ZINC COATINGS FOR SUSTAINABLE TRANSPORTATION INFRASTRUCTURE[1]

Martin Gagné, Frank E. Goodwin and Bernardo Duran

Introduction

Steel infrastructure is subject to the constant ravages of corrosion, with the direct costs of corrosion maintenance estimated to be over 3% of GDP every year(Koch 2001). The most effective corrosion protection for steel is provided by metallic zinc coatings, which act first as a barrier coating, keeping corrosive elements away from the steel, and secondly as a sacrificial anode (Porter 1994). The metallic zinc corrodes preferentially to protect the steel. Zinc coatings can be factory applied by hot-dip galvanizing or by thermal spraying. Hot-dip galvanizing involves the full immersion of the steel piece into a bath of molten zinc, which ensures complete coverage of all surfaces, inside and out. Zinc thermal spray involves projecting drops of liquid zinc onto the surface of the steel using compressed air or other gas. With thermal sprayed zinc coatings, there is no size limitation to the part to be coated, and the technology is fully portable, allowing easy field applications.

A sustainable product will reduce or avoid the depletion of natural resources. One approach to measuring sustainability is by using a Life Cycle Assessment (LCA). The LCA is used to identify environmental burdens and evaluate the environmental consequences of a material, product, process or service through production, use, and end of life (Van Genderen 2016). The measured life cycle may be from cradle to gate (typical for basic raw materials and commodities such as zinc metal) or cradle to grave (typical for products such as zinc coated steel).

The International Organization for Standardization (ISO) has standardized LCA, which forms the conceptual basis for a number of management approaches and standards that consider the life cycle impacts of product systems. Compared to paint, zinc coatings have been shown to have significantly lower life cycle impact in terms of embodied energy, global warming potential, acidification potential, and photo-chemical ozone creation potential. The results are often expressed as an Environmental Product Declaration.

Hot-Dip Galvanizing

The process of coating steel with metallic zinc by fully immersing the steel in a bath of molten zinc is called hot-dip galvanizing. The hot-dip galvanizing process involves surface preparation followed by immersion in molten zinc and a final inspection (Bablik 1950). Surface preparation consists of degreasing, pickling, and fluxing. Degreasingremoves organic contaminants such as dirt, paint markings, grease, and oil from the metal surface with a hot alkali solution, a mild acidic bath, or a biological cleaning agent. Welding slag, asphalt, vinyl and epoxieswhich cannot be removed by degreasing, must be removed before galvanizing by grit-blasting, sand-blasting or other mechanical means. After degreasing, the pickling process removes mill scale and iron oxides from the steel surface with a dilute solution of either sulfuric or hydrochloric acid. The steel surface can also be cleaned of scale and rust by using abrasive cleaning or air blasting sand, metallic shot, or grit onto the steel. Fluxing is the final surface preparation step. A zinc ammonium chloride solution is used to remove any remaining oxides from the steel surface and then deposits a protective layer on the steel to prevent any further oxides from forming on the surface prior to immersion in the molten zinc.

---

[1] 54th Annual Meetings of the *Canadian Transportation Research Forum*, May 26 - 29, 2019 at Vancouver, British Columbia

When the steel surface has been appropriately prepared, the steel is galvanized by immersion in a bath of molten zinc. The molten zinc metallurgically reacts with the iron in the steel to form a distinct coating structure approximately 100um thick (Figure 1). The hot-dip galvanized coating structure consists of a series of iron-zinc layers with a top surface layer of pure zinc. The intermetallic layers are tightly bonded to (9MPa), and harder than the base steel, offering excellent abrasion resistance. The metallurgically bonded zinc-iron alloy layersbecome an integral part of the steel rather than just a surface coating.

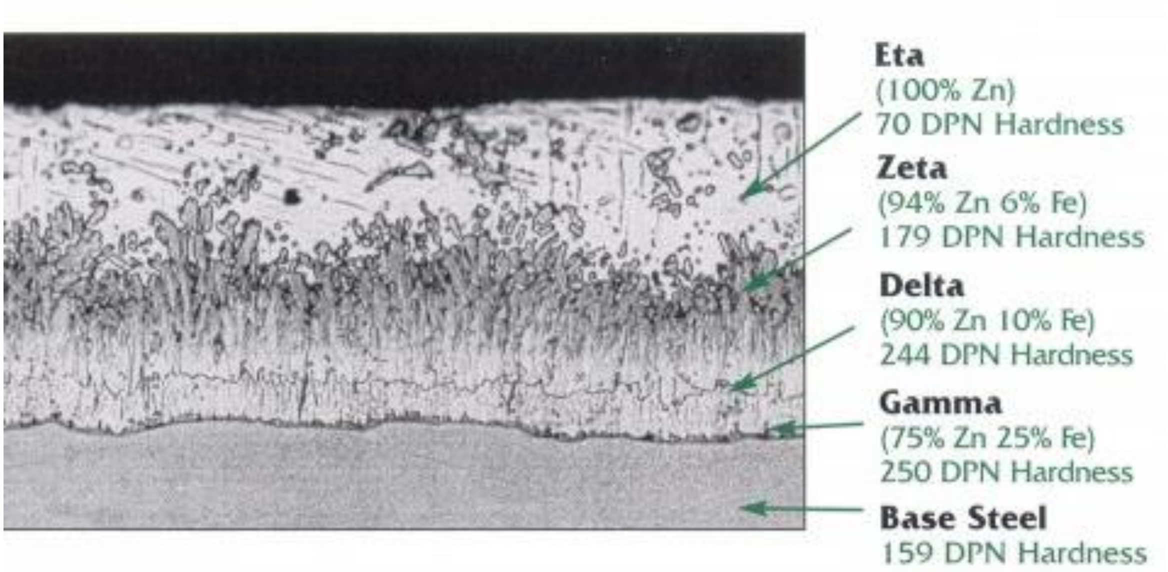


Figure 1: Galvanized coating structure

A unique characteristic of the hot-dip galvanized process is the full coverage of all surfaces. As hot-dip galvanizing is a total immersion process, all interior surfaces of hollow structures and difficult to access areas of complex structures are coated. Additionally, the metallurgical reaction allows the zinc-iron alloy layers to grow perpendicular to all surfaces, ensuring that both edges and corners have a coating thickness equal to or greater than flat surfaces. This uniform and complete coverage of all surfaces ensures that critical points where corrosion commonly starts have the same protection as accessible, flat exterior surfaces.

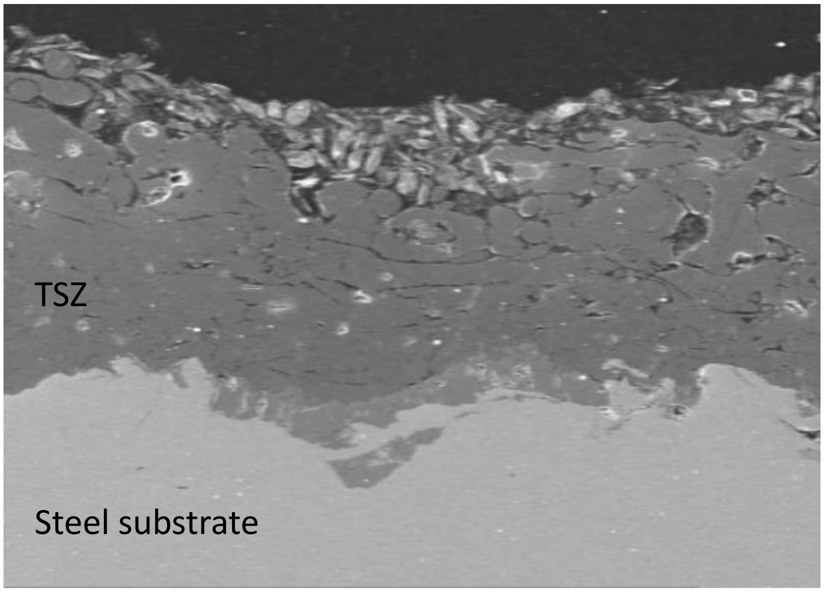
Zinc Thermal Spraying

Thermal sprayed zinc can be applied by either electric arc spraying or flame spraying (Prenger 2014). The flame spray technique uses an acetylene-oxygen flame to melt a zinc wire that is continuously fed into this flame. A stream of gas, generally compressed air, then propels the molten metal droplets in the direction of the steel surface. For the arc spraying technique, twozinc wires are brought together at an angle between 30 and 60°, and an imposed voltage difference between them creates an electric arc, which melts the zinc. A gas flow, of either compressed air or a special gas, then atomizes and propels the molten metal droplets toward the steel substrate.

The thickness of the thermal sprayed zinc coating depends on the time of spray. The deposition of semi-solid particles onto a roughened steel surfaceproduces a metallic layer with micro-pores and oxide coatings on the individually solidified particles, and a very rough surface (Figure 2).Porosity typically makes up 5-7% of the total coating volume.The overall coating has characteristics similar to solid metallic zinc, including a Vickers hardness of around 70.

Pure zinc coatings were first applied by thermal spray over 100 years ago. Since that time, a zinc-15% aluminum alloy has been developed with improved corrosion resistant properties and is now the alloy coating of choice for the most severe environments. A comparison of the melting rates for zinc and the Zn-15%Al alloy between the flame spray and arc spray techniques also shows an increase in deposition efficiency and coating rate with the arc spray process (Prenger 2012).

Figure 1 - The thermal sprayed zinc coating structure



Sustainability of Zinc Coatings

Extending the life of a structure reduces the replacement rate and the use of natural resources. To fully understand the sustainability of zinc and zinc coated steel products starts with documenting the resource requirements and environmental releases associated with upstream metal production operations, but it also involves understanding the impacts and the benefits of using zinc during other stages in the product life cycle. For zinc coated steel, this includes the significantly extended life of steel products, and also the credits through end-of-life recycling, which recovers both the zinc and the steel.

Special high-grade zinc [SHG] is widely used as the primary material for the galvanizing of steel, and for the production of zinc and zinc alloy wire for thermal spraying.To be representative of the industry, global data should be used for the life cycle assessment (Van Genderen 2016). The LCAfor the production ofSHG zinc (Table 1) was compiled from data from mining and smelting operations in Asia, Australia, Europe, North America, South Africa, and South America using the ISO standard 14040:2006 ‘Environmental management — Life cycle assessment — Principles and framework’.

Table 1: Selected LCA Parameters of Special High Grade (SHG) Zinc

LCA Parameter	**Inventory Results (per mt)**	**Unit**
Primary energy demand	37,444	MJ
- Non-renewable energy resources	27,301	MJ
- Renewable energy resources	10,143	MJ
Global Warming Potential (GWP)	2,660	kg CO2-eq
Acidification Potential (AP)	17.5	kg SO2-eq
Eutrophication Potential (EP)	2.55	kg PO4-eq

A life cycle assessment can similarly be made for products, such as galvanized steel, that documents the energy input and emission output for the production, use, and end-of-life phases. The results are presented as an Environmental Product Declaration (AGA 2016, EGGA 2016). For a hot-dip galvanized steel product, the production phase requires three life-cycle inventories as the finished zinc coated product cannot be created without first mining and producing both the zinc and the steel. Therefore, the production phase for hot dip galvanizing includes contributions from steel, zinc, and the galvanizing process.

The life cycle inventory for the galvanizing process provides the environmental impact of producing 1m^2 of hot-dip galvanized steel (AGA 2016). The product inventory is dominated by the steel component which forms the bulk of the galvanized steel product. The added environmental burdens of providing lifelong corrosion protection for steel components by galvanizing is small (Table 2). As well, hot-dip galvanizing is unique in that all material and energy inputs and emission outputs are isolated to the production phase, as there is no maintenance required for up to 70 years or more in most environments during use.

Table 2: Selected LCA Parameters for Galvanizing Steel

Production Phase (/m^2)	Primary Energy (MJ)	GWP CO_2 equiv. (Kg)	AP SO_2 equiv. (Kg)	EP PO_4 equiv. (Kg)
Galvanizing Steel	1.92	0.12	0.00105	0.000093

In contrast, paint coatings require near constant maintenance over the life of a steel structure, which adds significantly to the environmental burden and life cycle cost. An investigation of a balcony system showed that the embodied energy for the galvanized steel system was 23,700 MJ, less than half the embodied energy for the conventional painted steel system of 53,500 MJ (Cook 2004). The energy contribution from galvanizing the steel to the galvanized steel system was only 16%, or 3,808 MJ, compared to the paint contribution of 63% of the embodied energy, or 33,705 MJ, for the painted system. In addition to embodied energy, the investigation also showed that zinc coatings have significantly lower life cycle impact in terms of global warming potential, acidification potential, and photo-chemical ozone creation potential, compared to both a standard paint and a low VOC paint.

Metallic zinc coatings are an environmentally sustainable choice for corrosion protection of steel structures, and they are also cost effective. In a life cycle cost analysis for a complex bridge structure, the performance of a 116ton hot dip galvanized (HDG) steel bridge was compared to a 105 ton painted steel bridge in an aggressive industrial, or coastal marine environment (Rossi 2017). The model is based on a bridge structure with a maintenance surface of 1,346 m^2, and a bridge deck of 583 m^2. Maintenance events are defined as either ‘patch up’ involving 5% of the total bridge surface, or as ‘overcoating’ on 90% of the total bridge surface.

The initial construction costs for the painted steel bridge are shown to be about 90% of the cost of the HDG steel bridge. However, for the hot dip galvanized steel bridge, the life cycle cost over 80 years was approximately 30% more than the original cost of the bridge. In contrast, the painted steel bridge, with a minimum three coat paint system, required multiple maintenance ‘patch up’ and ‘overcoating’ repairs and had a life cycle cost almost 2.5 times the initial cost of the painted bridge. The model shows that the life cycle costs for the painted steel bridge are dominated by the maintenance events, particularly the significant ‘overcoating’ costs. While initially slightly more expensive, the HDG bridge becomes cost effective after only 18.5 years.

In a real-world example, two parallel bridges for the north and southbound lanes on highway I69 in Castleton, IN, cross over the eight lanes of E82nd Street. The composite bridges, with steel beams supporting a concrete deck, were built in 1970. The steel beams supporting the northbound lanes were hot dip galvanized, while the beams supporting the southbound lanes were painted.

The state of Indiana uses an average of 3,200 kg/lane km of deicing salts to maintain clear roads during winter months (TRB 1991). Therefore, the bridge decks on I69 are subjected to significant chloride exposure which can accelerate the corrosion of steel. The underside of the bridge will also be exposed to a salt fog from the eight lanes of trafficpassing underneath.

In 1984, after only 14 years, the paint coating on the steel supporting the southbound lanes had suffered severe degradation and needed to be repainted (AGA 2011). In 2002, the bridges were widened by adding one lane in each direction. Rather than repaint the steel supporting the southbound lanes, the old steel was cleaned, and along with the new steel for the new lanes, was protected with thermal sprayed zinc.

Inspected in 2012, the original galvanized steel beams on the northbound lanes were found to be in excellent condition. Zinc coating thickness measurements met or exceeded the requirements for new construction, even after 41 years of service. The thermal sprayed zinc applied to the steel beams supporting the new lanes and the existing southbound lanes was only 10 years old, andwas also in excellent condition. The zinc coatings are providing a corrosion and maintenance free steel structure, with significant life remaining.

The oldest known fully galvanized steel bridge is the Ehzer bridge, installed over the Twente canal in the Netherlands on the road between Almen to Laren. The bridge was installed in 1945 by Canadian forces during the liberation of the Netherlands in the Second World War. Inspected by the Dutch Galvanizers Association, the bridge was found to be in good condition (EGGA 2010). There was only light rust staining, and the steel had suffered only minor corrosion loss in some areas. Zinc coating thickness measurements revealed that much of the original coating was still protecting the bridge, and the bridge is expected to reach a 100 year life.

Conclusions

Zinc provides the most effective corrosion protection for steel by acting first as a barrier coating, keeping corrosive elements away from the steel, and secondly as a sacrificial anode. In life cycle comparisons with paint, the durability of metallic zinc coatings eliminates the repeat burdens of maintenance painting, significantly reducing the total life cycle cost of a project. Furthermore, zinc coatings have significantly lower environmental impact in terms of embodied energy, global warming potential, acidification potential, and photo-chemical ozone creation potential. Zinc coatings are readily available in every region of the globe and can be applied either by hot dip galvanizing or by thermal spraying.

References

AGA, 2016. Environmental Product Declaration, Hot-Dip Galvanized Steel

AGA, 2011, Project Gallery, Castleton Birdge

Bablik H, Galvanizing (Hot Dip), E. & F. N. Spon Ltd, London 1950

Cook, M., Vares, S. and Young, S. Life cycle assessment: Paint and hot-dip galvanizing compared, Hot dip galvanizing magazine, 2004**4**(4) 14-15

EGGA, 2016. Environmental Product Declaration, Hot-Dip Galvanized Steel

EGGA, 2010, Galvanizing and sustainable construction: a specifiers' guide.

Helsel, J.L., Lanterman, R. and Wissmar, K. Expected Service Life and Cost Considerations for Maintenance and New Construction Protective Coatings Work, NACE paper C2014-4088

Koch, G.H., Brongers, M.P.H., Thompson, N.G., Virmani, Y.P. and Payer J.H. Corrosion Costs and Preventive Strategies in the United States, Report FHWA-RD-01-156,

Porter, F.C. Corrosion Resistance of Zinc and Zinc Alloys, Marcel Dekker, New York, NY 1994

Prenger, F. Thermal Spraying Of Zinc And Zinc-Aluminum Alloys For Corrosion Protection, International Thermal Spray Conference, May 21-24, 2012, Houston, TX

Prenger, F. Thermal spraying with zinc and zinc alloys for Offshore Wind Energy Plants, Proc. Windforce 2014, Bremen, Germany, June 17-19, 2014 Windenergie Agentur, Bremerhaven

Rossi, B., Marquart, S. and Rossi, G. Comparative life cycle cost assessment of painted and hot-dip galvanized bridges, Journal of Environmental Management, Elsevier, 2017**197** (41-49)

TRB, Special Report 235, Highway Deicing, 1991

Van Genderen E, Wildnauer M, Santero N, Sidi N. A global life cycle assessment for primary zinc production. Int J Life Cycle Assess 2016, 21:1580–1593