Zinc Coatings

Microstructures of Various Zinc Coatings

HOT-DIP GALVANIZED  METALLIZED  ZINC PAINT  GALVANIZED SHEET  ELECTROPLATED
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INTRODUCTION

Zinc metal has a number of characteristics that make it well-suited for use as a coating for protecting iron and steel products from corrosion. Its excellent corrosion resistance in most environments accounts for its successful use as a protective coating on a variety of products and in many exposure conditions. The excellent field performance of zinc coatings results from their ability to form dense, adherent corrosion product films and a rate of corrosion considerably below that of ferrous materials, some 10 to 100 times slower, depending upon the environment. While a fresh zinc surface is quite reactive when exposed to the atmosphere, a thin film of corrosion products develops rapidly, greatly reducing the rate of further corrosion. Figure 1 shows the expected service life to first maintenance (5% red rust) of iron and steel based on the zinc coating thickness and the environment.

Figure 1. Service Life vs. Zinc Coating Thickness

<table>
<thead>
<tr>
<th>Thickness of Zinc in Micrometers</th>
<th>Service Life* (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1</td>
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<td>21</td>
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<td>118</td>
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</tr>
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<td>129</td>
<td>12</td>
</tr>
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</table>

*Service Life is defined as the time to 5% rusting of the steel surface.

In addition to creating a barrier between steel and the environment, zinc also has the ability to cathodically protect the base metal. Zinc, being anodic to iron and steel, will preferentially corrode and protect the iron or steel against rusting when the coating is damaged (see Figure 2).

A number of different types of zinc coatings are commercially available, each of which has unique characteristics. These characteristics not only affect applicability but also the relative economics and expected service life. The method of processing, adhesion to the base
metal, protection afforded at corners, edges and threads, hardness, coating density and thickness can vary greatly from one type of zinc coating to another.

Each of the major types of zinc coatings, applied by batch hot-dip galvanizing, continuous sheet galvanizing, electrogalvanizing, zinc plating, mechanically plating, zinc spraying and zinc painting, are discussed here as a practical aid to the specialist who must assess and select zinc coatings for corrosion protection.

**PRODUCTION PROCESSES FOR ZINC COATINGS**

**Batch Hot-Dip Galvanizing.** The hot-dip galvanizing process, also known as “batch” galvanizing, produces a zinc coating on iron and steel products by immersion of the material in a bath of molten zinc metal. The steel to be coated is first cleaned to remove all oils, greases, soils, mill scale and rust. The cleaning cycle usually consists of a degreasing step, followed by acid pickling to remove scale and rust, and fluxing to apply a protective surface to inhibit oxidation of the steel before dipping in the molten zinc.

Fluxing can be accomplished by pre-fluxing in a solution of zinc ammonium chloride (dry process), or by use of a molten flux blanket on the zinc bath surface (wet process) (see Figure 3 - previous page).

Materials to be hot-dip galvanized may range in size from small parts such as nuts, bolts and nails, to very large structural shapes. The upper limit is restricted by the size of available zinc baths and material handling capabilities. Molten zinc baths 60 feet long and six feet deep are common in North America. By double-dipping or progressive dipping (immersing one portion of the product and then the other), the maximum size that can be accommodated in the zinc bath is increased substantially, to near double bath length or depth.

Since the material is immersed in molten zinc, the zinc can flow into recesses and other areas difficult to access, allowing all areas of even the most
complex shapes to be thoroughly coated and protected against corrosion.

**Continuous Sheet Galvanizing.** The continuous sheet galvanizing process is also a hot-dip process. Steel sheet, strip or wire is cleaned, pickled and fluxed on a processing line 500 feet in length, running at speeds of over 300 feet per minute. In the coating of sheet or strip, the zinc bath contains a small amount of aluminum (0.15 to 0.25%). The aluminum (Al) suppresses the formation of the zinc-iron alloys, resulting in a coating that is mostly zinc. In-line heat treatment can be used to produce a fully alloyed (Fe-Zn) coating, called galvannealed steel.

Sheet products continuously coated with zinc-aluminum alloys are also commercially available. Two alloy compositions currently in use are 55% Al-43.6% Zn-1.4% Si and a 95% Zn-5% Al-trace mischmetal (cerium, lanthanum). These coatings are used to enhance the product life for certain applications.

**Electrogalvanizing.** Electrogalvanized coatings are applied to steel sheet and strip by electrodeposition. Electrogalvanizing is a continuous operation where the steel sheet is fed through suitable entry equipment, followed by a series of washes and rinses, into the zinc plating bath.

The most common zinc electrolyte-anode arrangement uses lead-silver, or other insoluble anodes, and electrolytes of zinc sulfates. Soluble anodes of pure zinc are also used. In this process, the steel sheet is the cathode. The coating is developed as zinc ions in the solution are electrically reduced to zinc metal and deposited at the cathode. Grain refiners may be added to help produce a smooth, tight-knit surface on the steel.

**Zinc Plating.** Zinc plating is identical to electrogalvanizing in principle in that both are electrodeposition processes. Zinc plating is used for coatings deposited on small parts such as fasteners, crank handles, springs and other hardware items.

The zinc is supplied as an expendable electrode in a cyanide, alkaline non-cyanide or acid chloride salt solution. Cyanide baths are the most operationally efficient but they potentially create a pollution and hazardous material problem.

After alkaline or electrolytic cleaning, pickling to remove surface oxides, and rinsing, the parts are loaded into a barrel, rack or drum and immersed in the plating solution. Various brightening agents may be added to the solution to add luster, but careful control of the bath and brightener is needed to ensure a quality product. Post-plating treatments may be used to passivate the zinc surface and at the same time impart various translucent colors to the coating. These post-plating treatments may be used to provide a desired color or to extend the life of the plated coating.

**Mechanical Plating.** Small iron and steel parts may be coated by drum tumbling with a mixture of proprietary promoter chemicals, zinc powder and glass beads. After cleaning, the parts, which are usually limited in size to about 8-9 inches (200-300 mm), and weighing less than one pound (0.5 Kg), are flash copper coated and loaded into a plating barrel. The barrel is then filled with chemicals, glass beads and zinc powder and tumbled (see Figure 4). The tumbling action causes the beads to peen the zinc powder onto the part. Thickness is regulated by the amount of zinc charged to the plating barrel and the duration of tumbling time. After coating, the parts are dried and packaged, or post-treated with a passivation film, then dried and packaged.
Materials mechanically plated must be simple in design. Complex designs with recesses or blind holes may not be thoroughly coated because of inaccessibility to the peening action of the glass beads. The media used as the compaction agent is also important: it must be large enough to avoid being lodged in any cavities, recesses or small threads in the parts.

**Zinc Spraying (Metallizing).** Zinc spraying is accomplished by feeding zinc in either wire or powder form into a heated gun, where it is melted and sprayed onto the part to be coated using combustion gases and/or auxiliary compressed air to provide the necessary velocity (see Figure 5).

Heat for melting is provided either by combustion of an oxygen-fuel gas flame or by electric arc. Processes have been developed for feeding molten zinc directly into the spray nozzle, primarily for use in shop rather than field applications.

Metallizing can be applied to materials of nearly any size, although some limits on the complexity of the structure may apply due to limited access to recesses, hollows and cavities by the metal spray. Abrasive cleaning of the steel is required before metallizing. The zinc coating is normally sealed with a thin coating of a low viscosity polyurethane, epoxy-phenolic, epoxy or vinyl resin.

**Zinc Painting.** Zinc-rich paints contain 92-95% metallic zinc in the film of the paint after it dries. The paints are usually applied by brushing or spraying onto steel that has been cleaned by sandblasting. While white metal blasting (NACE No. 1) is preferred, near white (SSPC-SP 10) or commercial blast cleaning (SSPC-SP 6) are acceptable.

When the zinc dust is supplied as a separate component, it must be mixed with a polymeric-containing vehicle to provide a homogenous mixture prior to application. Application is usually by air spray, although airless spray also can be used. The paint must be constantly agitated and the feed line kept as short as possible to prevent settling of the zinc dust. Uneven film coats may develop if applied by brush or roller, and cracking may occur if too thick a paint coating is applied.

Zinc-rich paints are classified as organic or inorganic, depending on the binder, and must be applied over clean steel.

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**Figure 5. Zinc Spraying (Metallizing)**
CHARACTERISTICS OF ZINC COATINGS

Batch Hot-Dip Galvanizing. The batch hot-dip galvanized coating consists of a series of zinc-iron alloy layers with a surface layer of zinc (see Figure 6). The coating is unique in that it is metallurgically bonded to the steel substrate, with the coating integral to the steel. The strength of the bond, measured in the range of several thousand psi, results in a very tightly adherent coating.

Batch hot-dip galvanizing produces thick coatings. The standard coating thickness requirement is 2 oz/ft² (600 g/m²), 3.3 mils (85 µm). Thicknesses of 6 to 8 mils (150-200 µm) on structural steels are common. For most steels, the coating thickness obtained is relatively insensitive to processing variables. Heavier coating thicknesses can be obtained by abrasive blast cleaning of the steel prior to galvanizing.

Coating thickness is proportional to coating weight, with 1 oz of zinc/ft² (320 g/m²) of surface equal to 1.7 mil (43 µm) thickness.

The zinc-iron alloys that make up the coating have hardness values that approach or exceed those of the most commonly galvanized structural steels, offering excellent abrasion resistance for applications such as stairs and walkways. The zinc-iron alloy layers are actually harder than the base steel.

The coating is generally uniform on all surfaces. Edges, corners and threads have coatings at least as thick, or thicker than, on flat surfaces providing excellent protection at these critical points.

The pure zinc layer and the zinc-iron alloy layers are anodic to steel, providing sacrificial protection in the event the coating is scratched. This ensures that the steel exposed as a result of damage to the hot-dip coating will not rust as long as there is sufficient coating on the surface of the steel.

Continuous Sheet Galvanizing. After galvanizing, the continuous zinc coating is physically wiped using air knives to produce a uniform coating across the width of the strip. The uniform coating consists almost entirely of unalloyed zinc and has sufficient ductility to withstand deep drawing or bending without damage. A variety of coating weights and types is available, ranging up to just under 2 mils (50 µm) per side. One of the most common coatings is Class G90, which has 0.9 oz./ft² of sheet (total both sides) or about 0.75 mils (18 µm) thickness per side.

Continuously galvanized sheet steels are used to make cars, appliances, corrugated roofing and siding, and culvert pipe. The coated product can be suitably treated for painting. Because of the thin coating, this product normally is used where exposure to corrosive elements is mild. It can be painted to increase service life.

Electrogalvanizing. The electrodeposited zinc coating consists of pure zinc tightly adherent to the steel substrate. The coating is highly ductile and the coating remains intact even on severe deformation. The coating is produced on strip and sheet materials to coating weights up to 0.2 oz./ft² (60 g/m²), or thickness of up to 0.14 mils (3.6 µm) per side. On wire, coating weights may range up to 3 oz./ft² (915 g/m²). Heat-treated and electro-coated wire can be cold drawn to about 95% reduction in area, depending on the chemical composition of the wire, heat treatment and diameter.

The electrogalvanized coating is paintable with suitable treatment, and the sheet product is used in automobile and appliance bodies. Due to the extremely thin zinc coating on the sheet, painting or other top-coating is recommended to improve the service life.

Zinc Plating. The normal zinc-plated coating is dull gray in color with a matte finish, although whiter, more lustrous coatings can be produced, depending on the process or agents added to the
plating bath or through post-treatments. The coating is thin, ranging up to 1 mil (25 μm), restricting zinc-plated parts to very mild (indoor) exposures. ASTM Specification B 633 lists four classes of zinc-plating: Fe/Zn 5, Fe/Zn 8, Fe/Zn 12 and Fe/Zn 25. The number indicates the coating thickness in microns. The coating finds application in screws and other light fasteners, light switch plates and other small parts. Materials for use in moderate or severe applications must be chromate conversion coated.

The coating is entirely pure zinc, which has a hardness about one-third to one-half that of most steels.

**Mechanical Plating.** The mechanically plated coating consists of a flash coating of copper followed by the zinc coating. Coating thickness requirements contained in ASTM Specification B 695 range from 0.2-4.3 mils (5 to 110 μm). While thicker coatings are possible, the common thickness on commercial fasteners is 2 mils (50 μm). The coating has a density of about 0.45 oz./ft.²/mil compared to the hot-dip galvanized coating density of about 0.6 oz./ft.²/mil. The hot-dip coating has over 30% more zinc per unit volume than the mechanical coating.

The coating, on micro cross-section, appears to consist of flattened particles of zinc loosely bonded together. The bond between zinc and steel, and zinc to zinc, being mechanical in this process, is weaker than the metallurgical bond found in hot-dip galvanizing. Edge, corner and thread coating thicknesses are usually lower at these sharp radii areas due to minimal peening action at these locations.

**Zinc Spraying (Metallizing).** The sprayed zinc coating is rough and slightly porous, with a specific gravity of 6.4, compared to zinc metal at 7.1. Zinc corrosion products tend to fill the pores as the zinc corrodes in the atmosphere. The coating adherence mechanism is mostly mechanical, depending on the kinetic energy of the sprayed particles of zinc. No zinc-iron alloy layers are present.

The coating can be applied in the shop or field, it gives good coverage of welds, seams, ends and rivets, and can be used to produce coatings in excess of 10 mils (250 μm). Coating consistency is dependent on operator experience and coating variation is always a possibility. Coatings may be thinner on corners or edges and the process is not suitable for coating recesses and cavities.

**Zinc Painting.** Organic or inorganic zinc-rich paints usually are applied to a dry film thickness of 2.5 to 3.5 mils (64-90 μm). Organic zinc paints consist of epoxies, chlorinated hydrocarbons and other polymers. Inorganic zinc paints are based largely on organic alkyl silicates. The zinc dust must be at a concentration high enough to provide for electrical continuity in the dry film. Otherwise, cathodic protection will not be available. Even so, there is some question as to whether cathodic protection is possible at all due to the encapsulation of the zinc particles in the binder.

Adhesion bond strengths of zinc-rich paints are in the order of a few hundred pounds per square inch (psi), while galvanized coatings measure in the several thousand psi range. Zinc-rich painting is similar to metallizing in that large articles can be coated in either the shop or field. Limitations include cost, difficulty in applying, lack of coating uniformity (particularly at corners and edges), and the requirement for a clean steel surface. Zinc-rich paints should be topcoated in severe environments.

Inorganic zinc-rich paints, which adhere by mild chemical reactivity with the substrate, have good solvent resistance and can withstand temperatures up to about 375°C (700°F). Cleanup is easier than with organics, and they do not chalk, peel or blister readily and are easy to weld through.

Zinc contents of inorganic zinc-rich paints range up to about 0.35 oz. zinc/ft.²/mil, about one-half less zinc per mil than hot-dip galvanized coatings.

The properties of organic zinc-rich paints depend on the solvent system. Multiple coats may be applied within 24 hours without cracking. Zinc-rich paints are often used to touch up galvanized steel that has been damaged by welding or severe mechanical impact.

Organic zinc-rich paints do not have the temperature resistance of inorganic zins, being limited to 200 to 300°F, are subject to ultraviolet (sunlight) degradation, and are not as effective as inorganics in length of corrosion prevention.

Zinc dust/zinc oxide paints (MZP) are classified under Federal Specification TT-P-641G as either Type I, Type II or Type III, depending on the vehicle. The vehicles used are linseed, alkyd resin and phenolic resin, respectively. These paints are widely used as either a primer or topcoat and show good adhesion to galvanized steel, making them the logical choices for painting that substrate. Type I is good for outdoor applications, Type II for heat-
resistant applications and Type III for water immersion or severe moisture conditions. Zinc dust/zinc oxide paints (MZP), because of their lower metallic zinc content, cannot provide sacrificial protection to the base steel. When used as a coating over galvanized steel, the service life of the galvanized coating is extended because of the increased barrier protection of the paint. The service life of the paint is extended in the event of a scratch or cut through the paint, since the volume of the zinc corrosion product, being considerably less than that of rust, reduces the incidence of lifting and separation of the paint film. MZPs can be top-coated with a variety of paint types if colors other than gray, green or tan (from pigmented additives) are required.

**Selection of Zinc Coatings**

After the decision is made to use a zinc coating for corrosion protection, some factors must be considered to ensure that the proper coating is selected for the intended application and service environment. Obviously, zinc coating processes that are limited to small parts such as fasteners or other small hardware, or operations limited to continuous lines in steel mills, such as continuous galvanizing and electrogalvanizing, cannot be considered for the protective coating of structural steel members.

*Figure 7 (page 9)* lists the different types of zinc coatings and representative applications for each. While a coating is not limited to those uses listed, the applications represent the most common types of products coated by the process.

**Coating Thickness vs. Coating Weight.** The usual criterion for determining the expected service life of zinc coatings is thickness: the thicker the coating, the longer the service life. This is an acceptable criterion when comparing zinc coatings produced by the same process (see *Figure 1, page 1*).

When comparing zinc coatings produced by different processes, the thickness criterion cannot be used without considering the amount of available zinc per unit volume. It is also important to keep in mind various ASTM or other specifications as they relate to coating weight or thickness, and reduce the coating requirements to a common denominator prior to making a comparison of different zinc coatings.

While the coating densities for some of the different types of zinc coatings are nearly identical, others differ considerably. The coating densities, in terms of thickness required to equal 1 oz. of zinc/ft$^2$ of surface, are:

- Hot-dip galvanizing (batch or continuous), 1.7 mils (43 $\mu$m)
- Electrogalvanizing, zinc plating 1.9 mils (48 $\mu$m)
- Mechanical plating 2.2 mils (55 $\mu$m)
- Zinc-rich paint 3-6 mils (75-150 $\mu$m)

Each of these thicknesses, representing the same weight per unit area of zinc, would be expected to provide equivalent service life; i.e. 1.7 mils of hot-dip galvanized would give about the same service life as 2.2 mils of mechanical plating or 3-6 mils (depending on the paint formulation) of zinc-rich paint.

It is also important to remember that for all continuous galvanized sheet materials, including electrogalvanized, the coating weight is given in weight per unit area of sheet. To obtain the amount of zinc per unit area of surface, the weight given must be divided in two, assuming equal distribution on both sides. For example, an ASTM A 653 Class G90 sheet contains 0.90 oz. zinc/ft$^2$ of sheet or about 0.45 oz./ft$^2$ on a surface. A G210 (2.10 oz/ft$^2$) sheet would have to be specified to obtain about 1 oz/ft$^2$ on each side of the sheet.

**Economic Considerations.** Selection from the wide range of coatings available for steel will normally depend on the suitability of the coating for the intended use and the economics of the protective system. Factors that affect the economics for a particular application include:

1. Initial cost of the coating;
2. Coating life to first maintenance;
3. Cost of maintenance;
4. Hidden costs, such as accessibility of the site, production loss due to maintenance re-coating, and rising wages for labor-intensive coatings, such as metal spraying and painting.

The choice of the most economical system cannot be precise, because neither the timing nor the cost of future maintenance can be accurately predicted. In addition, depreciation of capital investment, tax relief for investment and maintenance cost and the time value of money must be considered and can change over time.
A number of economic models from NACE, SSPC and the American Galvanizers Association are available for comparing the costs of different coatings. A model for predicting coating service life from field and test data is also available, as well as theoretical models of coating corrosion behavior, from the International Lead/Zinc Research Organization (ILZRO [www.ilzro.org]). By realistically estimating the costs of each coating being considered, including those costs listed above, these models enable the calculation of the net present value or the life-cycle cost of each coating being considered.

ACKNOWLEDGEMENTS

We acknowledge the assistance of the following who supplied illustrations for use in this booklet:

Cover Photo Courtesy of Cominco

Figure 3 Adapted from drawing courtesy Nordisk Förzinkningsförening Stockholm, Sweden from “Rust Prevention by Hot Dip Galvanizing.”

Figure 4 Courtesy Lester Coch, Tru-Plate Process, Inc. Jericho, New York from the Economics of Mechanical Plating, April 1978.

Figure 5 Courtesy Falconbridge Limited, Toronto, Ontario, from Zinc Metal by Thermal Spraying.
# Zinc Coatings

<table>
<thead>
<tr>
<th>Method</th>
<th>Process</th>
<th>Specification</th>
<th>Coating Thickness</th>
<th>Application</th>
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<tr>
<td>Electro-galvanizing</td>
<td>Electrolysis</td>
<td>ASTM A 879</td>
<td>Up to 0.28 mils¹</td>
<td>Interior. Appliance panels, studs, acoustical ceiling members.</td>
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<td>ASTM B 633</td>
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<td>AWS C2.2</td>
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<td>Interior or Exterior. Items that cannot be galvanized because of size or because on-site coating application is needed.</td>
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<td>Continuous Sheet Galvanizing</td>
<td>Hot-Dip</td>
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<td>Up to 4.0 mils¹</td>
<td>Interior or Exterior. Roofing, gutters, culverts, automobile bodies.</td>
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<td>ASTM A 123,</td>
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<td>SSPC-PS Guide</td>
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¹ Total for **both sides** of sheet.

² Range based on **ASTM minimum thicknesses** for all grades, classes, etc., encompassed by the specifications.

³ Range based on **ASTM and CSA minimum thicknesses** for all grades, classes, etc., encompassed by the specifications.