STEEL INNOVATIONS 2013 Christchurch February 21-22

Steel Innovations Conference 2013
Christchurch, New Zealand
21-22 February 2013

THERMAL METAL SPRAY FOR BRIDGES: A NEW ZEALAND PERSPECTIVE

Willie L. Mandeno[1]

ABSTRACT

Thermal sprayed metal (TSM) includes proven long term protective coating systems using zinc, aluminium and their alloys for steelwork in a marine environment; however specifiers have been slow to adopt these for the protection of bridge steelwork in New Zealand. This paper reviews the technology then looks at several projects in New Zealand and overseas, some where a failure has occurred, and discusses these and the lessons that should be learned. It concludes with recommendations as to how coating specifications could be improved so that TSM's potential long life performance can be achieved.

Introduction

The process of spraying molten metal onto steel was first patented in Switzerland by Dr Schoop and introduced to the UK in 1912, but did not become a commercial reality until the early 1920's (Meyer 1996). Metal spraying of bridge components (e.g. the Menai Straits Bridge) was carried out in Britain before World War II. Because of the significant reduction in maintenance, flame sprayed zinc supplemented by paint became widely specified by British engineers for many major structures around the world, including the Auckland Harbour Bridge (1958), the Forth Road Bridge (1964), and the Pierre-Laport suspension bridge across the St Lawrence at Quebec (where from 1978-84 some 165,000 sqm was coated after failure of the original paint system) (Snook 1983). Use of flame sprayed zinc as a primer declined with the introduction of the self-curing types of inorganic zinc silicates in the 1970's and has since mainly been used to coat steel components that could not be "galvanized", ie by dipping into a bath of molten zinc. Typical production deposition or melt rates of zinc wire when flame spraying were 10-20 kg/hr.

The arrival of arc spray technology in the mid 1960's greatly increased coating adhesion and gave typical application rates of 10-35 kg/hr using a 2.5 mm maximum sized wire, but the finish of the sprayed metal was rougher and spray efficiencies of 50% were typical. In 1990 "high deposition low energy" systems became available which were also much lighter and portable. These gave deposition rates of 20-90 kg/hr with deposition efficiencies of over 70% when arc spraying 4.8 mm wire. Other recent developments have reduced application costs, and have made thermal metal spray a very competitive long life coating system.

A description of the main processes involved in thermal spray, and a discussion of the advantages and disadvantages of TSM as a protective coating for steel when compared to galvanizing or coating with inorganic zinc silicate, have been given in an earlier paper by the author (Mandeno and Sutherland 1997).

This paper is a modified version of a recent update (Mandeno 2012) to this first paper.

[1]Technical Principal Corrosion Engineering, Opus International Consultants Ltd, PO Box 12003, Wellington 6144

Exposure Trials

In North America the TSM process is known as "metallizing" with early work being carried out by the American Welding Society (AWS) who in 1953, exposed panels coated with flame sprayed zinc and aluminium and various sealers. Very favourable results were reported after 19, 34 and 44 years of exposure at coastal and industrial sites (Bland, 1974, Kain and E Baker, 1987, Pikul, 1996). This work was followed up by the US Army Corps of Engineers with successful trials of TSM as a more abrasion resistant coating than vinyl on dam gates, and which resulted in a comprehensive design manual (USACE, 1999) which is available on the internet.

The US Federal Highway Agency noted (FHWA 1997) that work by the AWS and US Navy showed that *"properly applied metallized coatings (zinc, 85% Zinc/15% Aluminum, and Aluminum) of at least 6 mils thickness provide at least 20 years of maintenance free corrosion protection in wet, salt-rich environments and are expected to provide 30 years of protection in most bridge exposure environments".* The FHWA has sponsored several research projects coating steel bridge beams with TSM, including one of environmentally acceptable materials which found that the thermal sprayed zinc (TSZ) systems were the best performing over 40 coating systems tested (which included topcoated and single coat "high-ratio" and other inorganic zinc silicates) with no undercutting at scribe marks after 6.5 years exposure, and had the lowest Life Cycle Cost (Kogler, Ault and Farschon, 1997).

Thermal Sprayed Aluminium (TSA) has been widely used in offshore oil and gas industry and by 1997 over 400,000 sq metres of TSA had been applied to oil platforms in the North Sea to provide corrosion protection to flare stacks, riser pipes in the splash zone and submerged tethered legs (e.g. Conoco's Hutton platform built in 1984). Experience indicated that TSA coatings, when properly applied and with the use of specific sealer systems, will provide a service life in excess of 30 years with zero maintenance required (Tiong 2004).

Standards

The two main standards available for local specifiers are the International Standard ISO 2063 (with its various national equivalent versions such as BS EN ISO 2063) and the North American joint Standard, NACE 12/AWS C2.23M/SSPC-CS 23.00. These are supported by other standards that cover guidance in such matters as specification (ANSI/AWS C2.18-93R), operator qualification (ANSI/AWS C2.16M and ISO 14918), and adhesion testing (ASTM C633). In addition, individual groups such as oil companies and military organisations have their own in-house specifications (e.g. DEP 30.48.40.31-Gen from Shell and MIL-STD-2138A(SH) from the US Navy).

Expected durability of TSM systems in different atmospheric environments have been given in recent versions of AS/NZ 2312 which were initially derived from international sources such as BS 5493, ISO 14713 and ANSI/AWS 2.18. These expected lives to first major maintenance (when breakdown exceeds 2% rust as defined in ASTM D610) are given in the Tables below. The suffix 'S' denotes a sealed coating with the TSM thickness given in microns. Note that these Tables are likely to be further amended (e.g. to include 85/15 Zn/Al alloy) in the next edition of AS/NZS 2312 which is currently being revised.

Table 1: AS/NZS 2312:1994

Atmospheric Classification	**Years to first major maintenance**					
	>2 to 5	>5 to 10	>10 to 20	>20 to 25	>25 to 40	>40
Moderate	-	-	ZN100	ZN150	ZN175**	ZN300
Marine	-	ZN100 ZN75S	ZN150 ZN100S	ZN150S AL150	ZN350 AL275	ZN375S AL275S
Severe Marine	ZN100	ZN150	ZN250	AL275	AL325	

Note: ** This system designation was incorrect and should have been ZN275

Table 2: AS/NZS 2312:2004

System designation	Super-seded design-nation	Nominal coating thickness um	**Durability – Years to first maintenance**						
			Atmospheric corrosivity category						
			A Very low	B Low	C Medium	D High	E-I Very high indust-rial	E-M Very high marine	F Inland Tropical
TSZ100	ZN100	100	25+	25+	25+	15-25	NR	5-15	25+
TZS150	ZN150	150	*	*	25+	25+	NR	10-25	25+
TSZ200S	ZN200S	200+seal	*	*	*	25+	NR	25+	*
TSA150S	AL150S	150+seal	*	*	25+	25+	15-25	15-25	25+
TSA225S	AL225S	225+seal	*	*	*	25+	25+	25+	25+

NR = Not recommended * Very high durability but unlikely to be economic.

Sealing and Painting of TSM

Thermal sprayed metals, and zinc in particular, can have their performance in marine environments enhanced by sealing the pores and surface with a low viscosity material with good wetting properties such as vinyl, acrylic, or thinned epoxy or urethane. Silicone aluminium is used for high temperature applications. This is applied soon after spraying the metal and until absorption of the sealer is complete. Use of aluminium or coloured pigments can give a more uniform appearance to the metal coating, while the binder decreases exposure of the metal to the environment. Additional high-build paint coatings are unnecessary and, as for galvanizing, can reduce the system life by trapping salts and moisture against the metal at coating defects (Lester 1994). The increased life due to sealing is shown in Table 2 above, where sealing zinc is approximately equivalent to adding a third more metal thickness. Sealing of aluminium has less effect on its durability but is usually specified to prevent initial rust bleed through that may occur when a film of less than 150 microns is exposed to rain, before pores between the splats have been filled with oxidation products.

Australasian Experience with TSM

Discussion

Despite the potential for long life protection of assets in marine environments using TSM, its higher initial cost has meant it has not been widely accepted by specifiers in Australasia. This reluctance has been reinforced by problems on contracts due to lack of experience or expertise, and some premature failures that have resulted for various reasons, including poor quality control and unsuitable specifications. These are discussed in the remainder of this paper.

New Zealand Applications

The first major application was on the original Auckland Harbour Bridge (Figure 1) when in 1956 its coating specification was amended to the *"best protective treatment known at the time",* i.e. flame sprayed with zinc at 50 microns and top coated with 3 coats of phenolic paint (Mandeno 1990). Another early and successful application was in 1960 to the roof trusses to the main grandstand at the Ellerslie racecourse in Auckland (Mandeno and Sutherland, 1997). There have been many other applications of TSZ to steel items such oil piping, lighting columns, balcony supports; generally to components that could not be hot-dip galvanized.

Examples of the use of sealed TZA include wharf piles in Lyttleton and a highway bridge over geothermal steam pipelines at Wairakei (Figure 2). Sealed TSZ was used in 1999 to coat large I-beams for the Orewa motorway bridge (Figures 3 & 4) and box girders on the Newlands Interchange Bridge (Figure 5) in Wellington. Very recent applications include; the replacement Kopu Bridge (Figure 6) on State Highway 25 near Thames, the Te Rapa Bypass Rail Overbridge, the replacement Atiamuri Bridge on State Highway 1 that is currently under construction 39km North of Taupo, and Whangarei District Council's Lower Hatea bridge

(Figure 9). It was also used to maintain in situ RSJ bridge beams over Ship Creek (Figure 7) adjacent to a West Coast surf beach near Haast.

Figure 1. Auckland Harbour Bridge (1958)

Figure 2. Wairakei Bridge (2010)

Figure 3. Arc spraying Orewa Bridge Beam

Figure 4. Orewa Motorway Bridge (1999)

Figure 5. Newlands Bridge (1999)

Figure 6. New Kopu Bridge (2011) beside original

Duplex systems (TSZ with epoxy/polyurethane topcoats) have also been applied to several new bridges including the iconic Te Rewa Rewa Footbridge (Figure 8) near New Plymouth, some smaller footbridges such as at Petone Railway Station, and seismic strengthening under the Thorndon Overbridges in Wellington. Some of these and others that had problems are discussed in more detail in a later section.

Figure 7. Ship Creek (2003)

Figure 8. Te Rewa Rewa Footbridge (2010)

Figure 9. Lower Hatea bridge (2013)

Figure 10. Warragamba Pipeline (P2)

Australian Applications

An early and successful use of TSM in Australia was on the second Warragamba pipeline (3m diameter and 22km long) built between 1964 and 1969 (Figure 10). The first had been coated with the same heat-cured zinc silicate invented by Victor Nightingall and first used on the Morgan-Whyalla pipe line. While these have since been repainted several times, this has been due to delamination of the various overcoating systems and the underlying flame-sprayed TSZ is still sound (Salome 2012). These pipelines supply 80% of Sydney's water supply.

Use of TSM on bridges in Australia is rare, possibly due to lower cost of galvanizing and a preference for zinc silicate coatings which were first developed there. No Australian examples were included in the case history survey which formed part of the BHP Coatings Guide for New Steel Bridges (Szokolik and Rapattoni 1998).

Failures with TSM

LPC Coal Berth Piles.

TSA has been used since 2005 to protect structural steel used as beams and jackets to strengthen old timber wharves owned by the Lyttleton Port Company (LPC) and this has performed well where correctly applied (Figure 11).

In 2008 the author was asked to investigate premature failure of TSA coating on a new coal loading berth at the Lyttleton Port. As shown in Figure 12, the aluminium coating had disappeared in the tidal zone on most of the piles; some were more severely affected than others. The piles were designed with a sealed TSA coating to protect them above the low tide level, and below this as bare steel protected with sacrificial anodes. Inspection by divers found that the installed anodes were both undersized for the area they were required to protect and that some had become disconnected during driving. The TSA was therefore acting as a sacrificial anode and the protection system had to be replaced by a petrolatum wrap and HDPE jacket, plus bigger capacity anodes were retrofitted to the piles to protect the uncoated surfaces.

Figure 11. TSA on pile jacket

Figure 12. TSA “failure” on pile

Ahururi Bypass piles

An expressway near Napier Airport includes a bridge structure over the Ahuriri Lagoon. The steel jackets to its concrete piles were coated with 325 microns of sealed aluminium (TSA325S) in 2003. A few years later roughly circular rust patches approx. 100 to 200mm in diameter appeared in random locations below high tide level as shown in Figure 14. Its failure is currently under investigation with unsuitable repair methods (patching areas of low build with ultrahigh-build epoxy) being suspected as being responsible.

Figure 13. Ahuriri Bypass Bridge

Figure 14. Failure of TSA repair?

Thorndon Overbridge Catch frames

Seismic strengthening was carried out on the Thorndon Overbridges (TOB) in 1998. This elevated motorway structure is located beside the SW corner of Wellington Harbour. Where it crosses the Wellington Fault, “catch frames” were installed to eight pier heads, and steel jackets were added to improve the seismic capacity of all the concrete piers. The seventy steel jackets were coated with TSZ300 and sealed with an aluminium vinyl paint. The catch frame steelwork was coated with TSZ150 and overcoated with 50 microns of epoxy and a 50 micron finish coat of polyurethane.

The seal coating is delaminating from the upper levels of the pier jackets where windborne marine salts are not removed by rain washing (Figure 16) but no corrosion of the steel jackets has been observed. However red rusting has occurred on the catch frame steelwork which has recently been recoated but with an additional 200 micron epoxy intermediate coat added to the system over an epoxy-zinc patch primer. The corrosion was due to delamination of the duplex TSZ from flange edges of the fabricated I-beams and also pitting occurs where peaks of the zinc had inadequate barrier protection from the epoxy urethane (Figure 15).

Figure 15. Duplex TSZ failure on a TOB catch frame

Figure 16. Seal coat delaminating off TSZ

Petone Station Footbridge

This structure, located 600m from the Wellington Harbour, was coated with a duplex TSZ system in 2010 but required patch painting within two years. The specified system was 175 microns of TSZ, sealed with 50 microns of epoxy and topcoated with 75 microns of polyurethane. Premature failure occurred in areas where the peaks of the coarse surface profile of the TSZ had not been smoothed (as required by the specification) and so were close to the top surface of the paint on surfaces that were sheltered from rain washing.

Figure 17. Petone Footbridge

Figure 18. Failure of Duplex TSZ

Millennium Footbridge

Built as part of a waterfront walkway near Mission Bay, Auckland in 2001 (Figures 19 & 20), and designed by artist Virginia King, this had tubular steelwork that was coated with an unknown thickness of TSZ. The Galvanizing Association of New Zealand has reported (GANZ 2010) that this failed prematurely and in 2009 the flaking TSZ was removed and replaced with a duplex galvanizing/paint system at a cost of NZ$70,000.

Figure 19. Millennium Footbridge

Figure 20. Millennium Footbridge

Gas Platform

The duplex TSA coating on this platform in the Timor Sea began failing within a year of its construction and is currently undergoing extensive maintenance painting. Similar problems have been found on North Sea platforms where the performance of duplex TSA has been inferior to the excellent performance of more usual sealed TSA. This was investigated by SINTEF (Knudsen 1997) and failure is attributed to the formation of hydrochloric acid from hydrolysis of unstable aluminium chloride trapped under the thick organic coating.

Figure 19. Gas platform maintenance painting

Figure 20. Hydrogen bubbles from duplex TSA

Discussion

The above failures illustrate several lessons that protective coating specifiers and inspectors need to be aware of, in order for the potential long life of TSM coatings to be achieved.

Cathodic Protection

TSZ and TZA will provide cathodic protection (CP) to small coating defects and will protect small bare areas. However when used on structures that are immersed in seawater, their life as a barrier coating will be significantly reduced when connected to large areas of bare steel (or more cathodic metals) which must either also be coated or if bare, have a correctly designed and installed CP system to protect them, and also to ensure the TSM remains at a passive potential.

Duplex TSA

While sealed TSA performs better in salt water immersion and in the splash zone than sealed TSZ, the SINTEF study demonstrated that in marine environments *"TSA should not be painted with thick protective coatings*" due to the formation of an acidic electrolyte under the coating. As aluminium is not passive at pH <4 it corrodes actively with cathodic evolution of hydrogen gas and, according to their report, regeneration of the acidic environment. Formation of unstable aluminium chloride was observed to not occur when TSA is sealed with a thin single coat. Mills and Mayne 1981 reported that organic films <80 microns have significantly lower ionic resistance which may explain the superior performance of sealed TSA.

Duplex TSZ

Overcoated TSZ in seawater forms zinc chloride which is relatively stable, soluble and does not acidify the electrolyte. However when any zinc protective coating is overcoated with an organic coating, its ability to self-protect itself and any breaks in the coating with a large anodic surface is correspondingly reduced. This applies to TSZ just as it does to galvanized steel and inorganic zinc silicate coatings. Where these zinc coatings need to be coated for chemical or abrasion resistance, or to change their colour for safety or aesthetic reasons, it is important that a continuous and low permeability coating is applied of sufficient thickness to provide an effective barrier to corrodent materials, especially where these are not removed by rain washing.

SINTEF also reported that duplex TSZ had performed well on several road bridges in Norway where four coats of paint were applied over TZS100. A duplex TSZ system has been used successfully on New Zealand made air-bridges that have been supplied to several airports around Australasia (Figures 21 & 22). The future performance of the duplex coatings on the Te Rewa Rewa and similar bridges will be monitored with some interest.

Figure 21. A380 loading in Sydney

Figure 22. Duplex TSZ applied in NZ

Surface profile

TSM applied by arc spray equipment that has been set to achieve a high production rate may also produce a coarse surface profile. This may be desirable where a non-skid surface is required, but when it is to be part of a duplex system it is important to smooth the TSM surface by sanding followed by vacuuming prior to sealing. This will remove the ‘rogue peaks’ that may initiate premature corrosion at areas of low build. AS/NZS 2312 recommends a profile height of less than 50 microns for TSZ.

The surface profile of the steel substrate being sprayed is also important to ensure adequate adhesion. A very clean surface with a sharp angular profile of at least 50 microns is required for TSZ, and at least 75 microns for TZA. This may not be achieved on the flame cut edges of flanges on fabricated plate girders, unless the local surface hardening at gas-cut edges are removed by grinding prior to abrasive blasting. Sections cleaned using shot in a centrifugal blaster such as a Wheelabrator, will require a final blast with grit to achieve a suitable profile shape. The author has investigated delamination of TSZ from a local pier handrail where the surface profile was measured at <30 microns. A low surface profile may also have been the cause for the premature failure of TSZ on the Millennium Footbridge.

Specification

As with any coating system, it is important that the owner’s requirements for all stages of surface preparation, application, inspection and repair are clearly established in advance and then confirmed as being carried out by a suitable QC/QA system. It is insufficient to simply rely on following the recommendations in AS/NZS 2312, which is often all that is specified. Reference to ISO 2063 or NACE 12/AWS C2.23M/SSPC-CS 23.00 is recommended.

Also while TSM is capable of providing excellent protection, there are some intricate steel structures where hot-dip galvanizing may be a more appropriate coating system due to its lower risk of incomplete coverage.

Quality of application

In addition to the factors already discussed that can lead to premature failure of TSM, it is also necessary to stress that application of TSM requires a greater level of applicator skill than the spraying of wet protective coatings. The equipment setup and stand-off distance needs to be optimised to minimise porosity of the TSM, which will then maximise its cohesive and adhesive strength, and durability. Being a single coat system, it is important that application is carried out systematically to ensure that there are no areas of low build that can occur if there is insufficient overlap between spray patterns. Ideally a TSM applicator should be certified as competent to apply the different materials with the various different processes, in the same way as a welder is certified. Operator certification is the norm in Europe and North America and the introduction of a similar scheme run by AWS into Australasia is currently being investigated by the Australasian Corrosion Association. This would go a long way to improving the confidence of specifiers that the excellent potential performance of these coating systems will be realised.

Conclusion

Thermal sprayed metal has an established track record of providing long-term corrosion protection on bridges and other steel structures in severe environments. However in order to achieve this it is necessary to use an appropriate specification, and a competent applicator supported by a suitable QC/QA system to ensure that avoidable problems identified in this paper are not repeated.

Acknowledgments

The support of Opus International Consultants Ltd to allow presentation of this paper is thankfully acknowledged. Thanks also go to colleagues and www.flickr.com for provision of additional photographs to supplement those taken by the author.

References

ANSI/AWS joint Standard, 1993. (ANSI/AWS C2.18-93R) *Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and their Alloys and Composites.*

ANSI/AWS joint Standard, 2002. (ANSI/AWS C2.16M), *Guide for Thermal-Spray Operator Qualification.*

ASTM Standard, 2008 (ASTM C633-01), *Standard Test Method for Adhesion or Cohesive Strength of Flame Sprayed Coatings,* American Society for Testing Materials.

ASTM Standard, 2012 (ASTM D610-08), *Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces,* American Society for Testing Materials.

Australia New Zealand joint Standard (AS/NZS 2312:1994), *Guide to the protection of iron and steel against exterior atmospheric corrosion,* Standards New Zealand.

Australia New Zealand joint Standard (AS/NZ 2312:2002), *Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings*, incorporating Amendment No.1:2004

Bland, J., 1974. Corrosion Tests of Flame-sprayed Coated Steel. 19-Year Report, American Welding Society, *AWS C2.14-74*.

British Standard (BS 5493:1977), *Code of practice for protective coating of iron and steel structures against corrosion* (Section 11.2), British Standards Institute.

FHWA Bridge Coatings Technical Note, 1997. *Metallized Steel Bridge Coatings,* Federal Highway Administration, Washington, USA.

GANZ 2010. *Bright Ideas,* the official newsletter of the Galvanizing Association of New Zealand, May 2010.

International Standard (ISO 14713:1999) *Protection against corrosion of iron and steel in structures - Zinc and aluminium coatings – Guidelines.*

International Standard (ISO 14918:1998), *Thermal spraying - Approval testing of thermal sprayers*.

International Standard (ISO 2063:2005), *Thermal spraying: Metallic and other organic coatings. Zinc, aluminium and their alloys,* International Standards Organisation.

Kain, R., and E Baker, 1987. Marine Atmospheric Corrosion Museum Report on the Performance of Thermal

Spray Coatings on Steel, in *ASTM STP 947 Testing of Metallic and Inorganic Coatings*, pp. 211-234.

Knudsen, O., 2010. *Coatings systems for long lifetime: Thermally Sprayed Duplex Systems, Final Report*, SINTEF Materials Technology, Norway.

Kogler, R., P. Ault and C. Farschon, 1997. Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges", US Dept. Of Transportation, Pub. No *FHWA-RD-96-058*, Jan 1997.

Lester, T., 1994. *Metal Spray Coatings for Anti-corrosion on Structural Steel,* ACA Seminar, Auckland September 1994, (Also at Oil & Gas Conference in Aberdeen May 1996).

Mandeno, W., 1990. Painting State Highway Bridges - Past, Present and Future, Paper 62, *ACA Conference 30 Proceedings*, Auckland. Reprinted in *Journal of Protective Coatings & Linings*, 8 (1), 44-51.

Mandeno, W., and T Sutherland, 1997. "Inorganic Zinc Silicates vs. Metal Spray in Industrial Applications", *60 years of Inorganic Zinc Coatings* ed. R Francis, published by Australasian Corrosion Association

Mandeno, W., 2012. Thermal Metal Spray: Successes, Failures and Lessons Learned, *Corrosion and Prevention 2012 Conference Proceedings*, Australasian Corrosion Association (ACA), Melbourne. (Also scheduled for publication by ACA in *Corrosion and Materials* April 2013 issue).

Meyer, W., March 1996. Metal Spraying in the United States: A JTST Historical Paper, *Journal of Thermal Spray Technology*.

Mills, D. and J. Mayne, 1981. *Corrosion Control by Organic Coatings*, Ed. H Leidheiser, pg 12-17, NACE International, Houston, USA.

NACE/AWS/SSPC joint Standard. (NACE 12/AWS C2.23M/SSPC-CS 23.00: 2003), Specification for the *Application of Thermal Spray Coatings (Metallizing) of Aluminium, Zinc, and their alloys and composites for the corrosion protection of steel,* NACE International, Houston, USA..

Pikul, S., 1996. Appearance of Thermal Sprayed Coatings after 44 years Marine Atmospheric Exposure at Kure Beach, LaQue Centre for Corrosion Technology Inc. (Also referenced on page 72 of *ASTM STP 1399,* 2000).

Salome, F., 2012. CTI Consultants, Sydney, Personal Communication, 2012.

Shell Technical Specification (DEP 30.48.40.31-Gen. 2005), *Thermal Spray Coatings of Zinc, Aluminium and their Alloys*, Shell Global Solutions International BV, The Netherlands.

Snook, R., 1983. Corrosion Control by Zinc Thermal Spraying, *Third World Congress on Coatings Systems for Bridges and Steel Structures.*

Szokolik, A., and F. Rapattoni, 1998. *Coatings Guide for New Steel Bridges,* BHP Integrated Steel, Australia

Tiong, D., 2004. Experiences on Thermal Spray Aluminum (TSA) Coating on Offshore Structures, Paper 04022, *NACE Conference Proceedings*, New Orleans.

US Army Corps of Engineers, 1999. Engineer Manual 1110-2-3401, *Thermal Spraying: New Construction and Maintenance*.

US Navy 1992. MIL-STD-2138A(SH), *Metal Sprayed Coating Systems for Corrosion Protection aboard Naval Ships*. (Note cancelled in 2009 and replaced by NAVSEA SI 009-32).