Hybrid Zinc Coatings

Specifying Hot-Dip Galvanizing (HDG)
+ Thermal Spray Zinc (TSZ)

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Introduction

Metallic zinc coatings protect steel from corrosion both as a barrier coating and by galvanic sacrificial protection. Hot-dip galvanizing (HDG) and thermal spray zinc (TSZ) are two prominent methods for applying metallic zinc coatings to steel substrates. While the materials and final coatings produced share many similarities, each method brings unique strengths and benefits to suit projects with large differences in size of steel elements. This publication will review the important considerations when looking to specify HDG combined with TSZ, or a synergistic approach of combining the two steel corrosion protection systems.

Hot-Dip Galvanizing (HDG)

HDG is a factory-only process which produces a zinc coating by completely immersing the steel product in a kettle or bath of molten zinc. Prior to immersion in the galvanizing kettle, it is critical the steel is thoroughly cleaned, either chemically or by abrasive blasting to remove all oils, greases, soil, mill scale, and oxides. During immersion, the iron in the steel reacts with the zinc through diffusion, forming a series of intermetallic zinc-iron alloy layers metallurgically bonded to the steel. Hot-dip galvanized coatings have minimum average coating thickness requirements based on the material category and steel thickness. In practice, typical coating thicknesses range from 3 to 8 mils but can be greater depending on the chemical composition of the steel (silicon and phosphorus content influence coating growth).

Thermal Spray Zinc (TSZ)

TSZ, also referred to as metallizing, is achieved by melting and spraying zinc onto surfaces using a specialized thermal spray torch or gun (*Figure 1*). TSZ requires a skilled operator and an abrasively cleaned surface. The zinc is fed by wire, ribbon, or powder into a thermal torch or gun where it is melted and sprayed onto the substrate. The zinc then cools, mechanically bonding to the steel. For thinner metallized coatings (≤6 mils), sometimes a penetrating sealant (usually epoxy or polyurethane) is applied afterward for additional corrosion protection or to fill in the porosity of the TSZ coating. The use of a sealer is less common for TSZ specified above 6 mils where concern over coating porosity is reduced. Surface preparation for TSZ is vital, requiring all surfaces to be accessible for abrasive cleaning immediately prior to TSZ application. This can make hollow structures, deep nooks or crannies, and other hard-to-reach places difficult or impossible to coat. TSZ coatings are typically applied in increments of 2–4 mils per spray pass, with total thicknesses ranging from 4 to 20 mils, depending on application requirements.

While TSZ coatings can be composed of zinc alloys ranging from 2% to 22% Aluminum[1] (the most common being 85%Zn/15%Al), this guide focuses on 100% thermal spray zinc coatings which are fully compatible with HDG coatings. While there is currently no evidence indicating a significant risk of galvanic corrosion when combining 85%Zn/15%Al with HDG coatings, technical data on this specific issue is currently limited. For details on TSZ alloy feedstock options see the International Zinc Association's (IZA) TSZ guide.

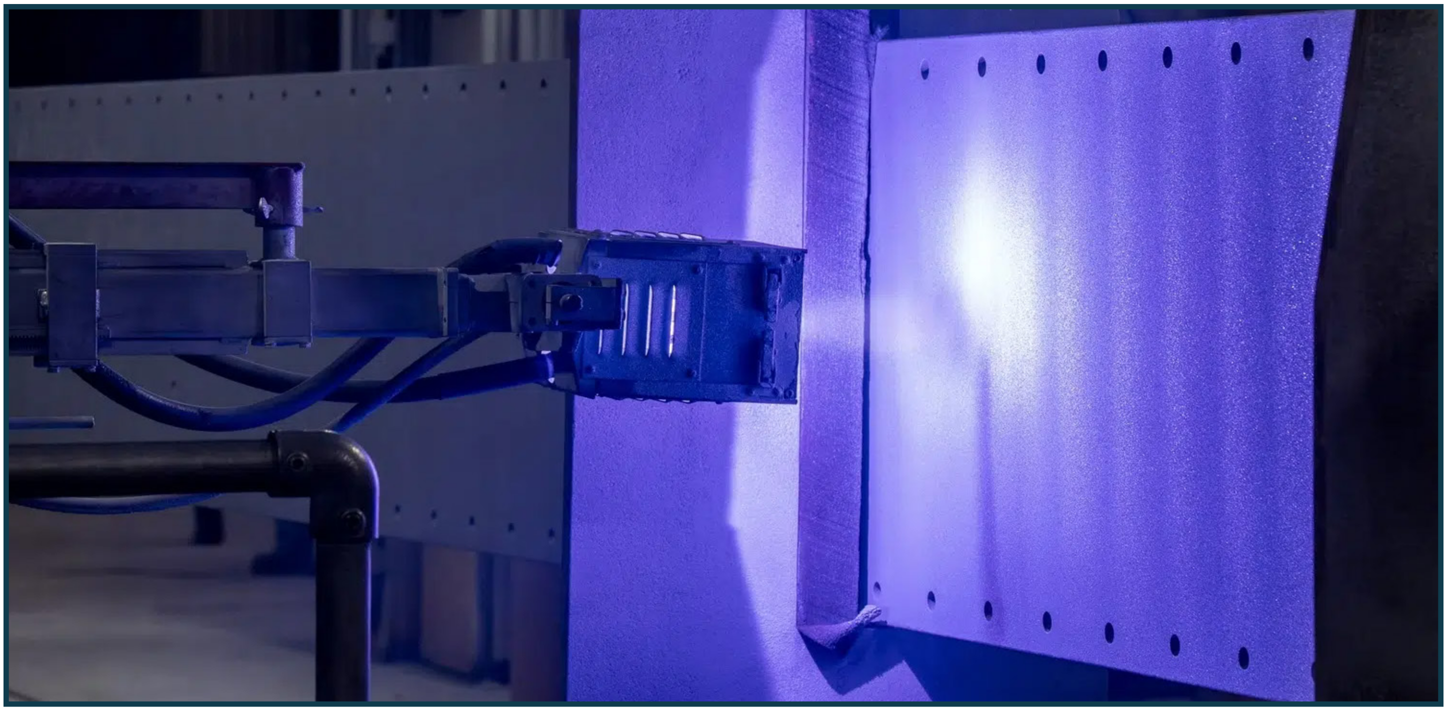


Figure 1: Zinc being applied to steel using the thermal spray process - Image courtesy of Industrial Steel Construction, Inc

Estimating HDG & TSZ Performance in Atmospheric Environments

Hot-dip galvanized steel, now in use for more than 170 years, has demonstrated maintenance-free lifespans of 75–120 years in various atmospheric environments, including industrial, urban, marine, and rural settings. Longevity can be estimated using the Zinc Coating Life Predictor (ZCLP) and the Time to First Maintenance Chart (TFM).

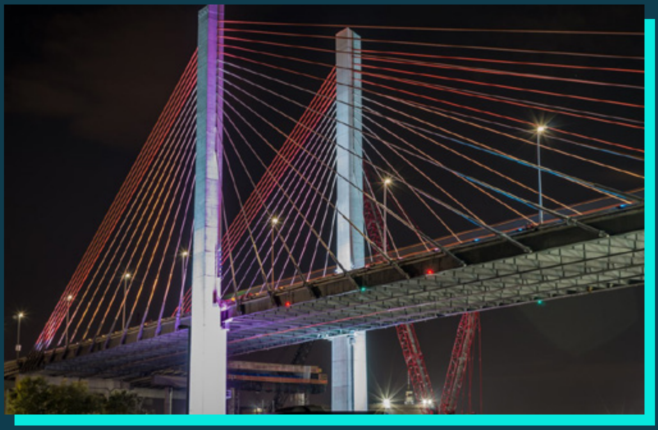
Estimates for the time to first maintenance of metallized coatings in atmospheric environments can be similarly calculated using the ZCLP and TFM chart when accounting for differences between TSZ and HDG. The porous nature of TSZ coatings may result in 5-8% less zinc per volume than an HDG coating of the same thickness. Therefore, when using AGA's TFM charts to evaluate TSZ, it is recommended to subtract 10% from the coating thickness to account for the porosity. If needed, porosity can be addressed by increasing the coating thickness. For more information on TSZ longevity, specifying TSZ coating thickness, and use of sealers see IZA's Guide or supplemental information in the Reference section of this document.

Figure 2: Initial appearance of HDG plates bolted to a TSZ bridge girder
Image courtesy of High Steel Structures

Case Study

The Kosciuszko Bridge

New York City, New York



Case Study: Specifying a Hybrid Solution

The Kosciuszko Bridge replacement is a great example of implementing both TSZ and HDG according to their strengths and limitations. TSZ was specified for girders, floor beams, and other items too large to fit into a galvanizing kettle. These components were primarily made up of large flat surfaces ideal for metallizing.

Anchor assemblies and anchor stay tubes on the other hand are relatively short in length and not too tall or wide. They are complex, with difficult to access surfaces, which makes them well suited for HDG to ensure complete coverage on all surfaces.

HDG? TSZ? Or Both?

Figure 3: TSZ bridge girder
Image courtesy of Industrial Steel Construction, Inc

Overall Strategy for a Hybrid Zinc Coating

HDG and TSZ each have unique benefits and challenges, warranting careful consideration when specifying zinc coating systems. Oftentimes during the bidding or design process, a general contractor will specify one or the other as a single solution. While a homogeneous coating system does have advantages, there can be disadvantages such as cost or performance. For example, when TSZ is specified for one or two items too large to galvanize, sometimes the rest of the steel is TSZ as well, even if HDG is well suited for some components. This can result in a significant and unnecessary cost premium. According to industry cost data TSZ costs 3.5 times more than HDG (see *Table 1*).

Type of Coating	Cost
Hot-Dip Galvanizing (HDG)	$2.70
Zinc Metallizing (TSZ) [8 mils no sealer]	$7.08
Table 1: Shop Coating Costs per Sq. Ft. Including Labor, Equipment, & Related Costs[2,3]	

Selecting the most optimal coating system for each component allows for the best long-term value by taking full advantage of the benefits offered by each coating solution. For projects containing a mixture of oversized parts and parts that fit within the galvanizing kettle, a hybrid zinc coating of HDG + TSZ should be considered for maximum cost efficiency while leveraging the benefits of both coatings. The flowchart on Page 9 describes this general strategy in addition to some exceptions that may also influence the decision to metallize, galvanize, or both.

Ideally, both TSZ and HDG would be specified according to their strengths considering the project requirements and application characteristics. On a practical level, this could mean galvanizing smaller or more complex components of a project that fit within the galvanizing kettle while metallizing large, oversize components that have accessible surfaces for TSZ application. It could also mean galvanizing each end of an oversized item, but metalizing any mid portion which was unable to be coated due to size.

A list of key topics considered in the decision to either HDG or TSZ are provided on the following pages. When utilizing the above strategy to combine HDG and TSZ to achieve a hybrid zinc coating, see subsequent section *Compatibility of HDG & TSZ: Factors to Consider when Combining.*

Size

HDG is a complete immersion process, which means parts must fit in the galvanizing kettle to be fully coated. Ultimately, size is limited by the dimensions of the galvanizing kettle. The average kettle length in North America is 40 ft (12 m) but many 50-60 ft (16-18 m) kettles are available. The American Galvanizers Association maintains a Galvanizer Locator directory on its website where you can verify kettle locations and filter by kettle dimensions (galvanizeit.org/galvanizers).

If an item is too large for total immersion in the kettle, a galvanizing practice known as progressive dipping can be utilized to sequentially immerse each end of the article to coat the entire item. In other words, if at least half the steel article can be submerged in the galvanizing kettle, the part can be partially galvanized at an angle, flipped and rehung, and then dipped on the remaining uncoated surface to fully coat the entire part with a small overlapping area between. In some cases, with a slender part or a part that is only a few inches tall, this practice can nearly double the size that can be coated. Progressive dipping of bulkier fabrications such as beams 2-4 ft in height may only gain 15-30% increase in length that can be galvanized. To assist you with these checks and calculations, the AGA provides Progressive Dip Charts (galvanizeit.org/pdcharts) and a Progressive Dip Calculator (galvanizeit.org/pdcalculator).

In addition to size, the decision to progressive dip should also consider the handling capabilities of the galvanizer, ability to mitigate the risk of warpage/distortion, and the acceptability of the finish near the overlap line.

When items are too large for total immersion into the galvanizing kettle and progressive dipping is not feasible, then TSZ should be considered. There is no size limit for TSZ.

Case Study

Jesup Bridge
Jesup, Iowa

Case Study: Size Constraints and Aesthetics

The Jesup bridge in Iowa was galvanized in 2014 and required progressive dipping for the large beams. In practice, progressively dipped articles result in a notably dark and rough overlap area visible on the part. The resulting progressive dip lines were photographed both during installation (Figure 4) and shortly after the bridge was opened to the public (Figure 5). One decade later, an AGA member returned to photograph the progressive dip lines to document and compare the difference in appearance resulting from 10 years of natural weathering (Figures 4,5,6,& 7). Initially, the progressive dip lines had a dark appearance and rough texture compared to the surrounding coating appearance, but after 10 years of weathering, the progressive dip line softened greatly as the zinc patina developed and provided a matte-gray color.

Figure 4: New progressive dip lines in Autumn 2013 during installation of the Jesup Bridge

Figure 5: Progressive dip lines on Jesup Bridge beams shortly after installation, Winter 2013

Figure 6: Jesup Bridge after over 10 years of weathering. Progressive dip lines are visible but far less pronounced. Photograph taken Spring 2024.

Figure 7: Close-up of fully-weathered progressive dip lines on the Jesup bridge. Spring 2024.

Figure 8: Large, flat surfaces are ideal for TSZ
Image courtesy of Industrial Steel Construction, Inc

Lifting Orientation and Handling

The maximum article size which can be hot-dipped may be further limited by the layout and lifting capabilities of the HDG plant. Discuss lifting orientation and lift points directly with the galvanizer to avoid clashing of the article with nearby walls or equipment at the plant for both passes to produce the coating. Additionally, confirm the article weight is within the safe working load limit of the available lifting equipment.

Warpage & Distortion

If an item does fit in the galvanizing kettle but cannot be designed in accordance with ASTM A384, it may be at risk of warpage or distortion. ASTM A384 details different possible risk factors for warping and distortion and guidelines on how to avoid them. When the risk of warpage and distortion is unable to be effectively mitigated, consider TSZ as it does not heat the steel sufficiently to relieve internal stress eliminating potential for warpage and distortion. For more information on minimizing warpage and distortion see AGA's publication Design of Products to be Hot-Dip Galvanized After Fabrication[15].

Accessibility

HDG's full immersion process allows cleaning solutions and molten zinc to flow into and access all surfaces resulting in equal and uniform protection. Internal areas, corners, nooks and crannies, delicate parts with many edges, and recessed areas are easily galvanized. On the other hand, molten zinc cannot enter overlapping surfaces welded together with narrow gaps less than 3/32-in., leading to uncoated areas. See AGA's publication Design of Products to be Hot-Dip Galvanized After Fabrication[15].

Large, flat, uniform surfaces which are readily accessible are ideal for TSZ *(Figure 8).* Meanwhile, some design factors can make other items difficult to blast clean or spray with the thermal gun. For example, the insides of hollow structures, elevated locations on installed projects, bridge undersides, etc. all propose significant difficulties - if not impossibilities - for equipment and personnel access and should be considered early on.

Schedule & Availability

HDG is performed after fabrication and therefore requires shipping materials to and from a galvanizing facility. Newly galvanized parts do not typically return to the fabricator but are transported directly to the jobsite unless additional requirements are specified. However, because HDG is a factory-controlled process, it can be accomplished 24/7, 365 days a year, rain or shine, ensuring reliable on-time delivery. Zinc solidifies upon withdrawal from the bath, so there are no delays for curing.

TSZ is convenient because it can be performed either in the fabrication shop or the field; however, proper temperature and humidity conditions are required when performed in the field. Procuring skilled metallizing operators and equipment is essential and may not be readily available in certain locations. Prior to specifying TSZ, it is important to contact a facility that performs metallizing and determine their proficiency and availability.

Durability & Abrasion Resistance

During immersion in the galvanizing kettle, iron within the steel and the molten zinc undergo a diffusion reaction forming a series of intermetallic alloy layers harder than the substrate steel with a softer layer of pure zinc on top. The alloy layers, metallurgically-bonded at 3600 psi, grow perpendicular to all surfaces including sharp corners and edges, giving all surfaces equally robust protection. This gives HDG exceptional durability and abrasion resistance. This is a great advantage when considering areas traditionally vulnerable during shipping, handling, and installation. Piles, posts, and other components to be driven into the ground also benefit from HDG's superior abrasion resistance.

A TSZ coating has a strong mechanical bond (approximately 1,500 PSI) with the substrate, but it does not have intermetallic alloy layers. SSPC-CS 23/AWS C2.23/NACE No. 12 specifies a minimum adhesion requirement of 500 PSI.

Slip Coefficients

HDG faying surfaces will have the friction properties as listed within AISC or RCSC specifications (Class A, mean slip coefficient, $\mu = 0.30$) or AASHTO LRFD Bridge Design Specifications (Class C, mean slip coefficient, $\mu = 0.30$). The application of zinc-rich paint over HDG has been shown to improve the slip coefficient if time allows for qualification and testing according to the procedures in the RCSC standard (Appendix A). For example, AASHTO LRFD Bridge Design Specifications now includes a Class D surface condition (mean slip coefficient, $\mu = 0.45$) to include blast-cleaned surfaces (including HDG) painted with organic zinc-rich coatings when qualified.

TSZ faying surfaces are characterized as Class B ($\mu = 0.50$) as long as TSZ coating thickness is 16 mils or less[16].

Duplex Systems

Both HDG and TSZ can be, and commonly are, painted or powder coated. Typically, this is done for aesthetics or safety but is also an option to increase corrosion protection, extending the steel's overall service life. The paint or powder coating benefit from the zinc's cathodic properties of the underlying HDG or TSZ surfaces, protecting against under-film corrosion. Meanwhile, the zinc coating benefits from the additional barrier protection provided by the paint or powder. These benefits work together to produce a synergistic effect extending the combined coating system's life significantly. Paint maintenance cycles are also extended by 50% leading to additional economic benefits regarding maintenance. For information on the longevity and specification of Duplex Systems, refer to the following tools, publications, and specifications:

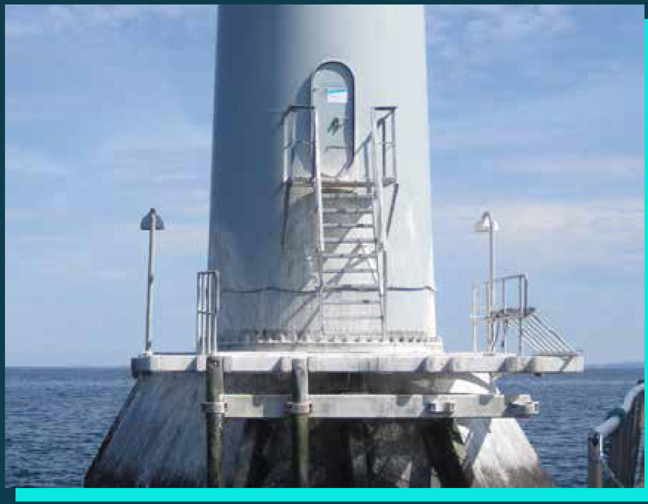
- AGA Life Cycle Cost Calculator
- AGA Preparing Hot-Dip Galvanized Steel for Powder Coating
- AGA Preparing HDG Steel for Paint
- ASTM D6386, Practice for Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Painting
- ASTM D7803, Practice for Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Powder Coating
- NCHRP 12-117, Guidelines for Corrosion Protection of Steel Bridges Using Duplex Coating Systems
- SSPC Guide 19, Selection of Protective Coatings for Use Over Galvanized Substrates

Case Study

Thunoe Knob Wind Farm

Bay of Aarhus, Denmark

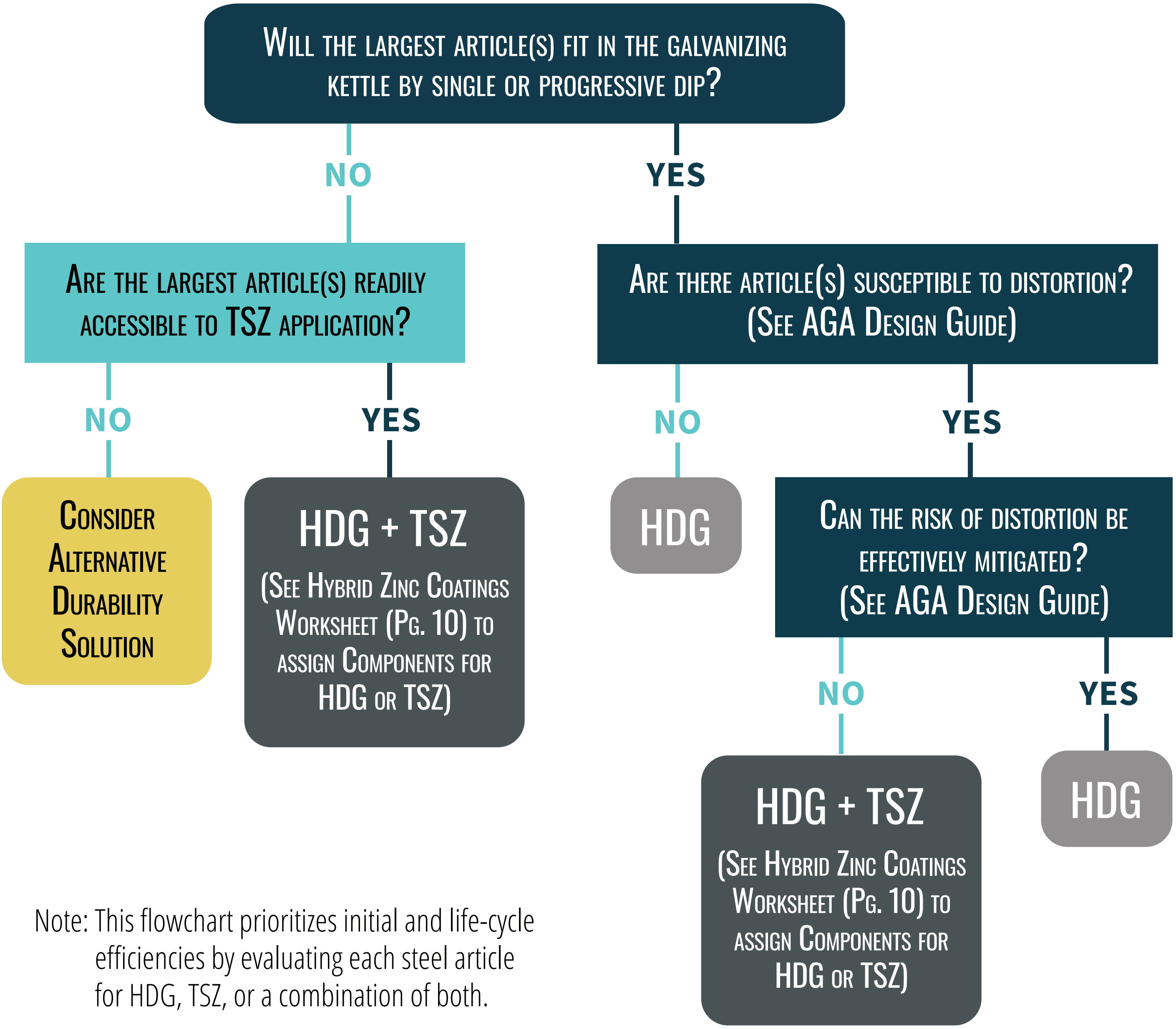
Case Study: Zinc Coatings in Offshore Applications



The Thunoe Knob wind farm off the coast of Denmark was in service for 25 years from 1995 to 2020. The turbine towers were duplex coated using thermal spray zinc top coated with Epoxy and Polyurethane while the stair and dock components were hot-dip galvanized. In 2014, the ten 500 KW turbine towers were inspected and found to have no wear or corrosion on zinc coated components. However, small, local, point impact damage to the paint and topcoat was found due to wind and wave movements causing lifeline shackles to impact and rub against the tower. Although this caused sufficient damage to fully remove the paint in some areas, the TSZ coating underneath was in great condition with no observable corrosion. Similarly, the galvanized components such as the landing dock and stairways were also in great condition with no visible signs of corrosion.

Ultimately the towers were decommissioned at the end of their design life and the Thunoe Wind farm's performance over a 25-year span will remain a testament to the resilience of zinc coatings in harsh coastal environments for years to come.

Hybrid Zinc Coating (HDG + TSZ) Selection Flowchart



Note: This flowchart prioritizes initial and life-cycle efficiencies by evaluating each steel article for HDG, TSZ, or a combination of both.

Hybrid Zinc Coatings Worksheet

The following worksheet is designed to be used in conjunction with the flow chart (page 9). This worksheet can also be downloaded as a standalone, single-page, fillable form with flowchart from the AGA website: galvanizeit.org/hybridzinccoatingsws

Physical Characteristics of Individual Steel Articles

The following questions relate to the size, shape, configuration, and application of each steel article to assess whether HDG, TSZ, or a combination of both would be the best fit to maximize your project's cost efficiency.

	Questions	Answers			Notes
1	What are the dimensions of the largest article?	____ L	____ W	____ H	Ideally, all steel articles are designed to fit in the galvanizing kettle in a single dip (immersion). Components larger than the kettle may be candidates for progressive dipping (see Q4). A TSZ coating is ideal for larger components that cannot fit in the kettle in a single dip and cannot be progressively dipped.
1a	What is the largest length steel article?	____ L			
1b	What is the largest width steel article?		____ W		
1c	What is the largest depth (height) steel article?			____ H	
2	What is the size of the galvanizing kettle?	____ L	____ W	____ H	Typical kettle sizes range from 30-60' L x 5-8' W x 6-12' D (9-18 m L, 1.5-2.4 m W, 1.8-3.6 m D). The average galvanizing kettle size in North America is 40' L x 6' W x 8' D (12 m L x 1.8 m W x 2.4 m D). Kettle sizes for all AGA member galvanizers can be found on the AGA website: galvanizeit.org/galvanizers.
3	Are all dimensions listed in Q1 < Q2?	_____ Yes _____ No			If YES, HDG is an ideal and cost efficient coating for all steel articles (Skip Q3a). If NO, Q4 will determine whether progressive dipping can be considered. It is important to verify this with the galvanizer to ensure the material handling capabilities of the galvanizer.
3a	Are the steel articles candidates for progressive dipping? (see Notes)	_____ Yes _____ No			Articles up to 90' in length have been successfully hot-dip galvanized by employing a progressive dip process (dependent on kettle size). The AGA has developed simple reference charts to determine if this is possible (galvanizeit.org/PDcharts) and a more comprehensive progressive dip calculator (galvanizeit.org/PDcalculator). See also: galvanizeit.org/knowledgebase/article/determining-overcoming-the-size-limitations-of-hot-dip-galvanizing.
4	Is the structure susceptible to distortion? (see Notes)	_____ Yes _____ No			Some fabricated structures and assemblies may distort at the galvanizing temperature as a result of relieving stresses induced during steel production and in subsequent fabricating operations. The following AGA Knowledgebase article highlights particular fabrications that are susceptible and design/fabrication techniques to mitigate distortion/warpage risk: galvanizeit.org/knowledgebase/article/warpage-and-distortion.
5	Does the steel design include tight recessed areas? (nooks, crannies, threads for connections)	_____ Yes _____ No			Tight recessed areas and other steel components can be difficult to blast clean or spray with the thermal spray gun. These components are ideally hot-dip galvanized depending on answers to Q1-Q4. See "Accessibility" for more information.
6	Is the article readily accessible for TSZ application?	_____ Yes _____ No			Large, flat, uniform surfaces which are readily accessible are ideal for TSZ. Meanwhile, some design factors can make other items difficult to blast clean or spray with the thermal gun (i.e. large, flat surfaces and not hollow fabrications, small parts with many edges, etc.). See "Accessibility" for more information.
7	Does the project require surfaces with increased abrasion resistance?	_____ Yes _____ No			If areas traditionally vulnerable during shipping, handling, and installation require increased durability and abrasion resistance, galvanizing is the preferred coating. Piles, posts, walkways and other components to be driven into the ground also benefit from galvanizing's superior abrasion resistance.

Schedule Impacts Considerations

The following questions relate to factors that may influence the project schedule. If accelerated timelines and/or hard deadlines are required it is important to consider the following factors when choosing to hot-dip galvanize, apply thermal-spray zinc, or use a hybrid coating solution utilizing both coating systems.

	Questions	Answers			Notes
8	When is the steel required to be delivered to the job site? (i.e. accelerated timeline?, hard deadlines?)	Project Delivery Date	Galvanizer Meet Delivery	TSZ Applicator Meet Delivery	Applying multiple coatings will increase the project timeline. It is important to verify with the coating facilities directly that they can accommodate the required project schedule.
		_____	Yes / No	Yes / No	
9	Does the fabricator offer in-house TSZ?	_____ Yes _____ No			If the steel fabricator offers in-house TSZ capabilities this can shorten the project delivery schedule by limiting transportation between coating facilities.
10	If the project includes slip-critical connections, which are acceptable for design?	_____ Class A/C _____ Class B _____ Class D			HDG and TSZ have different established friction properties as listed within RCSC and AASHTO specifications. Use of mixed connections or Class D may require project-specific testing prior to erection.

Compatibility of HDG & TSZ: Factors to Consider when Combining

Dissimilar Metals

When two different metals are in contact and exposed to a common electrolyte, one of the metals experiences accelerated corrosion while the other is protected. However, when combining TSZ (100% Zn alloy) the risk of galvanic corrosion is avoided. For more information on galvanic corrosion see the AGA's guidance on Dissimilar Metal Corrosion with Zinc[14].

Slip Critical Connections

As of the 10th edition of the AASHTO LRFD Bridge Design Specifications (Article 6.13.2.8), connections involving a hot-dip galvanized surface mated to a metallized faying surface are classified as a Class D surface condition for slip ($\mu = 0.45$). Some limitations on metallizing composition and coating thickness are applicable in the new definition of Class D.

> *Class D Surface: blast-cleaned surfaces with Class D coatings, or a mixed faying surface utilizing an unsealed pure zinc or 85/15 zinc/aluminum thermal-sprayed coating with a thickness less than or equal to 16 mils mating with a hot-dip galvanized surface.*

Although a Class D ($\mu = 0.45$) surface condition has a slightly lower slip coefficient value than Class B ($\mu = 0.50$) for TSZ alone, the difference between Class D and B does not cause a significant impact in the overall number of bolts required.

Figure 9: Initial appearance of a TSZ bridge

Figure 10: Initial appearance of an HDG bridge

As of this publication, AISC and RCSC do not yet define a slip coefficient value for slip-critical connections which combine HDG and TSZ faying surfaces. Therefore, projects outside the governance of AASHTO standards require project-specific or supplier-specific slip coefficient and tension creep testing in accordance with Appendix A of RCSC's Specification for Structural Joints Using High-Strength Bolts[13]. On a practical level, it is necessary to account for additional cost, limited laboratory availability, and additional time required to complete testing prior to erection. Projects which have pursued RCSC Appendix A testing of unsealed TSZ (6-9 mils) combined with HDG have successfully determined slip coefficients in the range of 0.45 - 0.50 for use in connection design. Alternative approaches continue to be investigated by AGA.

Repair

Three suitable repair materials for HDG are specified in ASTM A780: zinc-rich paint (ZRP), zinc-based solder, and thermal spray zinc (TSZ). However, repair of TSZ coatings typically involves reapplication of thermally sprayed zinc. According to SSPC-CS 23/AWS C2.23/NACE No. 12, TSZ shall be repaired only by re-application of TSZ[8]. While zinc-rich paints are occasionally specified for repairs for TSZ on a project-by-project basis or to extend the life of TSZ coatings, TSZ is the only repair material approved in both TSZ and HDG coating specifications. In practice, a mixture of repair methods should be considered to optimize cost.

Aesthetics & Natural Weathering

The appearance of both TSZ and HDG will change noticeably in the first 6 to 24 months as the zinc patina forms. Exposure to natural wet and dry cycles in the environment allows the zinc patina to form. This means any differences in the initial appearance will be greatly minimized within two years as both coating systems take on a permanent matte gray color regardless of initial differences in appearance.

For a more complete list of HDG appearances and causes, see AGA Publication HDG Appearance[9].

For information on the appearance and natural weathering of HDG repair materials, see the AGA's articles: Natural Weathering & Zinc Repairs[10], Examples of Natural Weathering on HDG Appearance[11], & Long-Term Effects of Weathering on the Aesthetics of Repaired HDG Steel[12].

Case Study

I-95 Overpass at Fairfield Avenue

Norwalk, Connecticut

Case Study: Combining HDG and Metallizing for Rapid Bridge Replacement

Utilizing the benefits of HDG and TSZ together can offer solutions where a quick turnaround time is needed. In May 2024 an oil tanker caught fire underneath the I-95 overpass in Norwalk, CT damaging the structural integrity overpass. The CT DOT closed the affected stretch of I-95 and scrambled for a quick repair.

A hybrid HDG and TSZ solution was specified by the general contractor to prioritize rapid replacement. The 165-foot-long plate girders were too large for a galvanizing kettle, instead, they were metallized and paired with hot-dip galvanized cross frames and supports. The engineers successfully planned for the design of slip-critical connections between the girders and crossframes.

This project was fabricated, shipped, coated, and installed on time utilizing the factory-controlled HDG process and the flexibility of TSZ on location. This enabled the affected stretch of I-95 to reopen in September 2024, just four months after the fire.

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