept in mind that macrocell galvanic corrosion reactions occur below the waterline and mudline. These might result in reduced TSMC life below the water line. Consideration should be given to applying TSMC on the whole pile to eliminate this galvanic corrosion.

3.5.2 Faying Surfaces

Faying surfaces are surfaces that are in contact with each other and joined by bolting or other means. Faying surfaces should be seal welded, or the TSMC should be applied to the faying surfaces before joining. TSMCs can be applied to slip critical surfaces.

3.5.3 Sheet Pile Interlock Joints

Figure 2 illustrates a typical sheet pile interlock joint. The surfaces within the joint are of relatively close tolerance and if coated with the full thickness of the TSMC, the combined thickness of both joints might prevent the piles from being joined together. The coating must be applied to a lesser thickness within the joint. The coating thickness should be no more than 3 to 5 mils (76 to127 µm) unless experience indicates that a thicker coating will work.

In some cases, sections of sheet pile might be already joined, and it will not be possible to put any coating on the inside of the joint. In this case, the coating should be as evenly applied as possible across the joint interface.

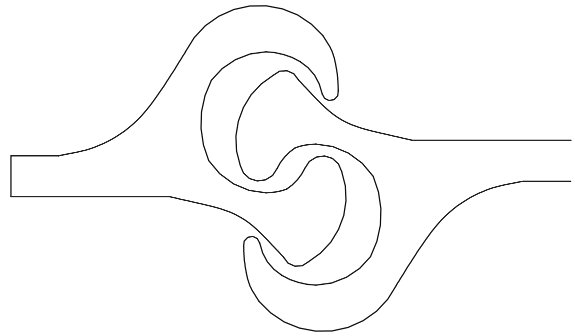

Figure 2. Schematic of an interlock joint.

3.6 Effect of Steel Composition

Small variations in steel hardness caused by alloy content will have little effect on the adhesion or performance of TSMCs; however, it is important to ensure that the appropriate surface profile is achieved prior to applying the TSMC. Hardened areas, such as the heat-affected zones of welds, might require special care to ensure an adequate surface profile. Flame-cut areas will require special care to ensure that an adequate profile is achieved.

3.7 Effect of Holidays on Protective Ability of Coating

Coating holidays will affect the ability of the metallic coating to protect the steel substrate. Small holidays, such as pinholes and narrow scratches, will be protected by the galvanic action of the coating. Large holidays, those exceeding $^1/_2$ in. (1.3 cm), in immersed areas should be protected by galvanic interaction with the coating. Large holidays in the atmospheric, splash, and tidal zones will not be fully protected by the coating. All holidays will eventually result in deterioration of the TSMC, leading to corrosion of the steel. The consequence of the corrosion (e.g., small hole leading to seepage through the piling, a large corroded area resulting in structural weakening of the pile, or aesthetic requirements) should be taken into consideration when determining whether to repair the coating on existing structures. All visible holidays on new structures should be repaired using appropriate materials prior to the pile being placed in service.

3.8 Thermally Sprayed Metal Wire Storage

Temperature, humidity, and dew point cause problems if thermal spray feedstock is not properly stored. All of the active metal wires will oxidize if exposed to moisture. The oxide film can cause feed problems in both flame and arc equipment. Extreme temperature changes may also cause zinc and zinc/aluminum alloy wire to recrystallize and become brittle. Thermal spray wires should be securely sealed and protected from moisture intrusion to prevent oxidation of the material until they are to be used.

4 SURFACE PREPARATION

4.1 Introduction

TSMCs require a very clean, rough surface that is free of oil, grease, dirt, scale, and soluble salts. Surface contaminants must be removed with solvents prior to removal of mill scale, corrosion products, and old paint by abrasive blasting.

4.1.1 Role of Surface Preparation

Surface preparation is the single most important factor in determining the success of a corrosion-protective TSMC system. Abrasive blasting or abrasive blasting combined with other surface preparation techniques is used to create the necessary degree of surface cleanliness and roughness.

4.1.2 Objective of Surface Preparation

The principal objective of surface preparation is to provide proper adhesion of the TSMC to the substrate being coated. Adhesion is the key to the success of the TSMC.

4.1.3 Purpose of Surface Preparation

The purpose of surface preparation is to roughen the surface, creating angular asperities and increased surface area for mechanical bonding of the TSMC to the steel substrate. The roughening is typically referred to as the anchor pattern or profile. The profile is a pattern of peaks and valleys that are cut into the substrate surface when high-velocity abrasive grit blast particles impact on the surface.

4.1.4 Surface Cleanliness

Surface cleanliness is essential for proper adhesion of the TSMC to the substrate. TSMCs applied over rust, dirt, grease, or oil will have poor adhesion. Premature failure of the TSMC may result from coating application to contaminated substrates.

4.2 Solvent Cleaning (SSPC-SP-1)

Solvent cleaning (SSPC-SP-1) is a procedure for removing surface contaminants, including oil, grease, dirt, drawing and cutting compounds, and soluble salts, from steel surfaces by means of solvents, water, detergents, emulsifying agents, and steam. Solvent cleaning is not designed to remove mill scale, rust, or old coatings and precedes the use of abrasive blast cleaning. Ineffective use of the solvent cleaning technique may spread or incompletely remove surface contaminants. Three common methods of solvent cleaning are water washing, steam cleaning, and cleaning with hydrocarbon (organic) solvents.

4.2.1 Hydrocarbon Solvent Cleaning

Hydrocarbon solvents used to remove grease and oil are typically petroleum-based distillates, as described by ASTM D235, "Standard Specification for Mineral Spirits (Petroleum Spirits) (Hydrocarbon Dry Cleaning Solvent)." Type I—Regular (Stoddard Solvent) with a minimum flash point of 100°F (38°C) can be used when ambient temperatures are below 95°F (35°C). Type II—High Flash Point mineral spirits with a minimum flash point of 140°F (60°C) should be used when ambient temperatures exceed 95°F (35°C). Aromatic solvents such as xylene and high flash aromatic naphtha 100 or 150 (ASTM D 3734 Types I and II) are sometimes used when a stronger solvent is needed. The use of aromatic hydrocarbons (e.g., benzene) should be limited because of their generally greater toxicity. Solvent cleaning using hydrocarbon solvents is typically accomplished by wiping the surface with solvent-soaked rags. Rags should be changed frequently to afford better removal and to prevent spreading and depositing a thin layer of grease or oil on the surface.

4.2.2 Water Washing

Low-pressure water cleaning, up to 5,000 psi (34 MPa), and high-pressure water cleaning from 5,000 to 10,000 psi (34 MPa to 70 MPa) are effective means of removing dirt and soluble salt contamination. When used with a detergent or emulsifying agent, the method can also be used to remove organic contaminants such as grease and oil. Thorough rinsing with clean water is necessary to ensure complete removal of the cleaning agent. If an alkaline cleaner is used, the pH of the cleaned surface should be checked after the final rinse to ensure that the cleaning agent has been completely removed.

4.2.3 Steam Cleaning

Steam cleaning is an effective means of removing dirt, salt, oil, and grease from both coated and uncoated substrates. The method employs a combination of detergent action and high-pressure heated water (280°F [138°C] to 300°F [149°C] at 3 to 5 gpm [11.3 to 18.9 l/min]). Thorough rinsing with steam or water should be used to remove any deposited detergent.

4.3 Abrasive Blast Cleaning

Abrasive blasting is performed in preparation for thermal spray after the removal of surface contaminants by solvent cleaning. Abrasive blasting is conducted to remove mill scale, rust, and old coatings, as well as to provide the surface roughness profile necessary to ensure good adhesion of the thermally sprayed coating to the substrate. Conventional abrasive blast cleaning is accomplished through the high-velocity (450 mph [724 km/h]) propulsion of a blasting media in a stream of compressed air (90 to 100 psi [620 to 698 kPa]) against the substrate. The particle mass and high velocity combine to produce kinetic energy sufficient to remove rust, mill scale, and old coatings from the substrate while simultaneously producing a roughened surface.

The Society for Protective Coatings (SSPC) and NACE International have published standards for surface cleanliness. These standards and an SSPC supplemental pictorial guide provide guidelines for various degrees of surface cleanliness. Only the highest degree of cleanliness, SSPC-SP-5 “White Metal Blast Cleaning,” or NACE #1, is considered acceptable for TSMCs. SSPC and NACE have developed blast-cleaning standards and specifications for steel surfaces. SSPC-SP-5 and NACE #1 describe the condition of the blast-cleaned surface when viewed without magnification as free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products, and other foreign matter. SSPC-SP-VIS 1-89 supplements the written blast standards with a series of photographs depicting the appearance of four grades of blast cleaning over four initial grades of mill scale and rust. The last two pages of the standard depict a white metal blast-cleaned substrate achieved using three different types of metallic abrasives and three types of nonmetallic abrasives. The resulting surfaces have slight color and hue differences caused by the type of media used.

Abrasive blast cleaning may be broadly categorized into centrifugal blast cleaning and air abrasive blast cleaning. Air abrasive blast cleaning may be further subdivided to include open nozzle, water blast with abrasive injection, open nozzle with a water collar, automated blast cleaning, and vacuum (suction) blast cleaning. Open nozzle blasting is the method most applicable to preparation for TSMC.

4.3.1 Equipment

An open nozzle abrasive blast-cleaning apparatus consists of an air compressor, air hose, moisture and oil separators/air coolers and dryers, blast pot, blast hose, nozzle, and associated safety equipment.

4.3.1.1 Air compressor. The air compressor supplies air to the system to carry the abrasive. Production rate depends on the volume of air that the compressor can deliver. A larger compressor can supply more air and can therefore sustain operation of more blast nozzles or larger blast nozzle diameters.

4.3.1.2 Air hose. The air hose supplies air from the compressor to the blast pot. The air hose should be as short as possible, with as few couplings and as large a diameter as possible to optimize efficiency. The minimum inside diameter (ID) should be 1.25 in. (31.75 mm) with measurements of 2 to 4 in. (50.8 to 101.6 mm) ID being common.

4.3.1.3 Moisture and oil separators/air coolers and dryers. If not removed, moisture from the air and oil mists from the compressor lubricants may contaminate the abrasive in the blast pot and, subsequently, the surface being cleaned. Oil/moisture separators are used to alleviate this problem. The devices should be placed at the end of the air hose as close to the blast pot as possible. Separators are typically of the cyclone type with expansion air chambers and micron air filters. Air coolers/dryers are commonly used to treat the air produced by the compressor.

4.3.1.4 Blast pot. Most blast pots used for large blasting projects are of the gravity-flow type. These machines maintain equal pressure on top of and beneath the abrasive. The typical blast pot consists of air inlet and outlet regulator valves, a filling head, a metering valve for regulating the abrasive flow, and a hand hole for removing foreign objects from the pot chamber. For large jobs, the pot should hold enough media to blast for 30 to 40 minutes. For continuous production, a two-pot unit can be used, allowing one pot to be filled while the other operates.

4.3.1.5 Blast hose. The blast hose carries the air-media mixture from the blast pot to the nozzle. A rugged multi-ply hose with a minimum 1.25-in. (31.75-mm) ID is common. A lighter, more flexible length of hose called a whip is sometimes used for added mobility at the nozzle end of the blast hose. Maximum blast efficiency is attained with the shortest, straightest blast hoses. Blast hoses should be coupled with external quick-connect couplings.

4.3.1.6 Blast nozzle. Blast nozzles are characterized by their diameter, material, length, and shape. Nozzle sizes are designated by the inside diameter of the orifice and are measured in sixteenths of an inch. A $^3/_{16}$-in. diameter orifice is designated as a No. 3 nozzle. The nozzle diameter must be properly sized to match the volume of air available. Too large an orifice will cause pressure to drop and productivity to decrease. Too small an orifice will not fully utilize the available air volume. The nozzle size should be as large as possible while still maintaining an air pressure of 90 to 100 psi (620 to 689 kPa) at the nozzle. Blast nozzles may be lined with a variety of different materials distinguished by their relative hardness and resistance to wear. Ceramic- and cast iron–lined nozzles have the shortest life. Tungsten and boron carbide are long-lived nozzles. Nozzles may be either straight bore or of the venturi type. The venturi nozzle is tapered in the middle, resulting in much higher particle velocities. Venturi nozzles have production rates 30 to 50 percent higher than straight bore nozzles. Long nozzles, 5 to 8 in. (127 to 203 mm), will more readily remove tightly adherent rust and mill scale and increase production rates. Worn nozzles can greatly decrease productivity and should be replaced as soon as they increase by one size ($^1/_{16}$ in. [1.6 mm]).

4.3.2 Blast-Cleaning Techniques

A proper blasting technique is important in order to accomplish the work efficiently with a high degree of quality. The blast operator must maintain the optimal standoff distance, nozzle angle, and abrasive flow rate. The best combination of these parameters is determined by an experienced blaster on a job-to-job basis.

4.3.2.1 Balance of abrasive and air flows. The blaster should balance the abrasive and air flows to produce a “bluish” colored abrasive airstream at the nozzle, which signals the optimum mix. Blasters often use too much abrasive in the mix, which results in reduced efficiency. The mix is adjusted using the valve at the base of the blast pot.

4.3.2.2 Nozzle-to-surface angle. The nozzle-to-surface angle should be varied to achieve the optimal blast performance for the given conditions. Rust and mill scale are best removed by maintaining a nozzle-to-surface angle of 80 to 90 degrees. A slight downward angle will direct dust away from the operator and improve visibility. The best nozzle-to-surface angles for removing old paint are 45 to 70 degrees. The final blast profile should always be achieved with a nozzle-to-surface angle of 80 to 90 degrees.

Inside corners—for example, the inside flange surface of a narrow H-pile—require special attention to achieve angles as close to the optimum angles as possible.

4.3.2.3 Standoff. Standoff, or nozzle-to-surface distance, will also affect the quality and speed of blast cleaning. The lower the standoff distance, the smaller the blast pattern will be, and the longer it will take to cover a given area. However, close standoff distances allow more kinetic energy to be imparted to the surface, allowing for the removal of more tenacious deposits, such as mill scale. A standoff distance of as little as 6 in. (153 mm) may be necessary for the removal of tight mill scale and heavy rust deposits. Greater standoff distances, on the order of 18 in. (457 mm), are more efficient for the removal of old, loosely adherent coatings.

4.3.3 Abrasive Media

The selection of the proper abrasive blast media type and size is critical to the performance of the TSMC. Blast media that produce very dense and angular blast profiles of the appropriate depth must be used.

4.3.3.1 Mix. Steel shot and slag abrasives composed of all rounded or mixed angular, irregular, and rounded particles should never be used to profile steel surfaces for thermal spraying. Mixed abrasives and lower-cost abrasives (e.g., mineral slag and garnet) may be used to initially clean the surface, but the final profile must be obtained with completely angular abrasives.

4.3.3.2 Type/size. New steel grit should conform to the requirements of SSPC-AB-3, "Newly Manufactured or Re-Manufactured Steel Abrasives." Various hardnesses of steel grit are available, but generally grit with Rockwell C hardness in the range of 50 to 60 is used. Harder steel grit (Rockwell C 60 to 66) may also be used, provided that the proper surface profile is obtained. Table 3 shows the recommended blast media types as a function of the thermal spray process and coating material.

4.3.3.3 Angularity. An angular blast media must always be used. Rounded media such as steel shot, or mixtures of round and angular media, will not produce the appropriate degree of angularity and roughness in the blast profile. The adhesion of TSMCs can vary by an order of magnitude as a function of surface roughness profile shape and depth. TSMCs adhere poorly to substrates prepared with rounded media and may fail in service by spontaneous delamination. Hard, dense, angular blast media such as aluminum oxide, silicon carbide, iron oxide, and angular steel grit are needed to achieve the depth and shape of blast profile necessary for good TSMC adhesion. Steel grit should be manufactured from crushed steel shot conforming to SAE J827. Steel grit media composed of irregularly shaped particles or mixtures of irregular and angular particles should never be used. Steel grit having a classification of "very angular," "angular," or "subangular," as classified by the American Geological Institute, should be used (also found in J. D. Hansink, "Maintenance Tips," *Journal of Protective Coatings and Linings*, Vol. 11, No. 3, March 1994, p. 66).

TABLE 3 Recommended blast media for thermal spray surface preparation

Thermal Spray Material	Spray Process	Blasting Media
Aluminum, zinc, 85:15 zinc-aluminum	Wire flame spray	Aluminum oxide Angular steel grit
Aluminum, zinc, 85:15 zinc-aluminum	Arc spray	Aluminum oxide Angular steel grit Angular iron oxide

4.3.4 Blast Profile

TSMCs are generally more highly stressed than paint coatings and as such require a deeper blast profile to dissipate the tensile forces within the coating. In general, the greater the thickness of TSMC being applied, the deeper the blast profile that is required. The minimum recommended blast profile for the thinnest coatings of zinc and 85 : 15 wt% zinc/aluminum (0.004 to 0.006 in. [100 to 150 μm]) is 0.002 in. (50 μm). Thicker coatings of zinc and 85 : 15 wt% zinc/aluminum, 0.010 in. (250 μm) or greater, require a minimum 0.003-in. (75-μm) profile. A 0.005-in. (125-μm) aluminum coating requires a minimum surface profile of 0.002 in. (50 μm), and a 0.010-in. (250-μm) aluminum coating requires a minimum 0.0025-in. (62.5-μm) profile. The specifier should specify the maximum and minimum surface profile required for the TSMC. The maximum profile for thicker TSMCs should not exceed approximately a third of the total average coating thickness. As a general rule, the maximum blast profile should be 0.001 in. (25 μm) greater than the specified minimum profile depth. Table 4 shows average profiles for various abrasive sizes.

4.3.5 Centrifugal Blast Cleaning

Centrifugal blast cleaning is commonly used in fabrication shops. The method is generally faster and more economical than open abrasive blasting. The method involves conveying the steel through a blast cabinet or enclosure where high-speed rotating wheels fitted with blades propel abrasive particles at the steel. The blasting debris falls to the bottom of the chamber, where it is reclaimed, cleaned, and then recycled. The degree of cleanliness achieved is determined by the abrasive velocity and the conveyor speed. Steel shot is usually used in centrifugal blast machines. For TSMCs, a subsequent profiling blast using angular media is required to achieve the desired blast profile depth and angularity. Centrifugal blast-cleaning machines are now available for fieldwork as well, but their use is not widespread.

4.3.6 Cleaning After Blasting

Cleanliness after abrasive blasting is important. Any remaining traces of spent abrasive or other debris must be blown, swept, or vacuumed from the surface prior to thermal spray application. A hard-to-see layer of abrasive dust may adhere to the substrate by static electric charge and must be removed. The thermal spray applicator may accomplish this by triggering just the compressed air from the flame or arc gun. Scaffolding, staging, or support steel above the thermal spray coating area must also be cleaned prior to application to prevent debris from falling onto the surfaces to be coated. Blasting and thermal spraying should not occur simultaneously unless the two operations can be adequately isolated to prevent contamination of the thermal spray surfaces.

TABLE 4 Average surface profiles for selected abrasive sizes

Abrasive	Size	Profile, mils (μm)
Steel grit	G40	2.4 ± 0.5 (61 ± 12.7)
Steel grit	G25	3.1 ± 0.7 (79 ± 17.8)
Steel grit	GL16	4.0 + (102)
Steel grit	G14	5.1 ± 0.9 (130 ± 22.8)
Aluminum oxide	16	4.0 + (102)

4.3.7 *Time Between Blasting and Thermal Spraying*

After completion and inspection of the final profiling blast, the steel substrate should be coated as soon as possible. The TSMC should be applied within the same work shift in which the final surface preparation is completed. A maximum holding period of 6 hours should be allowed to elapse between the completion of blast cleaning and thermal spraying. Shorter holding periods should be used under humid or damp conditions or when it is clear that the quality of the blast or coating is degraded. This period should allow adequate time for the changeover from blasting to thermal spraying. Thermal spray should commence prior to the appearance of any visible rust bloom on the surface. Foreign matter such as paint overspray, dust and debris, and precipitation should not be allowed to contact the prepared surfaces prior to thermal spraying. Under no circumstances should the application of thermal spray be allowed on re-rusted or contaminated surfaces.

In some cases, it may be possible to apply only a single spray pass or some other fraction of the total thermal spray system within 6 (maximum) hours of blasting. This single layer must cover the peaks of the surface profile. The partial coating is intended to temporarily preserve the surface preparation. Before applying additional sprayed metal to the specified thickness, the first layer of coating should be visually inspected to verify that the coating surface has not been contaminated. Any contamination between coats should be removed before any additional material is applied. The remaining coating should be sprayed to achieve the specified thickness as soon as possible.

In some cases, it may be possible to hold the surface preparation for extended periods using specially designed dehumidification (DH) systems. These systems supply dry air to a blast enclosure or other contained air space. The dry air prevents the reappearance of rust for extended periods of time and allows for thermal spray jobs to be staged in a different fashion. Dehumidification systems may be particularly useful for jobs in very humid environments, which are typical of many locations during the spring through fall maintenance season. These areas typically have dense morning fog and hot humid afternoons. Holding the quality of blast needed for TSMCs would be difficult under such conditions without the use of dehumidification.

4.3.8 *Pitted Steel*

Heavily corroded, deeply pitted surfaces are difficult to prepare for TSMC. Wide, shallow pits do not pose any particular problem, but deep and irregularly shaped pits can pose a problem. Pits with an aspect ratio of greater than unity (i.e., as deep as they are wide) should be ground with an abrasive disk or other tool prior to blasting. Pits with sharp edges, undercut pits, and pits with an irregular horizontal or vertical orientation must be ground smooth prior to abrasive blasting. Grinding does not need to level or blend the pit with the surrounding steel, but it should smooth all the rough and irregular surfaces to the extent necessary to allow the entire surface of the pit to be blasted and coated. Nozzle-to-surface angles of 80 to 90 degrees are optimal for cleaning pits. Heavily pitted steel on bridges or in other environments where soluble salt contamination is likely should be cleaned with high-pressure water after grinding to ensure that salt contaminants are removed from the pits.

4.3.9 Edges and Welds

4.3.9.1 Sharp edges. These present problems in achieving adequate surface preparation and coating. As a general rule, all sharp edges should be ground prior to blasting to a uniform minimum radius of $^1/_8$ in. (3 mm). A radius of $^1/_4$ in. (6 mm) is preferred.

4.3.9.2 Flame-cut edges. Flame cutting results in localized hardening of the steel on the cut edge. This will degrade the ability of abrasive blasting to provide an adequate surface profile in these areas because the hardened steel can be harder than the abrasive. The result will be poor coating adhesion on the hardened edge. The hardened edge must be removed either with a grinder or belt-driven abrasive, followed by abrasive blasting. Abrasive that is harder than the flame-hardened edge, such as alumina, can also be used.

4.3.9.3 Welded areas. Rough welds shall be ground to remove sharp edges, undercuts, pinholes, and other irregularities. Remove weld spatter. Welds can also result in locally hardened areas on the steel in the heat-affected zone, on which it could be difficult to achieve an adequate surface profile compared with the unaffected steel surface. Particular care should be taken in these areas to ensure that adequate surface profile is achieved. Surface profile testing should be conducted in weld heat-affected zones to develop the correct blasting procedure for that piece.

4.4 Water Jetting

High-pressure water jetting from 10,000 to 25,000 psi (70 MPa to 170 MPa) and ultra-high-pressure jetting above 25,000 psi (170 MPa) are used to prepare a surface for recoating. These methods will not produce a surface profile on the metal that is sufficient for the adhesion of TSMCs unless that profile already exists on the metal surface from prior abrasive blasting. Water jetting will also not remove mill scale. The flash rusting that can occur on a water-jetted surface can interfere with the adhesion of TSMCs. However, water jetting can be used to remove existing coatings as a preliminary step in preparing the surface prior to abrasive blasting. The use of high-pressure water jetting can result in savings in abrasive volume and reduced costs in disposal of wastes.

More information is available in the joint NACE International/SSPC Standard, NACE #5/SSPC-SP-12, "Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Water Jetting Prior to Recoating."

4.5 Surface Contamination

Surface contamination from chlorides (deicing salts and sea salts) prior to applying the TSMC can lead to loss of coating adhesion, particularly with aluminum TSMC. Surface contamination can be removed by detergent washing, power washing, water jetting, or wet abrasive blasting.

5 TSMC APPLICATION

5.1 Equipment

5.1.1 Thermally Sprayed Metal Processes

Metals can be applied by thermal spray in a variety of ways that can be categorized as either combustion or electric processes. Combustion processes include flame spraying, high-velocity oxygen fuel (HVOF) spraying, and detonation-gun spraying. Electric processes include wire-arc spraying and plasma spraying. This guide will address the flame and electric arc processes for wire.

5.1.1.1 Flame process. The flame spray process can be used to apply a wide variety of feedstock materials including metal wires, ceramic rods, and metallic and nonmetallic powders. In flame spraying, the feedstock material is fed continuously into the tip of the spray gun or torch, where it is then heated and melted in a fuel gas/oxygen flame and accelerated toward the substrate being coated in a stream of atomizing gas. Common fuel gases used include acetylene, propane, and methyl acetylene-propadiene (MAPP). Oxyacetylene flames are used extensively for wire-flame spraying because of the degree of control and the higher temperatures attainable with these gases. The lower-temperature oxygen/propane flame can be used for melting metals such as aluminum and zinc, as well as polymer feedstock. The basic components of a flame spray system include the flame spray gun or torch, the feedstock material and a feeding mechanism, oxygen and fuel gases with flowmeters and pressure regulators, and an air compressor and regulator.

With wire-flame spraying, the wire-flame spray gun or torch consists of a drive unit with motor and drive rollers for feeding the wire and a gas head with valves, gas nozzle, and an air cap that controls the flame and atomization air. Compared with wire-arc spraying, wire-flame spraying is generally slower and more costly because of the relatively high cost of the oxygen-fuel gas mixture compared with the cost of electricity. However, flame spraying systems are generally simpler and less expensive than wire-arc spraying systems. Both flame spraying and wire-arc spraying systems are field portable and may be used to apply quality metal coatings for corrosion protection.

5.1.1.2 Wire-arc process. Due to its high deposition rates, excellent adhesion, and cost-effectiveness, wire-arc spray is the preferred process for applying TSMCs to steel pilings. With the wire-arc spray process, two consumable wire electrodes of the metal being sprayed are fed into a gun such that they meet at a point located within an atomizing air (or other gas) stream. An applied DC potential difference between the wires establishes an electric arc between the wires that melts their tips. The atomizing air flow subsequently shears and atomizes the molten droplets to generate a spray pattern of molten metal directed toward the substrate being coated. Wire-arc spray is the only thermal spray process that directly heats the material being sprayed, a factor contributing to its high energy efficiency.

The wire-arc spray system consists of a wire-arc spray gun or torch, atomizing gas, flowmeter or pressure gauge, a compressed air supply, DC power supply, wire guides/hoses, and a wire feed control unit. Operation of this equipment must be in strict compliance with the manufacturers' instructions and guidelines.

5.1.2 Thermal Spray Guns (Wire-Arc and Flame)

Figure 3 illustrates a typical wire-arc spray gun or torch and Figure 4 illustrates a typical flame spray gun.

5.1.3 Air Compressors (Arc and Flame)

Compressed air should be free of oil and water. Accurate air regulation is necessary to achieve uniform atomization. Under continuous use conditions, the actual atomization air

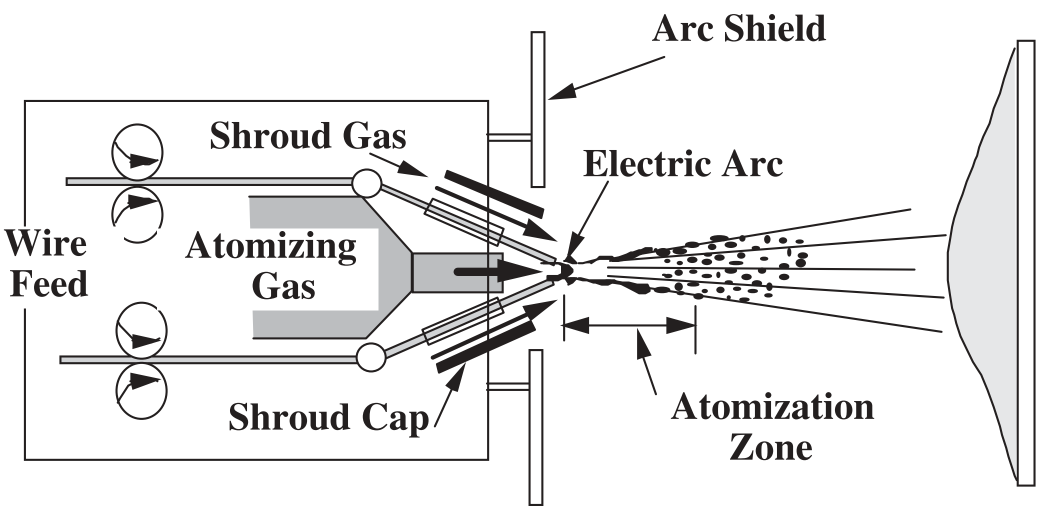

Figure 3. Schematic of a typical wire-arc spray gun.

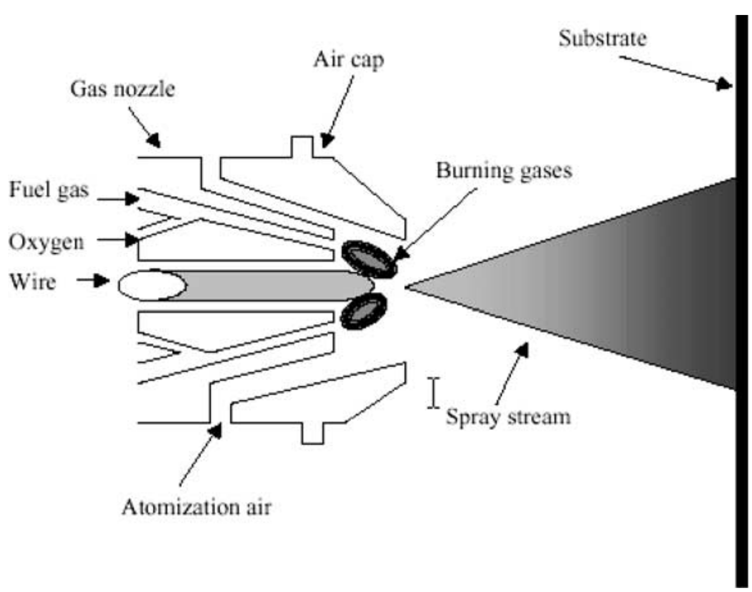

Figure 4. Schematic of a typical flame-wire spray gun.

pressure and volumetric flow rate should remain nearly constant and, ordinarily, should not deviate from the set value by more than 5 percent.

5.1.4 Atomizing Gas Supply (Wire-Arc and Flame Spray)

Provisions shall be made to monitor and control, read clearly, and adjust (by means of instruments), any deviations of the atomizing gas pressure and volumetric flow rates from the set values during the spraying process. These values shall be recorded during acceptance inspection. For the wire-arc spray process, the atomizing gas supply and control system shall be designed and constructed to allow continuous operation at selected pressures and flow rates.

5.1.5 Air Dryers (Wire-Arc and Flame Spray)

An air dryer is necessary to provide clean, dry air (as per ASTM D4285) for surface preparation and thermal spraying. Air dryers shall be inspected and tested regularly and replaced as necessary to maintain the desired moisture content in the process air streams.

5.1.6 Oxygen and Fuel Gas (Flame Spray)

The use of oxygen and fuel gas flowmeters allows for the best control of the flame and thus higher spray rates. Under continuous use conditions, the actual oxygen and fuel gas flow rates and pressures should remain nearly constant and, ordinarily, should not deviate from the set values by more than 5 percent. Flame spraying equipment shall permit spraying with the combustible gases, atomizing gas (if any), and powder carrier gas (if any) for which it was designed.

5.1.7 Gases for Flame Spraying

Gaseous oxygen equal or equivalent to Federal Specification BB-O-925 should be used for thermal spraying. Acetylene equal or equivalent to Federal Specification BB-A 106 should be used for thermal spraying. Other fuel gases (e.g., methyl acetylene-propadiene [MAPP] stabilized, propane, or propylene) as specified by the thermal spray equipment manufacturer may also be used.

5.1.8 Power Supply (Wire-Arc Spray)

In general, the higher the power output of the direct current (DC) power supply used, the greater the possible production spray rate of the unit. Under continuous use conditions, the actual current output should remain nearly constant and, ordinarily, should not deviate from the set value by more than 5 percent. Power supplies that are adequately sealed may be operated in dusty atmospheres and do not need to be located at a remote distance from the thermal spray operation. DC power supplies rated up to 600 A are common. A lightweight power supply mounted on pneumatic tires will have added portability. There is typically an optimum amperage for each coating material that may further depend on wire diameter and the particular equipment model.

The open-circuit voltage should be adjustable to accommodate different wire materials. The voltage should be set slightly above the lowest level consistent with good arc stability. This will provide smooth dense coatings with superior deposition efficiency. Higher voltages tend to increase droplet sizes, resulting in rougher coatings with lower densities. Under continuous use conditions, the actual arc voltage should remain nearly constant and, ordinarily, should not deviate from the set value by more than 5 percent.

5.1.9 Wire Feed Control (Wire-Arc and Flame Spray)

The wire feed and guide mechanisms should be designed to provide automatic alignment. Manual alignment of the wires is both time consuming and inexact. The wire feed mechanism must be capable of delivering wire to the arc tips at a rate commensurate with the power generated in the arc. Under continuous use conditions, the actual wire feed rate should remain nearly constant and, ordinarily, should not deviate from the set value by more than 5 percent.

For flame spray equipment, the spraying material feed unit shall comply with the following conditions:

- The unit shall permit uniform and consistent processing of the consumables for which it was designed.
- It shall enable adjustment of the feedstock material feed rate.
- The set-point values shall be constant and reproducible; a precondition of this is adequate and constant gas pressures and flow rates, atomizing air pressures (where used), and supply of electrical power, as appropriate.

5.1.10 Air Cap Selection (Wire-Arc Spray)

A range of different air caps is usually available for use with wire-arc spray equipment. Air caps used in wire-arc spraying include fan (elliptical) and circular spray patterns. Some air caps are adjustable. The nozzle system (contact tubes and air nozzle) shall permit a continuous and stable arc to be maintained and provide atomization of the feedstock materials without causing a buildup of deposits that may degrade gun operation.

5.1.11 Cable Length (Wire-Arc Spray)

Most manufacturers offer optional cable packages that allow operation of the spray gun or torch up to 100 ft (30 m) from the power supply. Longer cables provide added flexibility when thermal spraying in the field.

5.1.12 Arc-Shorting Control (Wire-Arc Spray)

Arc shorting is a phenomenon wherein the wires are fused or welded together, creating a short circuit and cessation of melting and spraying. Shorting sometimes requires that the wire ends be manually clipped before the arc can be restruck. This operation can be very time consuming and must only be conducted with the power supply de-energized and by appropriately trained personnel. Occasionally during arc shorting, lumps of unmelted wire are shorn off and deposited on the substrate, resulting in poor coating quality. An added feature available on some wire-arc spray equipment can control arc shorting.

5.1.13 Wire Tips (Wire-Arc Spray)

Wire guide tips that hold and align the wires as they enter the arc zone are subject to wear. Wear rate depends on the properties of the material being sprayed and the level of current used, since these tips are also part of the means by which electrical current is transferred to the wires. Properly designed equipment will allow cooler operating temperatures that will prolong tip life and reduce maintenance time. Easy-to-change contact tips are also beneficial.

5.1.14 Nozzles (Flame Spray)

Processing of the feedstock materials shall be possible without any degrading deposit buildup on the gun, air nozzle, or both.

5.2 Thermal Spray Equipment Setup and Validation

- The thermal spray equipment should be set up, calibrated, and operated as per the manufacturer's instructions and technical manuals.
- Spray parameters should be set for spraying the specified feedstock material and, at a minimum, be validated using the bend test.
- Validation of the TSMC procedure includes (1) successful surface preparation, (2) correct application procedures for the specified TSMC, (3) achievement of the required thickness, and (4) successful bend testing of at least one bend coupon at the beginning of each work shift.
- If the bend test fails, the problem shall be identified and fixed before spraying continues.
- Results of all validation tests shall be clearly identified and documented.

5.2.1 Procedures for Acceptance Inspection

5.2.1.1 Electrical power and wire feed unit (wire-arc spray). Compliance with the requirements specified for electrical power for continuous operation wire feed units shall be met by

(1) Spraying 85 : 15 wt% zinc/aluminum wire at maximum capacity for 20 minutes (alternate feedstock—for example, aluminum or zinc wire—may be specified by the purchaser).
(2) Measuring ≤ 5 percent deviations of the adjusted electrical values or other disturbances.

5.2.1.2 Atomizing gas (wire-arc spray). The equipment shall be deemed to comply with the requirements if the atomizing gas supply gauge pressure does not deviate by more than ± 5 percent from the set value over a 20-minute period of spraying.

5.2.1.3 Nozzle system (wire-arc and flame spray). The nozzle system shall be deemed to comply with the requirements if, after 20 minutes of spraying 85 : 15 wt% zinc/aluminum wire at the maximum spray rate, there are no degrading deposits of feedstock material visible on or inside the nozzle.

5.2.1.4 Monitoring (wire-arc spray). The limits of error of the measuring instruments shall not exceed ±5 percent for all set values and shall correspond to at least Class 2.5 instruments.

5.2.1.5 Gases (flame spray). Flame spray equipment shall be deemed to comply with the requirements if the values of supply gas pressure and gas flow volume meet the class deviations of the following from the set values over a 10-minute period of spraying.

Class Deviations for Supply Gas Pressure and Flow Volume

Class A	Class B
≤2%	≤5%

5.2.1.6 Validity of inspection report. The inspection report shall be deemed valid for as long as all specifications of this guide are in compliance.

5.2.1.7 Retests. The guidelines listed below should be followed for retests.

(1) If the values obtained during acceptance inspection of a thermal spraying system are altered by modification or repair work, retesting of the properties affected shall be carried out.
(2) Retests shall be carried out in the same way as the initial tests described in this guide.

5.3 Coating Application

5.3.1 Thickness

Table 2 provides recommended thickness values for various coatings and environments.

5.4 Application and Feed Rates

5.4.1 Feed Rates and Spray Rates

Table 5 provides information on typical feed rates for flame spray and arc spray. Table 6 provides information on spray rates for flame spray and arc spray for different wire diameters.

TABLE 5 Nominal feedstock required per unit area/unit thickness (deposition efficiency on a flat plate)

Feedstock Material (wire)	Flame Spray			Wire-Arc Spray		
	Deposit Efficiency (%)	Material Required kg/m²/μm	Material Required lb/ft²/mil	Deposition Efficiency (%)	Material Required kg/m²/μm	Material Required lb/ft²/mil
Aluminum (Al)	80–85	0.0027	0.014	70–75	0.0029	0.017
Zinc (Zn)	65–70	0.0098	0.050	60–65	0.011	0.054
85:15 Zn/Al	85–90	0.0070	0.036	70–75	0.0093	0.049

1 mil = 0.001 in.

TABLE 6 Nominal wire feedstock spray rates and coverage

Feedstock Material	Flame Spray (by wire diameter)						Wire-Arc Spray (per 100 amps)	
	2.4 mm	3.2 mm	4.8 mm	3/32 in.	1/8 in.	3/16 in.	Spray Rate **(Coverage)** kg/hr **(m^2/hr/100µm)**	Spray Rate **(Coverage)** lb/hr **(ft^2/hr/mil)**
	Spray Rate, kg/hr **(Coverage, m^2/hr/100µm)**			Spray Rate, lb/hr **(Coverage, ft^2/hr/mil)**				
Aluminum	2.5 (**8.73**)	5.4 (**18.9**)	7.3 (**25.3**)	5.5 (**370**)	12 (**800**)	16 (**1,070**)	2.7 (**8.26**)	6 (**350**)
Zinc	9.1 (**9.44**)	20 (**21.2**)	30 (**30.7**)	20 (**400**)	45 (**900**)	65 (**1,300**)	18 (**11.0**)	25 (**465**)
85:15 Zn/Al	8.2 (**11.8**)	18 (**26.2**)	26 (**38.0**)	18 (**500**)	40 (**1,110**)	58 (**1,610**)	16 (**9.68**)	20 (**410**)

1 mil = 0.001 in.

The values in these tables should be taken as approximate only. The wire feed rate should be adjusted to properly optimize the dwell time in the flame. Excessive feed rates may result in inadequate or partial heating and melting of the feedstock and may result in very rough deposited coatings. Too slow a feed rate may cause the wire to be over-oxidized, resulting in poor-quality coatings containing excessive levels of oxides and poor cohesion. Under continuous use conditions, the actual wire feed rate should remain virtually constant and, ordinarily, should not deviate from the set value by more than 5 percent.

5.4.2 Holding Period

5.4.2.1 Correct surface cleanliness and profile. TSMCs should always be applied to "white" metal (SSPC-SP-5/NACE # 1). It is common practice in fieldwork to apply the TSMC during the same work shift in which the final blast cleaning is performed. The logical end point of the holding period is when the surface cleanliness degrades or a change on performance (as per bend or tensile test) occurs. If the holding period is exceeded, the surface must be re-blasted to establish the correct surface cleanliness and profile.

5.4.2.2 Duration of the holding period. Thermal spraying should be started as soon as possible after the final anchor-tooth or brush blasting and completed within 6 hours for steel substrates subject to the temperature to dew point and holding-period variations. In high-humidity and damp environments, shorter holding periods should be used.

5.4.2.3 Extending the holding period—temperature/humidity. In low-humidity environments or in controlled environments with enclosed structures using industrial dehumidification equipment, it may be possible to retard the oxidation of the steel and hold the near-white-metal finish for more than 6 hours. With the concurrence of the purchaser, a holding period of greater than 6 hours can be validated by determining the acceptable temperature-humidity envelope for the work enclosure by spraying and analyzing bend test coupons or tensile adhesion coupons, or both. Should the sample fail the bend test, the work must be re-blasted and re-tested.

5.4.2.4 Extending the holding period—application of flash coat. When specified by the purchasing contract, a flash coat of TSMC equal to or greater than 1 mil (25 µm) may be applied within 6 hours of completing the surface preparation in order to extend the holding period for up to 4 hours beyond the application of the flash coat. The final TSMC thickness, however, should be sprayed within 4 hours of the application of the flash coat. This procedure should be validated using a tensile adhesion test or bend test, or both, by spraying a flash coat and waiting through the delay period before applying the final coating thickness.

5.4.2.5 Small and moveable parts. For small and movable parts, if more than 15 minutes is expected to elapse between surface preparation and the start of thermal spraying or if the part is moved to another location, the prepared surface should be protected from moisture, contamination, and finger/hand marks. Wrapping with clean print-free paper is normally adequate.

5.4.2.6 Rust bloom, blistering, or coating degradation. If rust bloom, blistering, or a degraded coating appears at any time during the application of the TSMC, the following procedure should be performed:

(1) Stop spraying.
(2) Mark off the satisfactorily sprayed area.
(3) Repair the unsatisfactory coating (i.e., remove the degraded coating and re-establish the minimum "white metal" finish and anchor-tooth profile depth as per the maintenance and repair procedure).
(4) Record the actions taken to resume the job in the job documentation.
(5) Call the coating inspector to observe and report the remedial action to the purchaser.

5.5 Overspray

5.5.1 Examples of Overspray

- TSMC material that is applied outside the authorized parameters, primarily the gun-to-substrate standoff distance and spray angle (perpendicular ± 30 degrees).
- TSMC material that misses the target or bounces off of the substrate.

5.5.1.1 Foreign matter. Foreign matter such as paint overspray, dust and debris, and precipitation should not be allowed to contact prepared surfaces prior to thermal spraying.

5.5.1.2 Masking. Cleaning, thermal spray application, and sealing should be scheduled so that dust, overspray, and other contaminants from these operations are not deposited on surfaces readied for TSMC or sealing. Surfaces that will not be thermally sprayed should be protected from the effects of blast cleaning and thermal spray application through the use of removable masking materials or other means. Mask all fit and function surfaces and surfaces and areas specified by the purchaser not to be abrasive blasted or to be thermally sprayed. Mask on complex geometries (e.g., pipe flanges, intersections of structural beams, and valve manifolds) to eliminate or minimize overspray. Ensure that the covers and masking are securely attached and will survive the blasting and thermal spraying operations. Masking should also be designed to avoid "bridging," which can lead to debonding or edge lifting.

5.5.1.3 Overspray-control area. For complex geometries where overspray cannot be eliminated, an overspray-control area should be established. Clean, metal masks or clean, removable masking materials should be used to prevent overspray from depositing on surfaces not already sprayed to the specified thickness.

5.5.1.4 Dust, fumes, and particles. Special care should be taken to prevent the entry of abrasive and thermally sprayed metal dusts and fumes into sensitive machinery and electrical equipment. Painted surfaces adjacent to surfaces receiving TSMCs should be adequately protected from damage by molten thermally sprayed metal particles.

5.5.1.5 High winds. High winds may affect the types of surface preparation and coating application methods that are practical for a given job. High winds will tend to carry surface preparation debris and paint overspray longer distances. This problem can be avoided by using methods other than open abrasive blasting and spray application of paints.

5.6 Temperature

5.6.1 Ambient Temperature

Although there are no high or low temperature limitations when applying thermally sprayed metal, it is often advisable to preheat the surface to 250°F (120°C) when first beginning to flame spray to prevent water vapor in the flame from condensing on the substrate. Preheat the initial 1- to 2-ft (0.1- to 0.2-m^2) starting-spray area.

5.6.2 Metal Surface Temperature

The steel surface temperature must be at least 5°F (3°C) above the dew point in order to prevent condensation on the surface that will adversely affect coating adhesion.

5.6.3 Low Ambient Temperature

Thermal spraying in low-temperature environments, below 40°F (5°C), must

(1) Meet the substrate surface temperature and cleanliness (Section 5.4.2.1) and holding period (Section 5.4.2.2). Moisture condensation on the surface is not permissible during thermal spraying.
(2) Be qualified using a bend test or a portable tensile-bond test, or both.
(3) Meet the substrate surface temperature (Section 5.4.2.3). Substrate heating may be required to improve the TSMC tensile adhesion to the substrate and reduce internal (residual) stresses because the TSMCs are mechanically bonded to the substrate.

5.7 Coating Thickness Build

5.7.1 Achieving Specified Coating Thickness

Manually applied TSMCs should be applied in a block pattern measuring approximately 24 in. (60 cm) on a side. Each spray pass should be applied parallel to and overlapping the previous pass by approximately 50 percent. Successive spray coats should be applied at right angles to the previous coat until the desired coating thickness is achieved. Approximately 0.002 to 0.003 in. (50 to 75 µm) of coating should be applied per spray pass. In no case should less than two spray coats applied at right angles be used to achieve the specified coating thickness. **Laying down an excessively thick spray pass increases the internal stresses in the TSMC and will decrease the ultimate tensile-bond strength of the TSMC.**

5.7.1.1 Minimizing thin spots—manual spraying. During manual spraying, use crossing passes to minimize the thin spots in the coating.

5.7.1.2 Minimizing thin spots—robotic spraying. During robotic spraying, program overlapping and crossing passes to eliminate thin spots and stay within the coating thickness specification. Validate the automated spraying parameters and spraying program using tensile-bond or metallographic analysis, or both.

5.7.1.3 Equipment. Use approved spray gun extensions, compressed-air deflectors, or similar devices to reach into recessed spaces and areas.

5.7.2 Spray Angle, Width, and Standoff Distance

5.7.2.1 Gun-to-surface angle. The gun-to-surface angle is very important because of the generally greater distances that the sprayed particles travel prior to striking the substrate, producing a porous and oxidized coating with reduced cohesion and adhesion for similar reasons as those described in Section 5.7.2.2. Porosity, oxide content, and adhesion are strongly affected by spray angle. In some cases, it may be necessary for the applicator to spray at less than 90 degrees because of limited access to the surface. In no case should the applicator spray at an angle of less than 45 degrees. Some degradation in performance might result even at the 45-degree angle. Spray gun extensions are available from some equipment manufacturers that allow better access to difficult-to-spray areas. A good spray technique consists of the applicator maintaining the spray gun perpendicular (at 90 degrees) or near perpendicular (90 ± 5 degrees) to the substrate at all times. Maintain the gun as close to perpendicular as possible and within ± 30 degrees from perpendicular to the substrate.

5.7.2.2 Standoff distance. Standoff distance depends on the type and source of thermal spray equipment used. Excessive standoff distance will result in porous and oxidized coatings with reduced cohesion and adhesion. The higher porosity may be attributed to the greater degree of cooling and the lower velocity that the thermal spray particles or droplets experience prior to impact. Adhesion is directly proportional to the kinetic energy of the spray particles, and the kinetic energy varies as the square of the particle velocity. Cooler, more slowly impacting particles will not adhere as well to each other or to the substrate, resulting in weaker, less adherent coatings. Excessive standoffs may occur because the applicator is not sufficiently familiar with the requirements of the equipment or because of fatigue or carelessness. Increased standoffs may also result from the applicator's arm or wrist arcing during application. It is very important that the applicator's arm move parallel to the substrate in order to maintain a consistent standoff distance. Holding the thermal spray gun too close to the surface may result in poor coverage and variations in coating thickness because of the reduced size of the spray pattern. Some degradation in performance might result at the higher standoff distance.

Use the manufacturer's recommended standoff distance for the air cap installed. Table 7 lists nominal standoff and spray pass width values.

5.7.3 Supplemental Surface Preparation

Surfaces that have become contaminated or that have exceeded the holding period must be recleaned to establish the required degree of cleanliness and profile.

Small areas that have been damaged and require coating repair should be treated according to Section 7, "Repair and Maintenance."

5.8 Inspection and Quality Control

5.8.1 Quality Control (QC) Equipment

Quality control (QC) equipment for thermal spray application should include the following:

- Substrate Temperature—Contact thermocouple or infrared pyrometer to measure substrate temperatures.
- Air Temperature, Dew Point, and Humidity—Psychrometer or an equivalent digital humidity measurement instrument.
- TSMC Thickness—Magnetic pull-off or electronic thickness gauge with secondary thickness standards per SSPC-PA-2.
- TSMC Ductility—2 in. × 4 to 8 in. × 0.050 in. (50 mm × 100 to 200 mm × 13 mm) (ANSI-SAE 10xx sheet) for bend test coupons and a mandrel of a diameter suitable for the specified TSMC thickness.
- Bend Coupon, Companion Coupon, and Sample Collection—Sealable plastic bags to encase bend coupons and other QC samples collected during the job.

5.8.2 Coating Thickness

The thickness of the TSMC should be evaluated for compliance with the specification. Magnetic film thickness gauges such as those used to measure paint film thickness should be used. Gauges should always be calibrated prior to use. Thickness readings should be made either in a straight line with individual readings taken at 1-in. (25-mm) intervals or spaced randomly within a 2-in.- (50-mm-) diameter area. Line measurements should be used on large flat areas, and area measurements should be used on complex surface geometry and surface transitions such as corners. The average of five readings constitutes

TABLE 7 Nominal flame-spray and arc-spray standoff distances and spray widths

Thermal Spray Method	Perpendicular Standoff in. [mm]	Spray Pass Width, in. [mm]	
		Air Cap	
		Regular	Fan
Wire-flame	5–7 [130–180]	0.75 [20]	Not Available
Wire-arc	6–8 [150–200]	1.5 [40]	3–6 [75–150]

one thickness measurement. A given number of measurements per unit area (e.g., five per 100 ft^2 [9 m^2]) should be specified in the contract documents. Areas of deficient coating thickness should be corrected before sealing begins.

5.8.3 Adhesion

5.8.3.1 Bend test. Each day, or every time the thermal spray equipment is used, the inspector should record and confirm that the operating parameters are the same as those used to prepare the job reference standard (Section 8.3.3). The thermal spray applicator should then apply the coating to prepared test panels and conduct a bend test. The bend test is a qualitative test used to confirm that the equipment is in proper working condition. The test consists of bending coated steel panels around a cylindrical mandrel and examining the coating for cracking. Details of the test are described in Section 8. If the bend test fails, corrective actions must be taken prior to the application of the TSMC. The results of the bend test should be recorded, and the test panels should be labeled and saved.

Test panels should be examined visually without magnification. The bend test is acceptable if the coating shows no cracks or exhibits only minor cracking with no lifting of the coating from the substrate. If the coating cracks and lifts from the substrate, the results of the bend test are unacceptable. TSMCs should not be applied if the bend test fails, and corrective measures must be taken. Figure 5 depicts representative bend test results.

Bend test samples can also be used for metallographic evaluations of porosity, oxide content, and interface contamination.

5.8.4 Appearance

5.8.4.1 Inspecting the coating. The applied TSMC should be inspected for obvious defects related to poor thermal spray applicator technique and/or equipment problems. The coating should

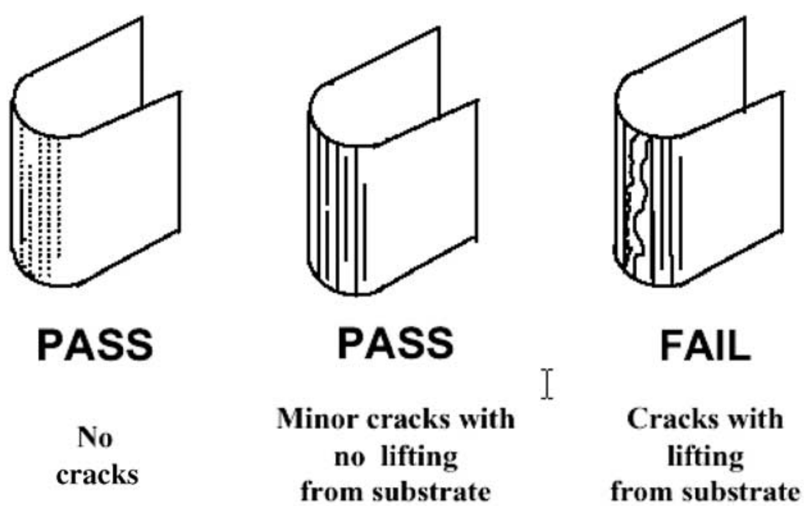

Figure 5. 180-degree bend test illustrating pass and fail appearance.

be inspected for the presence of blisters, cracks, chips or loosely adherent particles, oil, pits exposing the substrate, and nodules. A very rough coating may indicate that the coating was not applied with the gun perpendicular to the surface or that the coating was applied at too high of a standoff distance. Coatings that appear oxidized or powdery should be evaluated by light scraping. If scraping fails to produce a silvery metallic appearance, the coating is defective.

5.8.4.2 Coating appearance. The appearance of the coating should match that of the job reference standard.

5.9 Handling, Storage, and Transportation of Thermally Sprayed Metal Coated Piles

5.9.1 Aluminum, Zinc, and Zinc-Aluminum Coatings

Thermally sprayed metal surfaces are tough and are ready to be handled immediately after the application of the coating. However, aluminum, zinc, and zinc-aluminum coatings are softer than the steel substrate and are subject to scratching, gouging, and impact damage.

5.9.2 Handling Coated Piles

Coated piles should at all times be handled with equipment such as stout, wide belt slings and wide padded skids designed to prevent damage to the coating. Bare cables, chains, hooks, metal bars, or narrow skids shall not be permitted to come in contact with the coating. All handling and hauling equipment should be approved before use.

5.9.3 Loading Piles for Shipping by Rail

When shipped by rail, all piles should be carefully loaded on properly padded saddles or bolsters. All bearing surfaces and loading stakes shall be properly padded with approved padding materials. Pile surfaces should be separated so that they do not bear against one another, and the whole load must be securely fastened together to prevent movement in transit.

5.9.4 Loading Piles for Shipping by Truck

When shipped by truck, the piles should be supported in wide cradles of suitably padded timbers hollowed out on the supporting surface to fit the curvature of pipe, and all chains, cables, or other equipment used for fastening the load should be carefully padded.

5.9.5 Storing Piles

Stored piles should be supported on wooden timbers above the ground.

5.9.6 Hoisting Piles

Piles should be hoisted using wide belt slings. Chains, cables, tongs, or other equipment, no matter how well padded, are likely to cause damage to the coating and should not be permitted. Dragging or skidding the pile should not be permitted.

5.9.7 Repairing Damaged Coating

Damaged coating should be repaired in accordance with Section 7 of this guide.

6 SEALER SELECTION AND APPLICATION

6.1 Purpose

All TSMCs contain porosity that can range up to 15 percent. Many thermally sprayed coatings (e.g., aluminum, zinc, and their alloys) tend to be self-sealing. Over time, natural corrosion products fill the pores in the coating. This oxidation consumes a relatively small amount of the metal coating material. Interconnected or through-porosity may extend from the coating surface to the substrate. Through-porosity may impair the barrier performance of the TSMC. Aluminum coatings can "blush" or exhibit pinpoint rusting after several years. Aluminum coatings less than 0.006 in. (150 µm) thick and zinc coatings less than 0.009 in. (225 µm) thick should be sealed for this reason. Sealers are intended to fill porosity and improve the overall service life of the thermal spray system. Sealers are *not* intended to completely isolate the metal coating from the environment and are not intended to function as barrier coatings. Topcoats having higher film build properties are needed to perform the function of a barrier coating. Compared with unsealed TSMCs, sealed TSMCs generally have a longer service life, are easier to clean and maintain, and tend to improve the performance of externally applied cathodic protection somewhat by reducing the area of metal that must be protected.

In some cases, sealing is performed to improve the appearance and "cleanability" of the thermally sprayed metal coated surface. Sealers reduce the retention of dirt and other contaminants by the TSMC. In particular, the sealer may prevent the accumulation of corrosive salts, rain-borne corrosives, and bird droppings.

Thermally sprayed coatings on a steel substrate should be sealed or sealed and topcoated under any of the following conditions:

- When the environment is very acidic or very alkaline (the normal useful pH range for pure zinc is 6 to 12 and for pure aluminum is 4 to 11).
- When the metallic coating is subject to direct attack by specific chemicals.
- When a particular decorative finish is required.
- When additional abrasion resistance is required.
- Under conditions of frequent saltwater spray, splashing, or immersion service.
- Under conditions of frequent freshwater spray, splashing, or immersion service.

6.2 Characteristics

6.2.1 Characteristics of Sealers

Sealers must exhibit the following characteristics:

- They must be low-viscosity products in order to infiltrate the pores of the TSMC. The pigment particle size for colored sealers must be small enough to flow easily into the pores of the TSMC, as per ASTM D1210.

- They must be low-build products that may be applied at low film thickness, generally 0.003 in. (75 µm) or less.
- The resin chemistry of the sealer must be compatible with the thermally sprayed coating material. **Some oleoresinous sealers may saponify if applied over zinc metal surfaces because of the alkalinity of zinc. This will cause the sealer to dissolve at the metal interface, resulting in disbondment of the coating.**
- The selected sealer material must also be compatible with the intermediate coats and topcoats of paint, if used.
- Sealers must be suitable for the intended service environment.
- Sealers and topcoats should meet the local regulations on volatile organic compound (VOC) content. They should be applied in accordance with the manufacturer's instructions or as specified by the purchaser.
- As applied to TSMCs on a steel substrate, sealer must meet a minimum drop weight impact requirement of 188 ft-lbs (254 n-M) when tested in accordance with ASTM D2794 (Modified).

6.2.2 Characteristics of Topcoats

Topcoats must exhibit the following characteristics:

- The topcoat is used for additional chemical resistance and must be compatible with the service environment.
- The topcoat should be compatible with the sealer and the TSMC.
- The topcoat should be applied to relatively low film thickness, generally not exceeding 0.005 in. (125 µm).
- Full topcoats will greatly reduce or entirely diminish the cathodic protection effects of the TSMC in immersion or underground service.
- A conventional paint should not be applied over an unsealed TSMC.
- Topcoats should have gloss and color retention where appearance is a concern.

6.3 Types

Descriptions and specifications for sealers and topcoat paints may be found in

- The Steel Structures Painting Council's *Steel Structures Painting Manual*, Volume 2.
- Table 4C, Part 2, Product Section CP, "Pretreatment and Sealers for Sprayed-Metal Coatings," of BS 5493, *Code for Practice for Protective Coating of Iron and Steel Structures Against Corrosion* (1977).
- The U.S. Army Corps of Engineers Engineering and Design Manual, *Thermal Spraying: New Construction and Maintenance*, EM 1110-2-3401, Washington, D.C., January 29, 1999.
- The U.S. Army Corps of Engineers Guide Specification for Construction, *Painting: Hydraulic Structures,* CEGS-09965.

Many types of sealers are appropriate for use on steel pilings. These include vinyl, epoxy, and oleoresinous coatings. Of concern in the selection of a sealer is the volatile organic compound (VOC) content. Some sealers or thinned sealers might exceed VOC content regulations.

6.3.1 Vinyls

Vinyl-type coatings are well suited to sealing TSMCs. They are compatible with most service environments, including saltwater and freshwater immersion and marine, industrial, and rural atmospheres. Vinyls are compatible with zinc, aluminum, and 85 : 15 wt% zinc/aluminum coatings. They are very-low-viscosity materials with low film build characteristics. Vinyl sealers should be applied to a dry film thickness of about 0.0015 in. (37.5 μm). Vinyl sealers are readily topcoated with vinyl paint. Subsequent coats of vinyl should be applied to a dry film thickness of 0.002 in. (50 μm) per coat. The vinyl sealer should be thinned 25 percent by volume with the specified thinner. The approximate viscosity of the sealer should be 20 to 30 sec measured with a No. 4 Ford Cup Viscometer in accordance with ASTM D1200, "Test Method for Viscosity by Ford Cup Viscometer."

6.3.2 Epoxies

Three types of epoxy sealers are commonly used: coal tar epoxy, aluminum epoxy mastic, and epoxy sealer–urethane topcoat systems.

6.3.2.1 Coal tar epoxy. Coal tar epoxy may be applied as a relatively thick film single-coat sealer for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum thermal spray coatings. The coal tar epoxy sealer should be thinned approximately 20 percent by volume and applied in a single coat to a dry film thickness of 0.004 to 0.006 in. (100 to 150 μm). The sealer is applied at a thickness suitable for covering the roughness of the TSMC, providing a smooth surface that minimizes hydraulic friction.

6.3.2.2 Aluminum epoxy mastic. Aluminum epoxy mastic sealers are suitable for one-coat use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum thermally sprayed coatings for use in marine, industrial, and rural atmospheres as well as for use over aluminum and 90-10 aluminum-aluminum oxide in nonskid applications. The aluminum epoxy mastic should be thinned to the maximum extent recommended in the manufacturer's written directions and applied to a dry film thickness of 0.003 to 0.005 in. (75 to 125 μm). This sealer provides an aluminum finish.

6.3.2.3 Epoxy sealer–urethane topcoat systems. Epoxy sealer–urethane topcoat systems are suitable for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum coatings exposed in marine, industrial, and rural atmospheres as well as for use on nonskid aluminum and 90-10 aluminum-aluminum oxide coatings. The epoxy sealer coat should be thinned to the maximum extent recommended in the manufacturer's written directions and applied to a dry film thickness of 0.003 to 0.004 in. (75 to 100 μm). The polyurethane topcoat should be applied to a maximum dry film thickness of 0.003 in. (75 μm). The polyurethane topcoat may be procured in a variety of colors.

6.3.3 Oleoresinous

Two types of oleoresinous sealers are used: tung-oil phenolic aluminum and vinyl-butyral wash primer/alkyd (SSPC Paint No. 27).

6.3.3.1 Tung-oil phenolic aluminum (TT-P-38). This phenolic aluminum sealer is suitable for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum thermally sprayed coatings exposed in marine, industrial, and rural atmospheres. The sealer should be thinned 15 percent by volume and applied to a dry film thickness of 0.0015 in. (37.5 μm). A second coat of the phenolic aluminum should be applied to the dried sealer to a dry film thickness of approximately 0.002 in. (50 μm). This sealer system produces an aluminum finish.

6.3.3.2 Vinyl-butyral wash primer/alkyd (SSPC Paint No. 27). This wash primer/alkyd sealer system is suitable for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum thermally sprayed coatings exposed in marine, industrial, and rural atmospheres. The wash primer coat sealer should be thinned according to the manufacturer's instructions and applied to an approximate dry film thickness of 0.0005 in. (12.5 μm). Commercial alkyd sealer coatings should be applied over the dried wash primer coat to a dry film thickness of 0.002 to 0.003 in. (50 to 75 μm). Other topcoats can be applied per manufacturer's recommendations.

6.3.4 Low Surface Energy, High-Solids Epoxy

Low surface energy, high-solids sealers are deep-penetrating primers that penetrate the pores of the TSMC. They have a high solids content—up to 100 percent—but have a very low viscosity that permits them to penetrate through pores and cracks. The sealer is applied to a thickness of 1.0 to 2.0 mils (25 to 50 μm) per coat. They are two-part systems. They are designed for use with a topcoat and can be topcoated with acrylics, alkyds, epoxies, or polyurethanes.

6.3.5 Low-Viscosity Penetrating Urethane

These are single-component, micaceous-iron-oxide-pigmented, moisture-cured polyurethane coatings.

6.3.6 Other Sealers

Other sealers can be considered as long as they comply with the characteristics listed.

6.4 Application

6.4.1 Application Work Period

In general, surface preparation, thermal spray application, and sealing of a given area should be accomplished in one continuous work period of not longer than 16 hours, and preferably within 8 hours of the thermal spray coating step. Subsequent paint coats should be applied in accordance with the requirements of the painting schedule.

6.4.2 Preparation for Sealing

Surfaces to be sealed should first be blown down using clean, dry, compressed air to remove dust. If the sealer cannot be applied within 8 hours or if there is an indication of contamination, verify by visual (10x) inspection that the sprayed metal coating has not been contaminated and is dust free (ISO 8502-3 clear cellophane tape test) before applying the sealer. The thermally sprayed surfaces should be sealed before visible oxidation of the TSMC occurs.

6.4.3 Presence of Moisture

If moisture is present or suspected in the TSMC pores, the steel may be heated to 120°F (50°C) to remove the moisture prior to the seal coat application. When possible, the steel from the reverse side of the TSMC should be heated to minimize oxidation and contamination of the TSMC prior to sealing.

6.4.4 Application Techniques

Sealers should be applied by conventional or airless spraying, except that vinyl-type sealers must only be applied using conventional spray techniques. Spray application provides the level of control necessary to achieve thin, uniformly thick coatings. Thin sealer-topcoat systems are preferred to thicker films that may retain moisture and reduce the overall coating system life.

6.4.5 Regulations and Recommendations for Application

All paint sealer and topcoating should be applied according to SSPC-PA-1, "Shop, Field and Maintenance Painting," and the paint manufacturer's recommendations for use of the product with a TSMC system.

6.4.6 Thinning

Sealers may need to be suitably thinned to effectively penetrate the TSMC.

6.4.7 Dry Film Thickness

Typically the sealer coating is applied at a spreading rate resulting in a theoretical 1.5-mil (38-μm) dry film thickness.

6.4.8 Topcoat

A topcoat is essentially a full coat of paint and may be applied over a seal coat. Topcoats should normally be applied as soon as the sealer is dry and preferably within 24 hours.

6.5 Quality Control

6.5.1 Confirm Complete Coverage of Seal Coat

During application of the seal coat, visually confirm complete coverage. The seal coat should be thin enough when applied to penetrate into the body of the TSMC and seal the porosity. Added thickness to a porous TSC might not be measurable.

6.5.2 Confirm Complete Coverage of Topcoat

During application of the topcoat, visually validate complete coverage.

6.5.3 Measuring Thickness of the Topcoat

If required by the contract, measure the thickness of the topcoat per SSPC-PA-2 using a Type 2 fixed-probe gauge. The measurement may be made on either a companion coupon or the sealed TSMC if the TSMC thickness has been previously measured. Alternately, the thickness can be measured destructively using ASTM D4138, Test Method A. This method has the advantage of being able to observe all the layers; however, this type of measurement should be minimized since the areas tested must be repaired in order to maintain the coating integrity.

6.5.4 Correcting Areas of Deficient Thickness

Areas of deficient thickness should be noted and corrected, if practicable, by adding sealer or paint. Additional testing may be necessary to determine the extent of the area with deficient sealer or paint thickness. The sealer thickness should be checked prior to the application of paint coats, if practical, and the measurement procedure should be repeated for the sealer and paint.

6.5.5 Methods to Determine Sealer Coverage

The thickness of sealers is difficult to quantify because of the thin coats applied and the absorption of the sealer into the pores. A high film build of sealer over the thermally sprayed metal is *not* desired. In fact, sealer thickness is of value only in determining whether it has been uniformly applied to the surface. Two methods that can be used to determine sealer coverage include the following:

- Dry film thickness measurement. (This is probably the least reliable because of the very thin thickness of the sealer and the absorption of the sealer into the thermally sprayed coating. Dry film thickness measurements are best used as statistical comparisons between unsealed areas and sealed areas. A coupon that has been prepared with a known thickness of unknown thermally sprayed metal using the same techniques used to coat the structure [equipment, operator, number of passes, and deposition rate] can be used.)
- Tinting the sealer.

6.6 Generic Sealer Specification

Section 11 presents a generic sealer specification.

7 REPAIR AND MAINTENANCE

7.1 Introduction

Deterioration and damage to the TSMC can occur under several circumstances, including damage during installation, impact by foreign objects, abrasion, and corrosion. Damage that occurs during installation should be identified by the inspector and repaired according to the specifications. Repair to installation damage can vary from complete replacement of the coating to minor touch-up depending on the extent of the damage. This section can be used for minor repairs as defined by the specification or agreement between the owner and applicator. Damage that occurs during service requires periodic inspection to identify the need to repair TSMC systems.

7.2 Assessment

The first step in the repair of TSMCs is an assessment of the type of thermal spray coating system under evaluation and the nature of the damage or wear. Steps in assessing the need to repair a thermal spray coating system are listed below.

7.2.1 Identification of the Type of Thermal Spray and Sealer Material Originally Applied

Historic records should be reviewed for information on the type of TSMC and sealer used as well as any previous repairs. Chemical analyses may also be used. The experienced observer may also be able to distinguish between the various types of thermally sprayed materials.

7.2.2 Identification and Documentation of the Type and Extent of Deterioration

7.2.2.1 Test methods for quantifying coating deterioration. The following test methods have visual standards for quantifying coating deterioration:

- ASTM F1130, "Standard Practice for Inspecting the Coating of a Ship" (useful for standardizing the method of reporting the extent of corrosion and coating deterioration).
- ASTM D610, "Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces" (provides standard charts for quantifying the amount of rusting on a steel surface).
- ASTM D3359, "Test Method for Measuring Adhesion by Tape Test."
- ASTM D714, "Test Method for Evaluating Degree of Blistering of Paints."
- ASTM D4214, "Test Method for Evaluating Degree of Chalking of Exterior Paint Films."
- ASTM D660, "Test Method for Evaluating Degree of Checking of Exterior Paints."
- ASTM D661, "Test Method for Evaluating Degree of Cracking of Exterior Paints."
- ASTM D662, "Test Method for Evaluating Degree of Erosion of Exterior Paints" (a standardized reporting form should be developed and kept on file for the structure for future reference).

7.2.2.2 Identification of sealer defects. Sealer defects are difficult to identify unless a topcoat has been used. Sealer and topcoat defects include disbondment from the substrate, cracking, checking, and mechanical damage. These will expose the thermally sprayed metal to the environment, which can reduce its service life. Lesser defects include discoloration and chalking, which do not necessarily indicate that the substrate is exposed, but do indicate eventual exposure of the substrate.

7.2.2.3 Identification of defects in thermally sprayed metal. Defects in the thermally sprayed metal include worn coating (indicated by general or localized thickness reductions); coating oxidation (evident by the presence of a powdery residue on the coating surface); the presence of rust and bare steel; and cracked, blistered, and delaminated areas.

7.3 Determination of Repair and Recoat Intervals

7.3.1 TSMC

The need to repair or replace the metal coating depends on how much corrosion the structure can tolerate, the type of corrosion that can be tolerated, and the corrosion rate of the structure in the environment. For example, pitting on a pile often can be tolerated because it does not affect the structural integrity of the structure. On the other hand, a pit in a sheet pile might not be acceptable since a perforation would affect the ability of the structure to hold back water. In that case, even small pits must be repaired quickly.

The corrosion rate of the structure should be monitored at defects in the coating and repairs scheduled when it is determined that the amount of corrosion is threatening to reach the critical thickness. In a corrosive environment (e.g., seawater), repairs to the coating will have to be more frequent than in a less corrosive environment (e.g., freshwater).

7.3.2 Sealer and Topcoat

One approach to determining the time to repair and recoat detailed in G. H. Brevoort, M F. Melampy, and K. R. Shields, "Updated Protective Coating Costs, Products, and Service Life," *Materials Performance*, February 1997, pp. 39–51:

Maintenance painting can take the following sequence:

Action	% Breakdown	Occurrence
Original coating		Initially
Spot touch-up and repair	5–10*	33% of expected life
Maintenance repaint (spot prime and full coat)	5–10*	50% of expected life
Full recoat	5–10*	100% of expected life

* before active rusting of substrate

7.4 Repair Methods

7.4.1 Standards for Repair and Maintenance

The American National Standards Institute (ANSI) and the American Welding Society (AWS) have published a standard for the repair and maintenance of TSMCs. The TSMC repair procedures used depend on the type and extent of degradation and the presence or absence of sealer and paint topcoats. ANSI/AWS C2.18-93, “Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites,” addresses the maintenance and repair of TSMCs. This section summarizes the types of repairs that might be encountered and the procedures available.

7.4.2 Repair Procedures

7.4.2.1 Increasing TSMC thickness. Unsealed TSMCs that are worn thin or that were applied to less than the specified thickness may be repaired by repreparing the surface and applying more metal. If the coating was recently applied, it may be possible to simply apply additional coating directly onto the original coating. If the coating is oxidized, the abrasive brush blast procedure should be used prior to application of additional TSMC material.

7.4.2.2 Repair of small (<1 ft^2 [<0.1 m^2]) damaged areas with steel substrate not exposed. Repair by solvent cleaning, scraping with a flexible blade tool, wire brushing, edge feathering, lightly sanding to abrade the cleaned areas, and sealing and painting.

7.4.2.3 Repair of large (>1 ft^2 [>0.1 m^2]) damaged areas with steel substrate not exposed. Repair by solvent cleaning, abrasive brush blasting, edge feathering, and sealing and painting.

7.4.2.4 Repair of TSMCs with steel substrate exposed. Either of two procedures may be used to repair TSMCs damaged to the extent that the steel substrate is exposed. One method uses a rapid “paint only” repair procedure that is useful in emergency situations, and the other utilizes a TSMC plus sealer and paint coats procedure that is far more durable. The emergency repair procedure should always be followed by the more permanent repair when conditions permit.

7.4.2.4.1 *The rapid “paint only” repair procedure*. The rapid “paint only” repair procedure includes solvent cleaning, scraping with a hard blade tool, power tool cleaning, edge feathering, sealing, and topcoating.

7.4.2.4.2 *The thermal spray repair procedure*. The thermal spray repair procedure includes solvent cleaning, scraping with a hard blade tool, abrasive blast cleaning to near white metal, edge feathering, TSMC application, sealing, and topcoating.

7.4.3 Description of Repair Procedure

7.4.3.1 Solvent cleaning. Grease and oil should be removed by solvent cleaning. The solvent may be applied by wiping, brushing, or spraying. The following cleaning solvents may be used: Super Hi-Flash Naphtha, Type I (ASTM D3734) and n-Butyl Alcohol (ASTM D304). Precautions should be taken to protect any parts that may be affected by the solvents, and all appropriate safety precautions must be taken.

7.4.3.2 Flexible-blade scrape to bonded TSMC. Use a 1-in. (25-mm) flexible-blade paint scraper to remove loose paint and TSMC around damaged or worn areas until the tightly adherent paint and TSMC is reached. Care should be taken not to gouge or further damage the TSMC.

7.4.3.3 Hard-blade scrape to bonded TSMC. Use a hard-blade paint scraper to push the blade underneath the loose TSMC, and push and scrape away all loosely adherent paint and TSMC until reaching a well-bonded area.

7.4.3.4 Hand brush clean. Use a stiff hand-held stainless-steel or bristle brush to vigorously brush away loose debris. *Power tools should not be used as they will polish the thermally sprayed coating and may wear through the thermally sprayed coating to the substrate.*

7.4.3.5 Abrasive brush blast. Clean abrasive blasting media, such as fine mesh (30–60) angular iron oxide grit or aluminum oxide, may be used to abrasive brush blast away loose paint. *Use low enough blasting pressures to minimize abrasion and removal of thermal spray coating, but high enough pressure for reasonable paint and loose TSMC removal and the development of a sufficient anchor-tooth pattern for sealers and topcoat paints*.

7.4.3.6 Power-tool cleaning per SSPC-SP-3. For power-tool cleaning, hand-held power cleaning tools (e.g., disc sander with 80-mesh abrasive paper and stainless steel rotary brushes) should be used, using light pressure to clean and roughen the surface for painting. Do not polish the surface smooth.

7.4.3.7 Abrasive blast to near-white-metal finish and ≥ 2.5-mil (63-µm) profile. The surface should be abrasively (or mechanically) blasted to a near-white-metal finish with a ≥ 2.5-mil (63-µm) profile. The blasting nozzle should be kept perpendicular ± 10 degrees to the work surface; angle blasting into the TSMC/steel bond line may debond the bonded TSMC from the substrate.

7.4.3.8 Feathering. A 2- to 3-in. (50- to 80-mm) border should be feathered into the undamaged paint and TSMC area. Feathering is the operation of tapering off the edge of a coating.

7.4.3.9 Light abrasion. The prepared surface and the feathered area around the exposed TSMC should be lightly abraded with sand/grit paper to provide a mechanical bonding surface for the sealer or sealer and topcoat.

7.4.3.10 TSMC application. The thermal spray repair metal should be the same as that originally applied. Flame sprayed coatings should be repaired only by the flame spray technique. Wire-arc spray has a greater energy (particle impact velocity and temperature) and may delaminate marginal flame sprayed coatings. Wire-arc sprayed coatings may be repaired using either wire-arc or flame spray.

7.4.3.11 Sealers and topcoats. Apply the sealer and/or topcoat using proper application techniques.

7.5 Quality Control

Quality control provisions apply to the various repair procedures as detailed in the corresponding sections of the guide regarding

- Ambient air conditions,
- Surface temperature,

- Surface cleanliness,
- Surface profile,
- Adhesion,
- TSMC thickness,
- Sealer thickness, and
- Topcoat thickness.

8 QUALITY CONTROL AND INSPECTION

8.1 Introduction

Owners should make provisions to ensure the quality of the coating by providing detailed specifications and competent inspection. Wire manufacturers need to have quality control systems in place to ensure that the wire can be applied and will perform as intended. Applicators must ensure that they have the correct experience and equipment and competent applicators to prepare the structure and apply the coating.

Inspection is one of the most important aspects of coating. It provides a written record of the details of the coating application, ensures that the coating specifications are met, and finds and ensures the correction of inadequate coating areas before they become failure locations in the future requiring costly correction.

Particular attention must be directed toward difficult-to-coat areas, such as the inside surfaces of H-shapes and the interlock knuckles of sheet piling, because these are areas where optimum nozzle/gun angles and distances will be difficult to attain.

8.2 Quality Assurance Functions for Owners

8.2.1 Informed Selection

An informed selection should be made of TSMCs taking into account planned use of the coatings and the environment in which they are to be used.

8.2.2 Provide Definitive Specifications

Specifications should include, as a minimum and as an addition to contractual provisions, the following:

- Scope of work, to include the structure to be coated and portions not to be coated;
- All applicable references;
- Provisions for payment;
- Definitions;
- A list of required submittals;
- Safety provisions;
- Requirements for delivery, storage, and handling of materials and supplies;
- Chemical composition, finish, coil weight, and preparation of metallizing wire;
- Requirements for sampling and testing thermally sprayed materials and the applied sealer;
- A job reference standard with a description of appearance and adhesion requirements;
- Requirements for surface preparation;
- Metallizing application;
- Workmanship;
- Atmospheric and surface conditions;

- Sequence of operations;
- Approved methods of metallizing;
- Coverage and metallizing thickness;
- Progress of metallizing work;
- Sealing and painting instructions;
- Metallizing schedule; and
- Quality control requirements.

8.2.3 Coating Inspector

Provide a qualified coating inspector to provide full-time inspection services. This should be a third-party inspector with the power and ability to work out problems with the applicator to achieve the desired coating quality. Section 9.3 lists the necessary qualifications of an inspector.

8.3 Quality Control

8.3.1 Documentation

The documentation of inspection activities provides a permanent record of the thermal spray job. Thorough documentation provides a written record of the job in the event of a contract dispute or litigation. Inspection records may also be used to help diagnose a premature coating failure. Future maintenance activities may also be simplified by the existence of complete inspection records. As a minimum, at least one full-time inspector should be used on all thermal spray jobs to ensure adequate inspection and documentation. A qualified third-party inspector from a reputable firm should perform the inspection. As a minimum, the inspector should perform and document the inspection procedures described in this section. Sample documentation forms for industrial coating activities are available through NACE International and the Society for Protective Coatings.

The inspector should record the production and quality control information required by the purchaser or the purchasing contract. Among the items that should be recorded are

- Information about the contractor and purchaser;
- Surface preparation and abrasive blasting media requirements;
- Flame or wire-arc spray equipment used;
- Spraying procedure and parameters used;
- TSMC requirements;
- Safety precautions followed;
- Environmental precautions;
- Test data taken, including

  – Nature of the test,
  – When conducted,
  – Where conducted,

- Results, and
- Abnormalities and resolution; and

- Problems and resolution.

The inspector should keep records for the time period required for regulatory compliance and required by the purchasing contract.

8.3.2 Testing Frequency

The required frequency of inspection procedures should be documented in the specification. Inspection can be expensive, and care should be taken not to overspecify inspection procedures. Conversely, inspection has an intrinsic value that is sometimes intangible. It is difficult to measure the value added by inspection resulting from the conscientious performance of the contract. Thermal spray can be quite sensitive to the quality of surface preparation, thermal spray equipment setup, and application technique. Therefore, it is important to specify an appropriate level of inspection. Table 8 presents recommended frequencies for various inspection procedures.

8.3.3 Job Reference Standard and Material Samples

8.3.3.1 Material samples. Reference samples of each material used on a thermal spray job should be collected, including clean, unused abrasive blast media; thermal spray wire; sealer; and paint. Samples may be used to evaluate the conformance of materials to any applicable specifications.

- A 2.2-lb (1-kg) sample of blast media should be collected at the start of the job. The sample may be used to verify the cleanliness, media type, and particle size distribution of the virgin blast media. A 12-in. (30-cm) sample of each lot of thermal spray wire should be collected.
- The wire sample may be used to confirm that the manufactured wire conforms to the size and compositional requirements of the contract.
- One-quart (1-liter) samples of all sealers and paints should be collected for compliance testing.

TABLE 8 Recommended inspection frequencies for selected procedures

Inspection Procedure	Recommended Frequency per Unit Area
Surface profile	3 per 500 ft^2 (45 m^2) or less
Thermal spray coating thickness	5 per 100 ft^2 (9 m^2) or less
Thermal spray adhesion	2 per 500 ft^2 (45 m^2) or less
Sealer thickness	2 per 500 ft^2 (45 m^2) or less
Paint thickness	2 per 500 ft^2 (45 m^2) or less
Soluble salts	1 per 1,000 ft^2 (90 m^2) or less

8.3.3.2 Job reference standard. A thermal spray job reference standard (JRS) should be prepared. The JRS may be used at the initiation of a thermal spray contract to qualify the surface preparation, thermal spray application, and sealing processes. The JRS and the measured values may be used as a visual reference or job standard for surface preparation, thermal spray coating, sealing, and painting, in case of dispute.

8.3.3.3 Preparing the JRS. The JRS should be prepared prior to the onset of production work. To prepare the JRS, a steel plate of the same alloy and thickness to be coated, measuring 2 × 2 ft (60 × 60 cm) should be solvent and abrasive blast cleaned in accordance with the requirements of the contract. The abrasive blast equipment and media used for the JRS should be the same as those that will be used on the job.

One-quarter of the JRS plate should be masked using sheet metal, and the TSMC should be applied to the unmasked portion of the plate. The TSMC should be applied using the same equipment and spray parameters proposed for use on the job. The gun should be operated in a manner substantially the same as the manner in which it will be used on the job. The approximate traverse speed and standoff distance during spraying should be measured and recorded.

Two-thirds of the thermal spray–coated portion of the JRS should be sealed in accordance with the requirements of the contract. One-half of the sealed area should be painted in accordance with the contract if applicable. The sealer and paint should be applied using the same paint spray equipment that will be used for production.

The prepared JRS should be preserved and protected in such a manner that it remains dry and free of contaminants for the duration of the contract. The preserved JRS should then be archived for future reference in the event of a dispute or premature coating failure.

Once the JRS is qualified, the operating parameters should not be altered by the contractor, except as necessitated by the requirements of the job.

Figure 6 depicts a representative JRS.

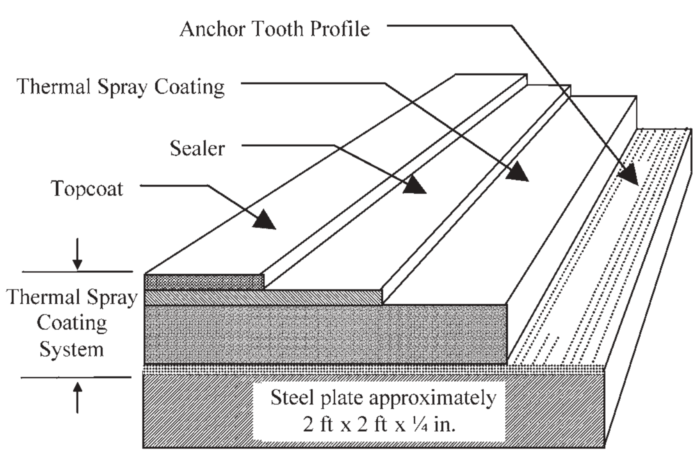

Figure 6. Job reference standard configuration (1 in. = 2.54 cm, 1 ft = 30.48 cm).

8.3.3.4 Evaluating the JRS. The surface cleanliness; blast profile shape and depth; thermal spray appearance, thickness, and adhesion; and sealer and paint thickness should be determined in accordance with the contract requirements and recorded.

8.3.4 Testing Prior to Surface Preparation

8.3.4.1 Ambient conditions measurement. An assessment of the local atmospheric conditions should be made before surface preparation and thermal spray application begins. Measurement of ambient conditions includes substrate temperature, air temperature, dew point, and relative humidity.

- A contact thermocouple or infrared pyrometer should be used to measure the substrate temperature.
- Air temperature should be measured using a sling psychrometer, thermometer, or digital measurement instrument.
- Dew point should be calculated using the appropriate psychrometric charts.
- Humidity should be determined in accordance with ASTM E337, "Test Method for Measuring Humidity with a Psychrometer (The Measurement of Wet-Bulb and Dry-Bulb Temperatures)."

8.3.4.2 Inspection preceding surface preparation. Prior to abrasive blasting, inspect the substrate for the presence of contaminants including grease and oil, weld flux and spatter, heat-affected zones, flame-cut edges, pitting, sharp edges, and soluble salts.

- *Grease and oil.* Painted surfaces and newly fabricated steel should be visibly inspected for the presence of organic contaminants such as grease and oil, as required by the project specification. Continue degreasing until all visual signs of contamination are removed. Conduct the UV light test, qualitative solvent evaporation test, or the heat test to detect the presence of grease and oil.

  – Use a UV lamp to confirm the absence of oil or grease contamination.
  – The solvent evaporation test should be made by applying several drops or a small splash of a residual-less solvent, such as trichloromethane, on the areas suspected of oil and grease retention (e.g., pitting and crevice corrosion areas and depressed areas, especially those collecting contamination, etc.). An evaporation ring will form if oil or grease contamination is present.
  – The heat test should be made by using a torch to heat the degreased metal to about 225°F (110°C). Residual oil/grease contamination should be drawn to the metal surface and is visually apparent.

- *Weld flux and spatter.* A visual inspection for the presence of weld flux and spatter should be performed, as required by the project specification. Weld flux should be removed prior to abrasive blast cleaning using a suitable SSPC-SP 1 "Solvent Cleaning" method. Weld spatter may be removed either before or after abrasive blasting using suitable impact or grinding tools. Areas that are power-tool cleaned of weld spatter should be abrasive blast cleaned.

- *Heat-affected zones caused by welding.* Heat-affected zones should be identified and marked prior to abrasive blasting as required by the specification. Extra care during surface preparation and extra attention to profile inspection should be given to these areas.
- *Flame-cut edges.* Flame-cut edges should be identified and marked prior to abrasive blasting as required by the specification. The demarcated areas should be ground using power tools prior to abrasive blast cleaning.
- *Pitting.* Deep pits or pitted areas should be identified and marked prior to abrasive blast cleaning as required by the specification. The demarcated areas should be ground using power tools prior to abrasive blast cleaning.
- *Sharp edges.* Sharp edges should be identified and marked prior to abrasive blasting as required by the specification. The demarcated edges should be prepared by grinding to a minimum radius of $^1/_8$ in. (3 mm) prior to blast cleaning.
- *Soluble salts.* When soluble salt contamination is suspected, the contract documents should specify a method of retrieving and measuring the salt levels as well as acceptable levels of cleanliness. Salt contamination is prevalent on structures exposed in marine environments and on structures such as parking decks and bridges exposed to deicing salts. Structures that are likely to have soluble salt contamination, including those in marine or severe industrial atmospheres, bridges or other structures exposed to deicing salts, and seawater immersed structures, should be tested. Soluble salt levels should be rechecked for compliance with the specification after solvent cleaning and abrasive blasting have been completed. Common methods for retrieving soluble salts from the substrate include cell retrieval methods and swabbing or washing methods. Various methods are available for assessing the quantity of salts retrieved, including conductivity, commercially available colorimetric kits, and titration. The rate of salt retrieval is dependent on the retrieval method. The retrieval and quantitative methods should be agreed upon in advance.

  The recommended testing procedure employs the Bresle cell (ISO 8502-6) to extract soluble salts from the substrate. Chloride ion concentration is readily measured in the field using titration strips available from Quantab. The test strip analyzes the collected sample and measures chloride ion concentration in parts per million. The unit area concentration of chloride ions is calculated in micro-grams per centimeter. The lower detection limit for the Bresle/Quantab method is about 2 μm/cm^2. SSPC-SP-12/NACE #5 describes levels of soluble salt contamination. It is recommended that surfaces cleaned to an SC-2 condition be used for TSMCs. An SC-2 condition is described as having less than 7 μm/cm^2 of chloride contaminants, less than 10 μm/cm^2 of soluble ferrous ions, and less than 17 μm/cm^2 of sulfate contaminants. The number of tests per unit area (e.g., 1 per 1,000 ft^2 [90 m^2]) should be specified in the contract documents. Also refer to "SSPC Technology Update: Field Methods for Retrieval and Analysis of Soluble Salts on Substrates," and SSPC-91-07.

8.3.5 Testing During Surface Preparation

8.3.5.1 Abrasive cleanliness. Abrasive blast media must be free of oil and salt to prevent contamination of the substrate. Recycled steel grit abrasive should comply with requirements of SSPC-AB-2, "Specification for Cleanliness of Recycled Ferrous Metallic Abrasives."

- *Evaluating for salt in abrasives.* Most abrasives used to prepare steel substrates for thermal spraying are unlikely to contain appreciable amounts of soluble salts. However, slag abrasives used for strip blasting may sometimes contain measurable quantities of salts. Slag abrasives should be evaluated in accordance with ASTM D4940, "Test Method for Conductimetric Analysis of Water Soluble Ionic Contamination of Blasting Abrasives."

- *Testing for oil in abrasives.* To test for oil in abrasives, a clear glass container should be half filled with unused abrasive, and then distilled or deionized water should be added to fill the container. The resulting slurry mixture should be stirred or shaken and allowed to settle. The water should then be examined for the presence of an oil sheen. If a sheen is present, the media should not be used, and the source of contamination should be identified and corrected.

8.3.5.2 Air cleanliness. The following guidelines apply to air cleanliness.

- The compressed air used for abrasive blasting, thermal spraying, sealing, and painting should be clean and dry. Oil or water in the blasting air supply may contaminate or corrode the surface being cleaned. Oil or water in the thermal spray, sealing, or painting air supply may result in poor coating quality or reduced adhesion. Compressed air cleanliness should be checked in accordance with ASTM D4285, "Method for Indicating Water or Oil in Compressed Air." The air compressor should be allowed to warm up, and air should be discharged under normal operating conditions to allow accumulated moisture to be purged. An absorbent clean white cloth should be held in the stream of compressed air not more than 24 in. (60 cm) from the point of discharge for a minimum of 1 minute. The air should be checked as near as possible to the point of use and always after the position of the in-line oil and water separators. The cloth should then be inspected for moisture or staining.
- If moisture or contamination is detected, the deficiency should be corrected before going further.

8.3.5.3 Blast air pressure. The contractor should periodically measure and record the air pressure at the blast nozzle. The measurement should be performed at least once per shift and should be performed on each blast nozzle. Measurements should be repeated whenever work conditions are altered such that the pressure may change. Pressures should be checked concurrently with the operation of all blast nozzles. The method employs a hypodermic needle attached to a pressure gauge. The needle is inserted into the blast hose at a 45-degree angle toward and as close to the nozzle as possible. The blast pressure is read directly from the gauge.

8.3.5.4 Blast nozzle orifice. The contractor should visually inspect the blast nozzle periodically for wear or other damage. Gauges are available that insert into the end of the nozzle and measure the orifice diameter. Nozzles with visible damage or nozzles that have increased one size should be replaced. Worn nozzles are inefficient and may not produce the desired blast profile. Damaged nozzles may be dangerous.

8.3.5.5 Surface cleanliness. The following applies to surface cleanliness.

- *Blast Cleanliness.* The final appearance of the abrasive cleaned surface should be inspected for conformance with the requirements of SSPC-SP-5. An SP-5 surface is defined as free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products, and other foreign matter. The appearance of SP-5 surfaces is dependent on the initial condition of the steel being cleaned. SSPC-VIS-1 may be used to interpret the cleanliness of various blast-cleaned substrates based on the initial condition of the steel and the type of abrasive used. Initial conditions depicted include the following:

- Rust Grade A—a steel surface completely covered with adherent mill scale with little or no rust visible;
- Rust Grade B—a steel surface covered with both mill scale and rust;
- Rust Grade C—a steel surface completely covered with rust with little or no pitting; and
- Rust Grade D—a steel surface completely covered with rust with visible pitting. The inspector should determine the initial substrate condition or conditions.

The final appearance of the surfaces should then be compared with the appropriate photograph. No stains should remain on the SP-5 surface. However, the appearance of the surface may also vary somewhat, depending on the type of steel, presence of roller or other fabrication marks, annealing, welds, and other differences in the original condition of the steel. The job reference standard should be used as the basis for judging the surface cleanliness.

- *Dust.* Abrasive blasting and overspray from painting or metallizing can leave a deposit of dust on a cleaned substrate. The dust may interfere with the adhesion of the TSMC. Residual dust may be detected by applying a strip of clear tape to the substrate. The tape is removed and examined for adherent particles. Alternatively, a clean white cloth may be wrapped around a finger and wiped across the surface. The cloth and substrate are then examined for signs of dust. The preferred method of removing residual dust is by vacuuming. Alternatively, the surface may be blown down with clean, dry compressed air.

8.3.5.6 Surface profile. The following applies to surface profile.

- ASTM D4417, "Test Methods for Field Measurements of Surface Profile on Blast Cleaned Steel," provides test methods for surface profile measurement. Methods A and B use either a needle depth micrometer to measure the depth of the valleys in the steel or comparator charts. Method C is the recommended method for measuring the surface profile depth. Methods A and B may provide unreliable measures of the blast profile.
- Method C employs replica tape and a spring gauge micrometer to measure the surface profile. With the wax paper backing removed, the replica tape is placed face down against the substrate, and a burnishing tool is used to rub the circular cutout until a uniform gray appearance develops. The replica tape thickness (compressible foam plus plastic backing) is then measured using the spring micrometer. The profile is determined by subtracting the thickness of the plastic backing material, 0.002 in. (50 μm), from the measured value. Three readings should be taken within a 16-in.^{2} (100-cm^2) area, and the surface profile at that location should be reported as the mean value of the readings. The number of measurements per unit area (e.g., 3 per 500 ft^2 [45 m^2]) should be specified in the contract document. Two types of replica tape are available, coarse (0.0008 to 0.002 in. [20 to 50 μm]) and X-coarse (0.0015 to 0.0045 in. [37.5 to 112.5 μm]). In most cases, the X-coarse tape will be used to measure profile. It may be possible to measure profiles as high as 0.006 in. (150 μm) using the X-coarse tape.

> The inspector must be aware that TSMCs create safety and health risks in the form of hot surfaces, fumes, ultraviolet light, and noise. Precautions must be taken to avoid these hazards—refer to Section 2.

8.3.6 Testing During and After Coating Application

8.3.6.1 Coating thickness. The following applies to coating thickness.

- Coating thickness is measured in accordance with SSPC-PA-2 using a Type 2 gauge.
- Calibrate the instrument using a calibration wedge that is close to the contract-specified thickness placed over a representative sample of the contract-specified abrasive-blasted steel or a prepared bend coupon, or both.
- Thickness readings should be made either in a straight line with individual readings taken at 1-in. (2.5-cm) intervals or spaced randomly within a 2-in. (5-cm) diameter area. Line measurements should be used for large flat areas, and area measurements should be used on complex surface geometry and surface transitions such as corners. The average of five readings constitutes one thickness measurement. A given number of measurements per unit area (e.g., five per 100 ft^2 [9 m^2]) should be specified in the contract documents. Figure 7 illustrates this method.
- Measure thickness according to ASTM D4138, "Test Methods for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive Means," Test Method A. This method uses a tungsten carbide-tipped instrument to scribe through the sealer and paint, leaving a V-shaped cut. A heavy dark-colored marking pen is first used to mark the coated surface. The scribing instrument is then drawn across the mark. This process sharply delineates the edges of the scribe. A reticle-equipped microscope is used to read the film thickness. A total of three thickness readings should be performed in a 16-$in.^2$ (100-cm^2) area, with the average of the three tests reported as a single measurement. The number of measurements per unit area (e.g., 1 per 500 ft^2 [45 m^2]) should be specified in the contract documents.

  Thickness testing using this method should be minimized because the test method destroys the sealer and paint. Areas damaged by adhesion testing must be repaired by

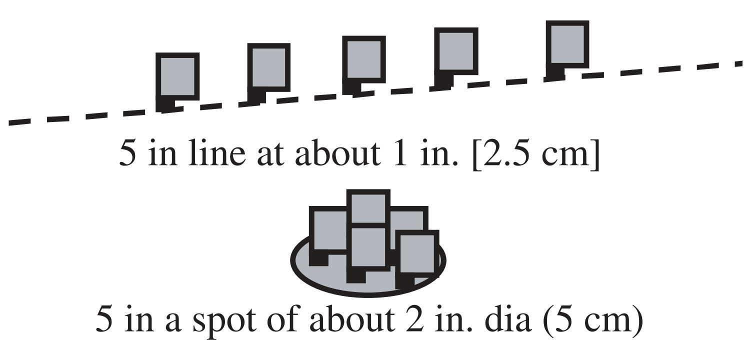

Figure 7. Methods of taking coating thickness measurements.

touch-up with sealer or paint using a brush or spray gun. Thickness testing should be performed in a small area (16 in.^{2} [100 cm^2]) to limit the area that must be repaired.

8.3.6.2 Adhesion tests. The following applies to adhesion tests.

- *Bend Test.* The bend test (180-degree bend on a mandrel) is used as a qualitative test for verifying proper surface preparation, equipment setup, and spray parameters. The bend test puts the TSMC in tension. The mandrel diameter for the threshold of cracking depends on substrate thickness and coating thickness.

  Table 9 summarizes a very limited bend-test cracking threshold for arc-sprayed zinc TSMC thickness versus mandrel diameter for steel coupons 0.050 in. (13 mm) thick.

  - Test panels—the test panels should be a cold-rolled steel measuring 3 × 6 × 0.05 in. (7.5 × 15 × 1.25 cm). The panels should be cleaned and blasted in the same fashion in which the panels will be cleaned and blasted for the job.
  - Application of thermal spray—the TSMC should be applied to five test panels using the identical spray parameters and average specified thickness that will be used on the job. The coating should be applied in a cross-hatch pattern using the same number of overlapping spray passes as used to prepare the job reference standard. The coating thickness should be measured to confirm that it is within the specified range.
  - Conduct bend test—test panels should be bent 180 degrees around a steel mandrel of a specified diameter, as shown in Figure 5. Pneumatic and manual mechanical bend test apparatus may be used to bend the test panels.
  - Examine bend test panels—test panels should be examined visually without magnification. The bend test is acceptable if the coating shows no cracks or exhibits only minor cracking with no lifting of the coating from the substrate. If the coating cracks and lifts from the substrate, the results of the bend test are unacceptable. TSMCs should not be applied if the bend test fails, and corrective measures must be taken. Figure 5 depicts representative bend test results. A knife blade can be used to facilitate the evaluation. Apply moderate pressure to the knife blade and if the coating cannot be dislodged, the adhesion can be considered satisfactory.

- *Tensile Adhesion.*

  - Field Measurement—Evaluate the adhesion of the TSMC with the specification in accordance with ASTM D4541, "Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers." A self-aligning Type IV tester, described in Annex A4 of ASTM D4541, should be used. A total of three adhesion tests should be performed in a 16-in^2 (100-cm^2) area, and the average of the three tests should be

TABLE 9 Bend-test mandrel diameter versus zinc thermal spray coating thickness (for steel coupons 0.050 in. [13 mm] thick)

TSMC Thickness (mils)	≥10 (254 µm)	≥15 (381 µm)	≥25 (635 µm)
Mandrel Diameter	1/2 in. (1.27 cm)	5/8 in. (1.59 cm)	<1 in. (2.54 cm)

reported as a single measurement. Portable instruments with large-diameter test specimens, for instance, 2-in. versus 1-in. (50-mm versus 25-mm) diameter, produce better statistical results.

The number of measurements per unit area (e.g., 1 per 500 ft^2 [45 m^2]) should be specified in the contract documents. Areas of deficient adhesion should be abrasive blasted, and the coating should be reapplied. Additional testing will probably be necessary to determine the extent of the area exhibiting poor adhesion. Adhesion testing should be minimized because the test method destroys the coating. Areas damaged by adhesion testing must be repaired by abrasive blasting and reapplication of the metallic coating. Adhesion testing is performed in a small area (16 in^2 [100 cm^2]) to limit the area that must be repaired.

As an alternative to testing adhesion to the failure point, the tests can be interrupted when the minimum specified adhesion value is achieved. This method precludes the need to repair coatings damaged by the test. The adherent pull stubs can then be removed by heating to soften the glue or by firmly striking the side of the stub.

Table 10 lists the recommended adhesion requirements for field- or shop-applied thermal spray coatings of zinc, aluminum, and 85 : 15 wt% zinc/aluminum.

As a caution in performing this type of test, the inspector must be aware that since the coating does contain some porosity, a low-viscosity adhesive might penetrate the coating and reach the substrate. If this occurs, the measured adhesion value will be influenced by the adhesion between the glue and the substrate. It is best to avoid low-viscosity liquid adhesives in favor of high-viscosity pastes. If there is any doubt, comparison tests should be performed to select the appropriate adhesive.

– Laboratory Measurement—Tensile-bond test specimens should be carbon steel, 1 in. (2.54 cm) in diameter and 1 in. (2.54 cm) in length, threaded per ASTM C 633, "Adhesion or Cohesive Strength of Flame-Sprayed Coatings."

- *Cut Test.* The thermal spray coating cut test consists of a single cut, 1.5 in. [40 mm] long, through the coating to the substrate without severely cutting into the substrate. All cuts should be made using sharp-edge tools. The chisel cut should be made at a shallow angle. The bond should be considered unsatisfactory if any part of the TSMC along the cut lifts

TABLE 10 Typical adhesion of field- and shop-applied thermally sprayed metal coatings measured by pull-off testing

Thermal Spray Material	Tensile Adhesion psi [MPa]
Zinc	500 [3.45]
Aluminum	1,000 [6.89]
85/15 Zinc-Aluminum	700 [4.83]
90/10 Aluminum Oxide	1,000 [6.89]

from the substrate. The cutting tool used (knife, hammer and chisel, or other tool) should be specified in the contract. Perform an adhesion test every 100 ft^2 (9.3 m^2). The tested area and coated surfaces that have been rejected for poor adhesion shall be blast cleaned and recoated.

8.3.7 *Appearance*

The coating should be free of blisters, cracks, chips or loosely adhering particles, oil, pits exposing the substrate, and nodules. A very rough coating might indicate that the coating was applied with the gun at too great an angle or too far from the surface. Evaluate coatings that appear powdery or oxidized by scraping. If scraping does not produce a silvery metallic appearance, the coating is defective and must be replaced.

8.3.8 *Coating Morphology*

Metallographic examination may be used for qualifying spraying parameters, but it is not normally used for process control for corrosion control applications. Parameters included in this examination include percent porosity, percent unmelted particles, percent oxides, and the presence and amount of interface contamination.

9 QUALIFICATIONS

9.1 Equipment

9.1.1 Qualification

Each type and source of thermal spray equipment should be qualified prior to use. The equipment should conform to the following requirements related to uniformity of operation, coating appearance, and coating adhesion. Equipment should be qualified using the type and size of wire to be used on the job. The operating parameters should be those selected by the contractor for use on the job. Equipment manufacturers may also qualify their equipment for use with specific feedstocks and operating parameters. Such qualified equipment should be accepted as prequalified, assuming the contractor proposes to operate the equipment in the same manner used for the qualification tests.

9.1.2 Wire-Flame Spray Equipment

9.1.2.1 Gases. Flame-spraying equipment shall permit spraying with the combustible gases, atomizing gas (if any), and carrier gas (if any) for which it was designed.

9.1.2.2 Oxygen and fuel gas flow rates. Under conditions of continuous use, the actual oxygen and fuel gas flow rates and pressures should remain nearly constant and should not deviate from the set values by more than 5 percent during a 15-minute period.

9.1.2.3 Atomization air pressure. Compressed air should be free of oil and water. Under conditions of continuous use, the actual atomization air pressure and flow volume should remain nearly constant and should not deviate from the set value by more than 5 percent during a 15-minute period.

9.1.2.4 Wire feed rate. It shall be possible to adjust the spraying material feed rate. Under conditions of continuous use, the actual wire feed rate should remain nearly constant and should not deviate from the set value by more than 5 percent during a 15-minute period.

- The set values shall be constant and reproducible; preconditions of this are adequate and constant gas pressures, atomizing air pressures, and supply of electrical power as appropriate.
- With regard to continuous operation, the equipment should not sputter, pop, or stop operating when operated continuously for 15 minutes.

9.1.2.5 Control unit and monitoring. It shall be possible to monitor and control, read clearly and correct, by means of instruments, any deviations from the set values of atomizing gas pressure and gas volume flow rate during the spraying process. These values shall be recorded during acceptance inspection. The limits of error of the measuring instruments shall not exceed ± 5 percent for all set values and shall correspond to at least Class 2.5 instruments. The reproducibility of the setting shall be proved.

9.1.2.6 Nozzle system. The nozzle system shall be considered acceptable if, after 20 minutes of spraying 85 : 15 wt% zinc/aluminum wire at the maximum spray rate, there are no degrading deposits of spraying material on or in the nozzle. Nozzles shall be acceptable if, after 20 minutes of spraying nozzle-compatible materials at the maximum spray rate, there are no degrading deposits of spraying material on or in the nozzle.

9.1.3 Wire-Arc Spray Equipment

9.1.3.1 Power. Under conditions of continuous use, the actual current output should remain nearly constant and should not deviate from the set value by more than 5 percent during a 15-minute period.

9.1.3.2 Voltage. Under conditions of continuous use, the actual voltage should remain nearly constant and should not deviate from the set value by more than 5 percent during a 15-minute period.

9.1.3.3 Wire feed mechanism. The wire feed mechanism should be designed for automatic alignment. Under conditions of continuous use, the actual wire feed rate should remain nearly constant and should not deviate from the set value by more than 5 percent during a 15-minute period.

9.1.3.4 Atomization air pressure. Under conditions of continuous use, the actual atomization air pressure and flow volume should remain nearly constant and should not deviate from the set value by more than 5 percent during a 15-minute period.

9.1.3.5 Continuous operation. When operated continuously for 15 minutes, the equipment should not sputter, pop, or stop operating.

9.1.3.6 On/off operation. The equipment should be capable of continuous start and stop operation for a minimum of 15 cycles consisting of 10 seconds on and 5 seconds off without fusing, sputtering, or deposition of nodules.

9.1.3.7 Nozzle system (contact tubes and air nozzle). The nozzle system shall permit a constant arc to be maintained and provide atomization without causing a buildup of deposits that will degrade gun operation. The nozzle system shall be acceptable if, after 20 minutes of spraying 85 : 15 wt% zinc/aluminum wire at the maximum spray rate, there are no degrading deposits of spraying material on or in the nozzle.

9.1.3.8 Coating appearance. The applied coating should be uniform and free of blisters, cracks, loosely adherent particles, nodules, and powdery deposits.

9.1.3.9 Coating adhesion. A 12- × 12- × 0.5-in. (30- × 30- × 1.25-cm) flat steel plate should be cleaned and prepared in accordance with SSPC-SP-1 and SSPC-SP-5. No. 36 aluminum oxide grit should be used to produce an angular blast profile of 0.003 ± 0.0002 in. (75 ± 5μm). The blast profile should be measured and recorded using replica tape in accordance with ASTM D4417. The coating of 85 : 15 wt% zinc/aluminum alloy (0.016 ± 0.002 in. [400 ± 50 μm]), zinc (0.016 ± 0.002 in. [400 ± 50 μm]), or aluminum (0.010 ± 0.002 in. [250 ± 50 μm]) should be applied in not less than two half-lapped passes applied at right angles to each other.

The adhesion should be tested in accordance with ASTM D4541 using a self-aligning Type IV adhesion tester as described in this guide. Scarified aluminum pull stubs should be attached to the TSMC using a two-component epoxy adhesive. The adhesive strength of the coating should be measured and recorded at five randomly selected locations. The average adhesion should not be less than 1,000 psi (6,895 kPa), 1,600 psi (11,032 kPa), and 750 psi (5,171 kPa) for 85 : 15 wt% zinc/aluminum alloy, aluminum, and zinc coatings, respectively. If the test fails, it should be repeated using a new test plate. If the adhesion fails on the second plate, the equipment should be deemed unacceptable.

9.1.4 Retests

If the values obtained during acceptance inspection of a thermal spraying system are altered by modification or repair work, retesting of the properties affected shall be carried out. Retests shall be carried out in the same way as the initial tests described in this standard.

9.2 Applicator

9.2.1 General Requirements

9.2.1.1 Terminology. When the term "certified thermal sprayer" is used, it should denote "thermal spray operator or technician."

9.2.1.2 Required skills. A thermal sprayer must have adequate instruction and training and shop and field experience to safely and proficiently apply thermal spray coatings of aluminum, zinc, and their alloys on steel. The thermal sprayer should demonstrate the ability to set up, operate (including field troubleshooting and repair), and secure thermal spray equipment. The sprayer should be knowledgeable in cleaning and preparing the steel. The sprayer should be skilled in spraying the TSMCs using the intended thermal spray equipment in accordance with the equipment manufacturer's instructions/technical manual and the purchaser's contract specifications. The thermal sprayer should be able to recognize proper masking and surface preparation. The thermal sprayer must be able to recognize unsatisfactory surface preparation and call for corrective action, or stop the job until deficiencies are corrected.

9.2.1.3 Standards and references for certification. The thermal sprayer knowledge and skill requirements do not supersede an employer's or contractor's ability to continue to certify thermal sprayers in accordance with the following other standards and references:

- ASTM D4228, "Practice for Qualification of Coating Applicators for Application of Coatings to Steel Surfaces."
- MIL-STD-1687A (SH), "Thermal Spray Processes for Naval Ship Machinery Applications," 2/11/87.
- Various original equipment manufacturers (OEMs) or after-market repair, or both. Thermal spray process and spray parameter specifications from the OEM or after-market repair facility.
- Material safety data sheets (MSDSs) for abrasive blasting and thermal spray feedstock materials.
- EN 657, *Thermal spraying—Terminology, classification,* April 1994.

9.2.1.4 Basic skills. Thermal sprayers must have basic knowledge and skills in safe assembly, setting up, operating, and closing down procedures for equipment; personal protection; fire hazards; dust explosions; electrical hazards; flash backs; leak detection; UV radiation; and noise.

9.2.2 Demonstration of Applicator Skills

9.2.2.1 Equipment setup and operation. The TSMC applicator should be qualified to SSPC-QP-1 in regards to field application of TSMC work on complex structures or as otherwise specified by the purchasing contract. The thermal spray operator must have normal or corrected 20/20 vision. The qualified applicator should be able to demonstrate a working knowledge of the application equipment to be used on the job by proper setup and operation of the equipment. The applicator should prepare a 12- × 12- × 0.5-in. (30- × 30- × 1.25-cm) flat steel plate cleaned in accordance with SSPC-SP-1 and SSPC-SP-5. Aluminum oxide or steel grit should be used to produce an angular blast profile of 3.0 ± 0.2 mils (76 ± 5 μm). The blast profile should be measured and recorded using replica tape in accordance with ASTM D4417. The applicator should apply the coating of 85 : 15 wt% zinc/aluminum alloy (16 ± 2 mils [400 ± 50 μm]), zinc (16 ± 2 mils [406 ± 50 μm]), or aluminum (10 ± 2 mils [250 ± 50 μm]) using the proper spray technique.

9.2.2.2 Coating appearance. The qualified applicator will have applied a coating that is uniform and free of blisters, cracks, loosely adherent particles, nodules, or powdery deposits.

9.2.2.3 Coating adhesion. The qualified applicator should be able to apply a firmly adherent coating that meets the adhesion requirements of the contract. The TSMC adhesion should be tested in accordance with ASTM D4541 using a self-aligning Type IV adhesion tester as described in Annex A4 of the method. Scarified aluminum pull stubs should be attached to the TSMC using a two-component epoxy adhesive. The adhesive strength of the coating should be measured and recorded at five randomly selected locations. The average adhesion should not be less than 1,000 psi (6,895 kPa), 1,600 psi (11,032 kPa), and 750 psi (5,171 kPa) for 85 : 15 wt% zinc/aluminum alloy, aluminum, and zinc coatings, respectively.

9.3 Inspector

9.3.1 Description of Inspector's Role

The TSMC inspector is a person who is knowledgeable in the concepts and principles of this guide and skilled in observing and measuring conformance to them. Ideally, a third disinterested party will employ the inspector. Specific qualifications of an inspector are listed below.

9.3.1.1 Vision requirements. The inspector must have normal or corrected 20/20 vision.

9.3.1.2 ASTM D3276. An inspector must have the knowledge and ability to meet the guidelines specified in ASTM D3276, "Standard Guide for Painting Inspectors (Metal Substrates)."

9.3.1.3 Training program. Completion of a formal training program, such as the one offered by NACE International, and certification as a NACE International Certified Coating Inspector are recommended.

9.3.1.4 Basic knowledge requirements. The inspector should meet the basic knowledge requirements of a qualified thermal spray operator with respect to the following:

- The inspector should be qualified to SSPC-QP-1 in regards to field application of TSMC work on complex structures or as otherwise specified by the purchasing contract.
- The inspector should have a working knowledge of the methods of TSMC application, particularly the method to be used at the job site.
- The inspector should be able to demonstrate a working knowledge of the application equipment to be used on the job by proper setup and operation of the equipment.

9.3.1.5 Observation and evaluation skills. The inspector should be skilled in observing and evaluating conformance of the application process to the contract specifications.

9.3.1.6 Job reference standard. The inspector should be skilled in setting up a job reference standard as described in Section 8.

9.3.1.7 Knowledge and skills in use of inspection equipment. The inspector should be knowledgeable and skilled in the use of inspection equipment to measure and validate the coating applicator's conformance to the purchasing contract. Specifically (further details are provided in Section 8 and in referenced test methods), the inspector should be

- Skilled in measuring surface temperature, dew point, and ambient air temperature and in calculating the dew point. Specific skills include the use of a surface temperature gauge, sling psychrometer, psychrometric charts, and digital measuring equipment.
- Skilled in the use of water break, UV light, solvent evaporation, and heat tests to detect grease and oil.
- Skilled in the use of conductivity, commercially available colorimetric kits, and titration kits for the measurement of soluble salts and skilled in the use of a Bresle kit for soluble salt measurement.
- Knowledgeable about SSPC-AB-2, "Specification for Cleanliness of Recycled Ferrous Metallic Abrasives," and ASTM D4940, "Test Method for Conductimetric Analysis of Water Soluble Ionic Contamination of Blasting Abrasives," for the detection of salt in abrasives.
- Skilled in the detection of oil in abrasives.
- Knowledgeable about ASTM D4285, "Method for Indicating Water or Oil in Compressed Air."
- Skilled in measuring blast air pressure and nozzle orifice condition.
- Knowledgeable about SSPC surface preparation standards, specifically SSPC-SP-5 and SSPC-VIS-1.
- Skilled in testing surface profile using ASTM D4417, Method C.
- Skilled in measuring coating thickness per SSPC-PA-2 using a Type 2 gauge, in accordance with ASTM D4138, "Test Methods for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive Means."

- Skilled in conducting adhesion tests, including the bend test, tensile adhesion test (ASTM D4541, "Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers," using a self-aligning Type IV tester, described in Annex A4 of ASTM D4541), and cut test as described in Section 8.
- Knowledgeable about the ASTM test methods available to quantify coating defects.

9.3.1.8 Communications and conflict-resolution skills. The inspector should be skilled in communications and conflict resolution so that when application errors are found, they may be corrected without significant disruption to the schedule.

9.3.1.9 Reports. The inspector should submit timely oral and written reports to the purchaser.

10 REFERENCED DOCUMENTS

Reference	Title	Address	Comments
		American Geological Institute 4220 King St. Alexandria, VA 22302-1502 www.agiweb.org	Provides classification of mineral angularity.
ANSI/AWS C2.18-93	*Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc & Their Alloys and Composites*	American National Standards Institute 1819 L Street, NW Washington, DC 20036 www.ansi.org	Provides guidelines for the selection, surface preparation, application, and inspection of thermal spray metal coatings. TO BE SUPERCEDED BY ANSI/AWS C2.18A-XX
ANSI/AWS C2.18A-XX **SSPC CS 23.00A-XX** **NACE TPC #XA**	*Guide for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc & Their Alloys & Composites for the Corrosion Protection of Steel* (in preparation)	SSPC: The Society for Protective Coatings 40 24th Street, 6th Floor Pittsburgh, PA 15222-4656 www.sspc.org	Will provide guidelines for the selection, surface preparation, application, and inspection of thermal spray metal coatings when completed.
ANSI/AWS C2.23-XX **SSPC CS 23.00B-XX** **NACE TPC #XB**	*Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc & Their Alloys for the Corrosion Protection of Steel* (in preparation)	NACE International 1440 South Creek Dr. Houston, TX 77084-4906 www.nace.org	
ANSI/AWS C2.16A	*Guide for Thermal Spray Operator Qualification*	ANSI/AWS	Provides procedures and documents for operator and equipment qualification.

Reference	Title	Address	Comments
ANSI Z49.1	*Safety in Welding and Cutting*	American National Standards Institute 1819 L Street NW Washington, D.C. 20036 www.ansi.org	
ANSI Z87.1	*Standard Practices for Occupational and Educational Eye and Face Protection*		
ANSI Z89.1	*Safety Requirements for Industrial Head Protection*		
ANSI Z88.2	*Standard Practices for Respiratory Protection*		
ANSI/NFPA 51B	*Standard for Fire Prevention in Use of Cutting and Welding Processes*		
ANSI/NFPA 70	*National Electrical Code*		
ASTM B833	*Standard Specification for Zinc and Zinc Alloy Wire for Thermal Spraying (Metallizing)*	ASTM International 100 Barr Harbor Drive W. Conshohocken, PA 19428-2959 www.astm.org	

Reference	Title	Address	Comments
ASTM C633	*Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings*	ASTM International 100 Barr Harbor Drive W. Conshohocken, PA 19428-2959 www.astm.org	Laboratory testing of the tensile adhesion of thermal spray metal coatings.
ASTM D610	*Test Method for Evaluating Degree of Rusting on painted Steel Surfaces – provides standard charts for quantifying the amount of rusting on a steel surface*		
ASTM D660	*Test Method for Evaluating Degree of Checking of Exterior Paints*		
ASTM D661	*Test Method for Evaluating Degree of Cracking of Exterior Paints*		
ASTM D662	*Test Method for Evaluating Degree of Erosion of Exterior Paints*		
ASTM D714	*Test Method for Evaluating Degree of Blistering of Paints*		

Reference	Title	Address	Comments
ASTM D1186	*Standard Test Methods for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Base*		
ASTM D3359	*Test Method for Measuring Adhesion by Tape Test*		
ASTM D4214	*Test Method for Evaluating Degree of Chalking of Exterior Paint Films*		
ASTM D4285	*Standard Test Method for Indicating Oil or Water in Compressed Air*		
ASTM D4417	*Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel*		
ASTM D4541	*Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*		Tensile adhesion testing of coatings using a dolly attached to the coating with an adhesive. The dolly is pulled off the surface using a hand-held device and the tensile force is indicated. Tests using different devices can yield inconsistent results.

Reference	Title	Address	Comments
ASTM D4940	*Test Method for Conductimetric Analysis of Water-Soluble Ionic Contamination of Blasting Abrasives*	ASTM International 100 Barr Harbor Drive W. Conshohocken, PA 19428-2959 www.astm.org	
ASTM E337	*Test Method for Measuring Humidity with a Psychrometer (wet/dry bulb temperatures)*		
ASTM F1130	*Standard Practice for Inspecting the Coating of a Ship – useful for standardizing the method of reporting the extent of corrosion and coating deterioration*		
AWS C2.1	*Recommended Safe Practices for Thermal Spraying*	American Welding Society 550 NW LeJeune Rd. Miami, FL 33126 www.aws.org	
AWS TS1	*Recommended Safe Practices for Thermal Spraying*		
AWS TSM	*Thermal Spray Manual*		
AWS TSS	*Thermal Spraying: Practice, Theory and Application*		

Reference	Title	Address	Comments
BS 5493	*Code of Practice for Protective Coating of Iron and Steel Structures against Corrosion*	British Standards Institution 389 Chiswick High Rd. London W4 4AL United Kingdom www.bsi-global.com	Provides selection and application guidance for various coatings including thermally sprayed aluminum and zinc. Current but partially replaced with EN standards.
Compressed Gas Association CGA G7.1	*Commodity Specification for Air*	Compressed Gas Association 4221 Walney Rd., 6th Floor Chantilly, VA 20151-2423 www.cganet.com	
EN 473	*Non-destructive Testing – Qualification and Certification of Personnel*	European Committee for Standardization Rue de Stassart 36 B-1050 Brussels, Belgium www.cenorm.be	
EN 582	*Thermal Spraying – Determination of the Adhesive Tensile Strength*		
EN 657	*Thermal Spraying – Terminology – Classification*		
EN 1395	*Thermal Spraying – Acceptance Testing of Thermal Spraying Equipment*		

Reference	Title	Address	Comments
EN 13214	*Thermal Spraying – Thermal Spray Coordination – Tasks and Responsibilities*	European Committee for Standardization Rue de Stassart 36 B-1050 Brussels, Belgium www.cenorm.be	
prEN 13214	*Thermal Spraying – Thermal Spray Coordination – Tasks and Responsibilities*		
EN ISO 14918	*Thermal Spraying – Approval Testing for Thermal Sprayers*		
prEN ISO 14919	*Thermal Spraying – Wires, Rods and Cords for Flame and Arc Spraying – Classification – Technical Supply Conditions*		
EN 22063	*Metallic and Other Inorganic Coatings – Thermal Spraying – Zinc, Aluminum and Their Alloys*		
FHWA-RD-96-058	*Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges*	Federal Highway Administration Turner Fairbank Highway Research Center 6300 Georgetown Pike McLean, VA 22101-2439 www.tfhrc.gov	Research report on the use of environmentally friendly coatings, including thermally sprayed metal coatings.

Reference	Title	Address	Comments
ISO 14918	*Thermal Spraying – Approval Testing of Thermal Sprayers*	International Organization for Standardization 1, rue de Varembe Case postale 56 CH-1211 Geneva 20, Switzerland www.iso.org	Gives procedural instructions for approval testing of thermal sprayers. Defines essential requirements, ranges of approval, test conditions, acceptance requirements and certification.
ISO 14922-1	*Thermal Spraying – Quality Requirements of Thermally Sprayed Structures – Part 1 Guidance for Selection and Use*		Specifies guidelines to describe thermal spraying quality requirements suitable for application by manufacturers for coating new parts, repair and maintenance. Reference to European (EN) Standards.
ISO 14922-2	*Thermal Spraying – Quality Requirements of Thermally Sprayed Structures – Part 2: Comprehensive Quality Requirements*		Provides general guidance and reference to European (EN) Standards.
ISO 14922-3	*Thermal Spraying – Quality Requirements of Thermally Sprayed Structures – Part 3: Standard Quality Requirements*		Provides general guidance and reference to European (EN) Standards.

Reference	Title	Address	Comments
ISO 14922-4	*Thermal Spraying – Quality Requirements of Thermally Sprayed Structures – Part 4: Elementary Quality Requirements*	International Organization for Standardization 1, rue de Varembe Case postale 56 CH-1211 Geneva 20, Switzerland www.iso.org	Provides general guidance and reference to European (EN) Standards.
ISO 2063	*Metallic Coatings – Protection of Iron and Steel against Corrosion – Metal Spraying of Zinc, Aluminum and Alloys of these Materials*		
ISO 8502	*Preparation of Steel Structures Before Application of Paint and Related Products – Tests for the Assessment of Surface Cleanliness*		
JIS H 8300	*Zinc, Aluminum and their Alloys Sprayed Coatings – Quality of Sprayed Coatings*	Japan Standards Association 4-1-24 Akasaka Minato-ku Tokyo 107-8440 Japan www.jsa.or.ip	Contains QA provisions for thermally sprayed aluminum and zinc.

Reference	Title	Address	Comments
MIL-80141C	*Metallizing Outfit, Power Gas, Guns and Accessories*	Commander Naval Sea Systems Command SEA 5523 Department of the Navy Washington, DC 20362-5101 http://stinet.dtic.mil	
MIL-M-6712C	*Metallizing Wire*		Provides specifications for chemistry, dimensions, winding and finish of wire for flame spray, including zinc and aluminum.
MIL-STD-1687A(SH)	*Thermal Spray Processes for Naval Ship Machinery Applications*		Provides information for thermally spraying metal coatings onto machinery. Contains requirements for qualification of procedures and operators, use of thermal spray equipment and material, quality assurance requirements and qualification tests.
MIL-STD-2138A(SH)	*Metal Sprayed Coatings for Corrosion Protection aboard Naval Ships (Metric)*		Provides specifications for surface preparation, application and testing of thermally sprayed aluminum to ships. Note that zinc is not included because of health hazards.

Reference	Title	Address	Comments
NACE Publication 1G194	*Splash Zone Maintenance Systems for Marine Steel Structures*	NACE International 1440 South Creek Dr. Houston, TX 77084-4906 www.nace.org	
NACE Publication 6G186	*Surface Preparation of Contaminated Steel Surfaces*		
NACE Standard RP0287	*Standard Recommended Practice, Field Measurement of Surface Profile of Abrasive Blast Cleaned Steel Surfaces Using a Replica Tape*		
NACE TM0170	*Visual Comparator for Surfaces of New Steel Airblast Cleaned with Sand Abrasive*		
NACE TM0175	*Visual Standard for Surfaces of New Steel Centrifugally Blast Cleaned with Steel Grit and Shot*		
NACE Technical Report T-60-5	*A Manual for Painter Safety*		

Reference	Title	Address	Comments
NIOSH	*Respiratory Protection – An Employer's Manual*	National Institute for Occupational Safety & Health Robert A. Taft Laboratories 4676 Columbia Parkway Cincinnati, OH 45226 www.cdc.gov/niosh	
NIOSH	*Respiratory Protection – A Guide for the Employee*		
OSHA CFR 29 Part 1910	*Occupational Safety and Health Standards*	Occupational Safety & Health Administration 200 Constitution Ave. NW Washington, D.C. www.osha.gov	
SAE J827	*Peening Media, General Requirements of High Carbon Cast Steel Shot*	Society of American Automotive Engineers 755 W. Big Beaver Suite 1600 Troy, MI 48084 www.sae.org	

Reference	Title	Address	Comments
SS-EN 1395	*Thermal Spraying – Acceptance Inspection of Thermal Spraying Equipment*	Swedish Standards Institute SIS Forlag AB 118 80 Stockhom, Sweden www.sis.se	Provides acceptance inspection requirements for thermal spraying equipment for plasma, arc and flame spraying.
SSPC SP-0/NACE No. 2	*Near-White Blast Cleaning*	SSPC – The Society for Protective Coatings 40 24th Street, 6th Floor Pittsburgh, PA 15222-4656 www.sspc.org	
SSPC SP-5/NACE No. 1	*White-Metal Blast Cleaning*		
SSPC VIS-1-89	*Visual Standard for Abrasive Blast Cleaned Steel*		
SSPC AB-1	*Mineral and Slag Abrasives*		
SSPC AB-2	*Specification for the Cleanliness of Recycled Ferrous Metallic Abrasives*		
SSPC AB-3	*Newly Manufactured or Re-Manufactured Steel Abrasives*		

Reference	Title	Address	Comments
SSPC CS-23.00	*Guide for Thermal Spray Metallic Coating Systems*	SSPC – The Society for Protective Coatings 40 24th Street, 6th Floor Pittsburgh, PA 15222-4656 www.sspc.org	Provides guidance for surface preparation, application and testing of aluminum, zinc-aluminum and zinc thermal spray metal coatings. IT IS TO BE REPLACED BY SSPC CS 23.00A-XX PRESENTLY IN PREPARATION. SEE ALSO ASTM AND NACE DOCUMENTS.
SSPC PA-1	*Shop, Field and Maintenance Painting*		
SSPC PA-2	*Measurement of Dry Paint Thickness with Magnetic Gages*		
SSPC PA Guide 3	*A Guide to Safety in Paint Application*		
SSPC QP-	*Standard Procedure for Evaluating Qualifications of Painting Contractors*		
SSPC SP-1	*Solvent Cleaning*		Provides details for removing grease and oil contamination prior to final surface preparation.

Reference	Title	Address	Comments
SSPC SP-3	*Power Tool Cleaning*	SSPC – The Society for Protective Coatings 40 24th Street, 6th Floor Pittsburgh, PA 15222-4656 www.sspc.org	Provides details for removing scaling and heavy corrosion prior to final surface preparation.
SSPC SP- 5/NACE 1	*White Metal Blast Cleaning*	SSPC/NACE	Provides details on proper surface preparation quality prior to thermal spray metal application.
SSPC SP COM	*Surface Preparation Commentary*		Provides a discussion and information about the factors that influence surface preparation.
US Army Corps of Engineers (USACE) Engineering Manual EM 1110-2-3401	*Engineering and Design, Thermal Spraying: New Construction and Maintenance*	U.S. Army Corps of Engineers Champaign, IL http://www.usace.army.mil/inet/usace-docs/	Provides information on thermal spray metal coatings for coating selection, surface preparation, application, testing and quality assurance.
US Army Corps of Engineers (USACE) Guide Specification for Construction CEGS-9971	*Section 09971, Metallizing: Hydraulic Structures*		Provides specific recommendations for the selection of thermal spray metal coating systems in different environments for Corps of Engineers structures.
US Army Corps of Engineers (USACE) Guide Specification for Construction CEGS-09965	*Section 09965, Painting: Hydraulic Structures*		Provides specific recommendations for the selection of coating systems for Corps of Engineers structures.

11 GENERIC SEALER SPECIFICATION

1. SCOPE

This specification provides a general specification for sealers to be used on thermally sprayed metal coatings. A sealer is defined as a material applied to infiltrate and close the pores of a thermal spraying deposit for the purpose of improving the life expectancy of the thermally sprayed metal coating. A sealer is not intended to provide a dielectric barrier coating over the surface and is not intended to provide an aesthetic finish coat. Further intermediate or topcoats applied over the seal coat must be used for barrier coating protection and aesthetic purposes.

This specification does not cover intermediate and finish coatings. Intermediate and finish coats must be compatible with the thermally sprayed metal coating and sealer.

2. APPLICABLE DOCUMENTS

2.1 AASHTO, "Thermally Sprayed Metal Coating Guide."

2.2 U.S. Army Corps of Engineers (USACE) Guide Specification for Construction CEGS-09965, *Section 09965, Painting: Hydraulic Structures.*

2.3 MIL-STD-2138A (SH), "Metal Sprayed Coatings for Corrosion Protection Aboard Naval Ships."

2.4 ASTM D1210, "Test Method for Fineness of Dispersion of Pigment-Vehicle Systems."

2.5 ASTM D2794 (Modified), "Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)."

2.6 ISO 8502-3, "Clear Cellophane Tape Test."

2.7 The sealer manufacturer's product technical data sheets.

3. SAFETY AND ENVIRONMENTAL

3.1 Safety

3.1.1 Solvents used for cleaning or to apply sealers or topcoats (e.g., acetone, xylene, or alcohol) emit vapors that are harmful and can be fatal.

3.1.1.1 Use solvents only with adequate ventilation or proper respiratory protection and other protective clothing as needed. Avoid breathing solvent vapors and skin contact with solvents.

3.1.1.2 Most solvents are also flammable liquids. All solvent tanks must have lids and be covered when not in use. Take proper safety precautions.

3.1.1.3 Keep all solvents and flammable materials at least 50 ft (15.2 m) away from welding, oxyfuel cutting and heating, and thermal spraying operations.

3.1.2 Sealers and paint coats are typically applied by spray application. Spray application is a high-production rate process that may rapidly introduce very large quantities of toxic solvents and vapors into the air.

3.1.2.1 Airless spray systems operate at very high pressures. Very high fluid pressures can result in penetration of the skin on contact with exposed flesh.

3.1.2.2 Tip guards and trigger locks should be used on all airless spray guns. The operator should never point the spray gun at any part of the body.

3.1.2.3 Pressure remains in the system even after the pump is turned off and can only be relieved by discharging or "blow-down" through the gun.

3.1.3 The contractor should maintain current MSDSs for all materials used on the job. These materials include cleaning solvents, compressed gases, thermal spray wires or powders, sealers, thinners, and paints or any other materials required to have an MSDS (as specified in CFR 29 Part 1910, Section 1200). The MSDSs should be readily available to all personnel on the job site in a clearly labeled folder.

3.2 Environmental

3.2.1 Ensure compliance with the purchaser's and all pertinent government agency requirements and regulations for air-quality and hazardous-materials control.

3.2.2 The applicator and the purchaser should coordinate the specific requirements, responsibilities, and actions for the containment, storage, collection, removal, and disposal of the debris produced by the thermal spray coating operations.

3.2.3 All sealers must comply with federal, state, and local volatile organic compound (VOC) requirements for the area in which they are to be applied.

4. MATERIAL

4.1 The sealer must have the characteristics listed below.

4.1.1 The sealer must be capable of penetrating the pores of the thermally sprayed metal coating. Pigmented sealers must have a particle size nominally 5-fineness of grind (ASTM D1210).

4.1.2 The sealer must be capable of being applied to a low film thickness of 0.003 in. (76 µm) or less.

4.1.3 The sealer must be compatible with the thermally sprayed metal coating. For example, on zinc thermally sprayed coating, do not use a sealer that saponifies the zinc.

4.1.4 The sealer must be compatible with intermediate coats and topcoats.

4.1.5 The sealer must be suitable for the intended service.

4.1.6 The sealer must meet local regulations on VOC content.

4.1.7 The sealer must meet all color and other aesthetic requirements for the application.

4.2 Acceptable materials for steel pilings include those listed below.

4.2.1 Vinyl butyral wash primer (SSPC Paint 27). This is suitable for use over zinc, aluminum, and 85 : 15 weight percent (wt%) zinc/aluminum. Thin wash primer per manufacturer's instructions and apply to a dry film thickness of 0.0005 in. (12.7 µm).

4.2.2 U.S. Army Corps of Engineers paint specification V-766E vinyl acetate–vinyl chloride copolymer (CEGS-09965).

4.2.3 MIL-P-24441 Formula 150 polyamide epoxy thinned after the required period of induction with an equal volume amount of super hi-flash Naptha (boiling range 315°F to 353°F [157°C to 179°C]). The thinned coating shall not exceed local VOC limits (see MIL-STD-2138A [SH]).

4.2.4 Polyamide epoxy thinned 50 percent with approved solvent (or as directed by manufacturer) and applied to 1.5-mil (38.1-µm) dry film thickness.

4.2.5 High-solids low-penetrating epoxy.

4.2.6 Penetrating polyurethane.

4.2.7 Coal tar epoxy. This is suitable for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum. Thin approximately 20 percent and apply to 0.004 to 0.006 in. (101 to 152 µm).

4.2.8 Aluminum epoxy mastic. This is suitable for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum. Thin to the maximum extent per manufacturer's recommended extent and apply to 0.003 to 0.004 in. (76 to 101 µm).

4.2.9 Tung-oil phenolic aluminum (TT-P-38). Suitable for use over zinc, aluminum, and 85 : 15 wt% zinc/aluminum. Thin about 15 percent by volume and apply to a dry film thickness of 0.0015 in. (38 µm).

5. APPLICATION

5.1 Apply all paint sealer and topcoating according to SSPC-PA-1, “Shop, Field and Maintenance Painting,” and the paint manufacturer's recommendations for use of the product with a thermally sprayed metal coating system. The thermally sprayed metal coating before sealing shall have a uniform appearance. The coating shall not contain any of the following: blisters, cracks, chips or loosely adhering particles; oils or other internal contaminants; pits exposing the substrate; or nodules.

5.2 Surfaces that have had the thermally sprayed metal coating applied shall be inspected and approved by the inspector. The sealer shall be applied within 8 hours of the thermally sprayed metal coating application. If this is not possible, verify that the surface has not been contaminated and is dust free (cellophane tape test [ISO 8502-3]). Visible oxidation of the thermal spray coating requires that the surface be further prepared to remove the oxidation by brush blasting. Subsequent paint coats are applied in accordance with the requirements of the painting schedule.

5.3 Blow down surfaces to be sealed using clean, dry compressed air to remove dust.

5.4 Where moisture is present or suspected in the thermal spray coating pores, heat the surface to 120°F (49°C) to remove the moisture prior to the seal coat application. When possible, the steel on the reverse side of the thermally sprayed metal coating should be heated to minimize oxidation and contamination of the thermally sprayed metal coating prior to sealing.

5.5 Apply sealers by conventional or airless spraying. Vinyl-type sealers must be applied using conventional spray techniques.

5.6 Thin sealers as recommended by the sealer manufacturer to effectively penetrate the TSMC.

5.7 Unless otherwise specified by the manufacturer or the project specifications, apply the sealer at a spreading rate resulting in a theoretical 1.5-mil (38-µm) dry film thickness.

5.8 Apply intermediate coats and topcoats as soon as the sealer is dry and preferably within 24 hours, in accordance with the coating manufacturer.

6. QUALITY CONTROL

6.1 Visually confirm complete coverage during application. Look for uniform coverage using tint and wetness of the surface as guides.

6.2 Measure the thickness of the topcoat per SSPC-PA-2 using a Type 2 fixed-probe gauge. The measurement may be made on either a companion coupon or the sealed thermal spray coating if the thermal spray coating thickness has been previously measured. Alternately, the thickness can be measured destructively using ASTM D4138, Test Method A. This method has the advantage of being able to observe all the layers; however, this type of measurement should be minimized because the areas tested must be repaired in order to maintain the coating integrity.

6.2.1 As an alternative, measure the thickness of the sealer as applied to a flat panel that was attached to the surface being sealed. Refer to SSPC-PA-2.

6.3 Note and correct areas with deficient sealer coverage. Correct by adding sealer. Additional testing is necessary to determine the extent of the area with deficient sealer or paint thickness. The sealer thickness must be checked prior to the application of subsequent paint coats, and the measurement procedure repeated for the sealer and paint.

6.4 As applied to thermally sprayed metal coatings on a steel substrate, sealer must meet a minimum drop weight impact requirement of 188 ft-lbs (254 N-m) when tested in accordance with ASTM D2794 (Modified).

GLOSSARY

Abrasive — A material used for wearing away a surface by rubbing; a fine, granulated material used for blast cleaning. Abrasive particles of controlled mesh sizes are propelled by compressed air, water, or centrifugal force to clean and roughen a surface. Blast-cleaning abrasives often are simply referred to as metallic or nonmetallic and as shot- or grit-like.

Acceptance Testing — The purchaser's testing of received products to determine that the quality of manufactured products meets specified requirements.

Adhesion — The degree of attraction between a coating and a substrate or between two coats of paint that are held together by chemical or mechanical forces or both. Adhesion often is called the "bonding strength" of a coating. Adhesion should not be confused with "cohesion," which is the internal force holding a single coating together.

Air Contaminant — Any substance of either artificial or natural origin in the ambient air, such as particulates (dust, fly ash, smoke, etc.), mists (other than water), fumes (gases), etc.

Aliphatic Solvents — Hydrocarbon solvents compounded primarily of paraffinic and cyclo-paraffinic (naphthenic) hydrocarbon compounds. Aromatic hydrocarbon content may range from less than 1% to about 35%.

Alkyd Resins — Synthetic resins formed by the condensation of polyhydric alcohols with polybasic acids. They may be regarded as complex esters. The most common polybasic alcohol used is glycerol, and the most common polybasic acid is phthalic anhydride.

Alternate Immersion — An exposure in which a surface is in frequent, perhaps fairly long, immersion in either freshwater or saltwater alternated with exposure to the atmosphere above the water.

Ambient Air Quality — Average atmospheric purity, as distinguished from discharge measurements taken at the source of pollution. The general amount of pollution present in a broad area.

Anchor Pattern — See Profile.

Aromatic Solvents — Hydrocarbon solvents composed wholly or primarily of aromatic hydrocarbon compounds. Aromatic solvents containing less than 80% aromatic compounds are frequently designated as partially aromatic solvents.

Atomization	The mechanical subdivision of a bulk liquid or meltable solid, such as certain metals, to produce droplets, which vary in diameter (depending on the process) from under 10 to over 100 µm.
Bend Test	(Also flexibility test) Test applied to cured films to determine if they are able to elongate without fracture or debonding.
Blasting	Cleaning materials using a blast of air that directs small abrasive, angular particles against the surface.
Blistering	Formation of dome-shaped projections in coatings resulting from local loss of adhesion and lifting of the film from an underlying paint film or the base substrate.
Bond Strength	The force required to pull a coating free of a substrate, usually expressed in kPa (psi).
Brackish Water	Water with salinity between 0.5 and 17 parts per thousand.
Cathodic Protection	A technique to reduce the corrosion rate of a metal surface by making it a cathode of an electrochemical cell.
Centrifugal Blast Cleaning	Use of motor-driven bladed wheels to hurl abrasive at a surface by centrifugal force.
Chalking	Formation of a friable powder on the surface of a coating caused by the disintegration of the binding medium due to disruptive factors during weathering.
Checking	That phenomenon manifested in paint films by slight breaks in the film that do not penetrate to the underlying surface. The break is a “crack” if the underlying surface is visible.
Coating System	The applied and cured multilayer film or the components of a system based on non-paint type coating.
Corrosion	The deterioration of a metal by chemical or electrochemical reaction resulting from exposure to weathering, moisture, chemicals, or other agents in the environment in which it is placed.
Cracking	The splitting of a dry paint film, usually as the result of aging.
Crevice Corrosion	Corrosion that occurs within or adjacent to a crevice formed by contact with another piece of the same or another metal or with a nonmetallic material.
Deposition Efficiency	The ratio (usually expressed as a percentage) of the weight of spray deposit on the substrate to the total weight of the material sprayed.

Deposition Rate The weight of material deposited per unit of time.

Dew Point The temperature at which water vapor present in the atmosphere is just sufficient to saturate it. When air is cooled below the dew point, the excess water vapor appears as tiny water droplets or crystals of ice, depending on the temperature of the air mass.

DFT Dry film thickness.

Edge Effect Loosening of the adhesive bond between a sprayed deposit and the substrate at the workpiece edges.

Electrode A component for the electrical circuit through which current is conducted to the arc.

Epoxy Resin Cross-linking resins based on the reactivity of the epoxide group.

Flame Spray Any process whereby a material is brought to its melting point and sprayed onto a surface to produce a coating. The process includes metallizing, thermospray, and plasma flame.

Flash Point The lowest temperature of a liquid at which it gives off sufficient vapor to form an ignitable mixture with the air near the surface of the liquid or within the vessel used.

Flash Rusting Rusting that occurs on metal within minutes to a few hours after blast cleaning or other cleaning is completed. The speed with which flash rusting occurs may be indicative of salt contamination on the surface, high humidity, or both.

Freshwater Water having salinity less than 0.5 parts per thousand.

Galvanic Corrosion Accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte. The term “dissimilar metal corrosion” is sometimes used.

Galvanic Protection Reduction or elimination of corrosion of a metal achieved by making current flow to it from a solution by connecting it to a metal that is more active on the electromotive series (galvanic anode). The galvanic anode for steel would be a sacrificial metal, such as zinc, magnesium, or aluminum.

Industrial Environment Environments with a large quantity of atmospheric pollutants, including sulfur-containing solids and gases that strengthen the electrolyte film. Corrosion significantly influenced by humidity, time of wetness, and wind direction.

Interface The contact surface between a sprayed deposit and the substrate.

Marine Environment An atmospheric exposure that is frequently wetted by salt mist, but which is not in direct contact with salt spray or splashing waves. This environment contains a high concentration of chlorides.

Masking Protecting a substrate surface from the effects of blasting or adhesion of a sprayed deposit.

Matrix The major continuous substance of a thermally sprayed coating as opposed to inclusions or particles of materials having dissimilar characteristics.

Mechanical Bond The adherence of a thermally sprayed deposit to a roughened surface by the mechanism of particle interlocking.

Metallizing Spraying a coating of metal onto a surface. See also Thermal Spraying.

Nozzle A device that directs a shielding media; a device that provides atomizing air in a wire-arc spray gun; the anode in a plasma gun; the gas burning jet in a rod or flame-wire spray gun.

Overspray Atomized paint or sprayed coating particles that deflect from or miss the surface being sprayed; Spray particles that are not molten enough to fuse when they reach the surface being sprayed. As a result, overspray may contaminate property beyond the surface being sprayed.

Oxide A chemical compound, the combination of oxygen with a metal forming a ceramic; examples include aluminum oxide and iron oxide.

Parameter A measurable factor relating to several variables; loosely used to mean a spraying variable, spraying condition, spray rate, spray distance, angle, gas pressure, gas flow, etc.

Particle Size The average diameter of a given powder or grit granule.

Pass A single passage of the thermal spray device across the surface of a substrate.

Plasma Spraying A thermal spray process in which the coating material is melted with heat from a plasma torch that generates a nontransferred arc; molten powder coating materials are propelled against the base metal by the hot, ionized gas issuing from the torch.

Polyurethant	Coating vehicles containing a polyisocyanate monomer reacted in such a manner as to yield polymers containing a ratio, proportion, or combination of urethane linkages; active isocyanate groups; or polyisocyanate monomer.
Porosity	Small voids, such as in concrete, that allow fluids to penetrate an otherwise impervious material; The ratio is usually expressed as a percentage of the volume of voids in a material to the total volume of the material including the voids.
Profile	Surface contour of a blast-cleaned or substrate surface viewed from the edge.
Psychrometer	A test instrument that is used to determine humidity and dew point.
Quality Control	The system whereby a manufacturer ensures that materials, methods, workmanship, and the final product meet the requirements of a given standard.
Replica Tape	A specially constructed tape used to measure surface profile. The tape is pressed against the surface, after which the impression created by the profile is measured with a micrometer.
Residual Stress	Stresses remaining in a structure or member as a result of thermal or mechanical treatment, or both.
Resin	General term applied to a wide variety of more or less transparent and fusible products, natural or synthetic. Any polymer that is a basic material for coatings and plastics.
Rural Environment	An atmospheric exposure that is virtually unpolluted by smoke and sulfur gases and that is sufficiently inland to be unaffected by salt contamination or the high humidity of coastal areas. Corrosion depends on temperature, humidity, and moisture retention.
Rust	The reddish, brittle coating formed on iron or ferrous metals resulting from exposure to a humid atmosphere or chemical attack.
Sacrificial Protection	The use of a metallic coating to protect steel. In the presence of an electrolyte, such as salt water, a galvanic cell is set up and the metallic coating corrodes instead of the steel. See also Galvanic Protection.
Seawater	Water having salinity above 17 parts per thousand.
Seal Coat	Material applied to infiltrate and close the pores of a thermally sprayed deposit.

Silicone One of a class of compounds consisting of polymerizable, high-temperature-resistant resins; lubricant greases, and oils; organic solvent-soluble water repellants; surface tension modifiers for organic solvents; etc.

Soluble Salt Contaminant Water-soluble inorganic compounds (such as chlorides and sulfates) that contaminate a product. When soluble salts are present on a prepared steel surface, they may cause premature coating failure. Soluble salt contaminants are sometimes referred to as "ionic contaminants" or "invisible contaminants."

Spalling The flaking or separation of a sprayed coating.

Spraying Method of application in which the coating material is broken up into a fine mist that is directed onto the surface to be coated.

Spray Angle The angle of particle impingement, measured from the surface of the substrate to the axis of the spraying nozzle.

Spray Distance The distance maintained between the thermal spraying gun nozzle tip and the surface of the workpiece during spraying.

Spray Rate The rate at which surfacing feedstock material passes through the gun.

Substrate Basic surface on which a material (e.g., a coating) adheres.

Surface Preparation Any method of treating a surface to prepare it for coating. Surface preparation methods include washing with water, detergent solution, or solvent; cleaning using hand or power tools; water washing or jetting without abrasive; or abrasive blast cleaning.

Thermally Sprayed Coating Applicator The technician or specialist who applies the thermally sprayed coating.

Thermally Sprayed Metal Coating (TSMC) Solid coating materials that are melted (or at least softened) before dispersion (spraying) onto a surface.

Thermal Spraying Spraying finely divided particles of powder or droplets of an atomized material for overlay coating of a substrate.

Topcoat The last coating material applied in a coating system, specifically formulated for aesthetic and/or environmental resistance. Also referred to as finish coat.

Traverse Speed The linear velocity at which the thermal spraying gun traverses across the workpiece during the spraying operation.

Undercutting The penetration of a coating and the spread of delamination or corrosion from a break or pinhole in the film or from unprotected edges.

Vehicle The liquid portion of paint, in which the pigment is dispersed; it is composed of binder and thinner.

Vinyl Coating Coating in which the major portion of binder is from the vinyl resin family. Vinyl resins include polyvinyl acetate, polyvinyl chloride, copolymers of these, the acrylic and methacrylate resins, the polystyrene resins, etc.

White Metal Blast Blast cleaning to white metal. This standard is defined in SSPC-SP-5 as a cleaned surface that, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products, and other foreign matter.

Wire-Arc Spraying A thermal spray process using an electric arc discharge between two consumable wire electrodes of surfacing material. A jet of compressed gas is used to atomize and propel the surfacing material to the substrate being coated.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation