THERMAL METAL SPRAY: SUCCESSES, FAILURES AND LESSONS LEARNED

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SUMMARY: Thermally sprayed metal (TSM) includes proven long term protective coating systems for steelwork in a marine environment such as thermal sprayed zinc (TSZ) and thermal sprayed aluminium (TSA); however specifiers have been slow to adopt these in Australia. This paper reviews the technology then looks at several projects in New Zealand and overseas, some where a premature 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.

Keywords: Thermal metal spray, Protective coating, TSZ, TSA, Specification

1. 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 [1]. 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) [2]. 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 give deposition rates of 20-90 kg/hr with deposition efficiencies of over 70% when arc spraying 4.8 mm wire. However there was an inherent problem of arc shorting when spraying large diameter wire at low amperages (250-400 A) which was overcome by a patented control system that can adjust the arc gap while spraying in less than 0.02 of a second [3]. This and other recent developments in atomisation control giving smoother finishes 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 [4].

2. EXPOSURE TRIALS

In North America the TSM process is known as "metallizing" with early work being carried out by the American Welding Society 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 [5,6,7]. This work was followed up by the US 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 [8] which is available on the internet.

The US Federal Highway Agency (FHWA) noted [9] 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 TSZ systems were the best performing over 40 coating systems tested (which included uncoated and topcoated “high -ratio” and other IOZ’s) with no undercutting at scribe marks after 6.5 years exposure, and had the lowest Life Cycle Cost [10].

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 [11] 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 [12].

3. STANDARDS

The two main standards available for local specifiers are the International Standard ISO 2063 [13] (with its various national equivalent versions such as BS EN ISO 2063) and the North America joint Standard, NACE 12/AWS C2.23M/SSPC-CS 23.00 [14]. These are supported by other standards that cover guidance in such matters as specification [15], operator qualification [16], and adhesion testing [17]. In addition, individual groups such as oil companies and military organisations have their own in-house specifications [18,19].

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 [20], ISO 14713 [21] and ANSI/AWS 2.18 [15]. These expected lives to first major maintenance (when breakdown exceeds 2% rust) 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 as part of the current revision of AS/NZS 2312.

Table 1: AS/NZS 2312:1994 [22]

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	

Table 2: AS/NZS 2312:2004 [23]

System designation	Superseded designation	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 industrial	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+
TSZ200A	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

4. SEALING AND PAINTING OF TSM

Thermal sprayed metal, 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 of the coating, while the binder decreases exposure of the metal to the environment. 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 [24]. The increased life due to sealing is shown in the table 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.

5. AUSTRALASIAN EXPERIENCE WITH TSM

5.1 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 Australia. 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.

5.2 New Zealand Applications

The first major application was on the Auckland Harbour Bridge 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 [25]. Another early and successful application was in 1960 to the roof trusses to the main grandstand at the Ellerslie racecourse in Auckland [4]. 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.

Recent applications have ranged from use of sealed TZA on wharf piles in Lyttleton and a highway bridge over geothermal steam pipelines at Wairakei. Sealed TSZ has been used to maintain in situ RSJ bridge beams over Ship Creek adjacent to a West Coast surf beach near Haast and also to coat new steel box girders on the Newlands Interchange Bridge in Wellington. Duplex systems (TSZ with epoxy/polyurethane topcoats) have also been applied to several new bridges including the replacement Kopu Bridge on State Highway 25 near Thames, the iconic Te Rewa Rewa Footbridge near New Plymouth, some smaller footbridges such as at Petone Railway Station, and seismic strengthening under the Thordon Over Bridges in Wellington. Some of these are pictured below and others that had problems are discussed in more detail in a later section.

Figure 1. Auckland Harbour Bridge (1958)

Figure 2. Wairakei Bridge (2010)

Figure 3. Ship Creek (2003)

Figure 4. Newlands Bridge (1999)

Figure 5. Te Rewa Rewa Footbridge (2010)

Figure 6. Kopu Bridges (2011)

5.3 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. The first had been coated with the same heat-cured zinc silicate 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 TSZ is still sound [26]. These pipelines supply 80% of Sydney's water supply.

Possibly the largest recent TSM project that has been carried out was in 1998 at the Port Stanvac Mobil Refinery (currently being demolished) near Adelaide. Some 11,000 sqm of new pipe spooling and structural steel was coated with 275 microns of TSA and 1500 sqm of existing steelwork was coated in situ with 350 microns of TSZ. Problems that occurred on this project due to applicators inexperience with arc spraying were discussed by Naylor [27] at the 1999 ACA conference.

5.4 Other Australasian Applications

Eleven tonnes of flame sprayed zinc powder was used in 1976 to coat the radial spillway gates on the Late Dam near Noumea in New Caledonia which are reported to still be in excellent condition, as are LPG spheres beside the harbour [28]. A TSA duplex system was recently used to coat a gas platform near East Timor but this suffered premature failure which is discussed later in this paper.

Figure 7. Warragamba Pipeline (P2)

Figure 8. Port Stanvac refinery

Figure 9. Late Dam gates, New Caledonia

Figure 10. Gas and oil storage, Noumea

6. FAILURES WITH TSM

6.1 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 for the Lyttleton Port Company (LPC). As shown in Figure 12, the aluminium coating had been removed in the tidal zone on most of the piles; some were more severely affected than others. The piles were designed as bare steel protected with sacrificial anodes with a sealed TSA coating to protect them above the low tide level. Inspection by divers found that the installed anodes were undersized for the area they were required to protect and some had become disconnected during driving. The TSA was therefore acting as a sacrificial anode and 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

6.2 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 TSA325 in 2003. A few years later roughly circular rust patches approx100 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 UHB epoxy) being suspected as being responsible.

Figure 13. Ahuriri Bypass

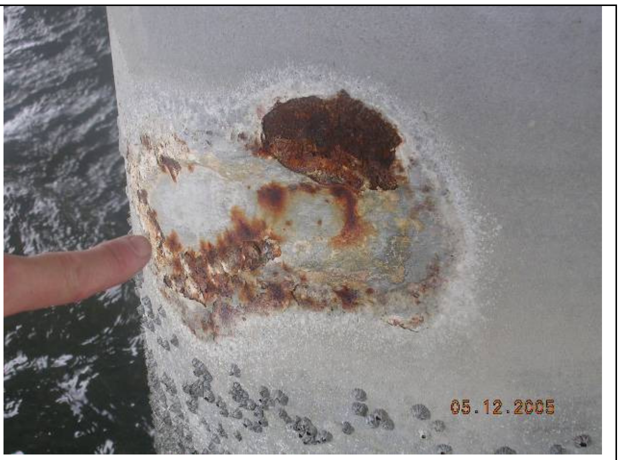

Figure 14. Failure of TSA repair

6.3 TOB 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 and where it crosses the Wellington Fault, "catch frames" were installed to eight pier heads, and steel jackets were added to improve the capacity of all the concrete piers. The seventy steel jackets were coated with TSZ300 and sealed with an aluminium vinyl. 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 has been observed. However red rusting has occurred on the catch frame steelwork which is currently being recoated but with an additional 200 micron epoxy intermediate coat added to the system over an epoxy zinc patch primer. The corrosion is due to delamination of the duplex TSZ from flange edges of the fabricated I-beams and also pitting corrosion where peaks of the zinc had inadequate barrier protection from the epoxy urethane (Figure 15).

	
Figure 15. Duplex TSZ failure on catch frame	Figure 16. Seal coat delaminating on TSZ

6.4 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

6.5 Millenium Footbridge

Built as part of a waterfront walkway near Mission Bay, Auckland in 2001, the steelwork that was designed by artist Virginia King, was coated with TSZ. GANZ has reported [29] that this failed prematurely and in 2009 the flaking TSZ was removed and replaced with a duplex galvanizing system at a cost of $70,000.

	
Figure 19. Millenium Footbridge	Figure 20. Millenium Footbridge

6.6 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 sealed TSA. This was investigated by SINTEF [30] and failure is attributed to the formation of hydrochloric acid from unstable aluminium chloride trapped under the organic coating.

	
Figure 19. Gas platform maintenance painting	Figure 20. Hydrogen bubbles from duplex TSA

7. 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.

7.1 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 have a correctly designed and installed CP system to protect them, and also to ensure the TSM remains at a passive potential.

7.2 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 regeneration of the acidic environment. Formation of unstable aluminium chloride was observed to not occur when TSA is sealed with a thin single coat which if <80 microns is thought to have low ionic resistance [31].

7.3 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 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 Kopu bridges (Figures 5 & 6) will be monitored with some interest.

Figure 21. A380 loading in Sydney

Figure 22. Duplex TSZ applied in NZ

7.4 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 pier hand railing where the surface profile was measured at <30 microns.

7.5 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. 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 a lower risk of incomplete coverage.

7.6 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 into Australasia is currently being investigated by the ACA. This would go a long way to improving the confidence of specifiers that the potential performance of these coating systems will be realised.

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