

HOT-DIP GALVANIZED STEEL USE IN BRIDGE CONSTRUCTION



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BIOGRAPHY

Dr. Langill has been with the American Galvanizers Association for 22 years as its Technical Director. He has been active in helping shape the research programs for galvanizing programs. He has contributed to the ASTM committees that deal with the specifications used by the galvanizing industry and is Chairman of three separate ASTM Subcommittees including the subcommittee that maintains the standards for the hot-dip galvanizing process, A05.13. The other two subcommittee that he chairs deal with corrosion issues, G01.04 on atmospheric corrosion and G01.14 on corrosion of construction materials. Dr. Langill is also Chairman of the ASTM Main Committee A05 on Metallic-Coated Iron and Steel Products. Dr. Langill also serves on other ASTM Committees such as A01 on Steel Materials, B02 on Non-ferrous Metals, F16 on Fasteners, and D01 on Paint and Related Coatings. He has provided technical support for many specifiers and engineers who have technical questions about galvanized steel or its use in a particular environment. He writes a regular feature in the American Galvanizers Association Magazine on problems related to hot dip galvanizing. He has authored and presents a seminar series on Processing Details in the Hot Dip Galvanizing Industry as well as the Inspection of Hot-Dip Galvanized Products Seminar.

SUMMARY

This paper will address technical issues with the use of hot-dip galvanized steel in bridge construction. Some key technical issues that will be addressed are the slip factor of hot-dip galvanized, painted, and metallized coatings in slip critical connections as well as the potential for cracking in bridge components during and after the hot-dip galvanizing process. Hot-dip galvanized coatings are used in small to medium sized bridges but are limited by the size of the zinc bath to coating small to medium sized structural beams. Both hot-dip galvanizing and zinc metallizing can produce coating of zinc metal and can be in contact with no corrosion interactions. Large beams that cannot be hot-dip galvanized because of their size can be thermal spray metallized while the smaller pieces can be hot-dip galvanized. When hot-dip galvanizing in the zinc bath at a temperature of 850 F, the expansion and contraction of different sized parts in steel assemblies could produce significant stresses in the steel sometimes resulting in distortion. Suggestions to avoid the potential cracking situations will be presented. Other design issues with corrosion protection of bridge components will be addressed.

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INTRODUCTION

Connecting the width and breadth of our nation, transportation elements such as bridges, guardrail, mechanically stabilized earth, and reinforcing steel knit together communities across the country. This transportation system is also a key facilitator of economic movement, sending goods and people to and fro to conduct business and stimulate the economy. Steel is a principal construction material in the bridge market due to its unmatched strength-to-weight ratio. Because steel used in the bridge market is constantly exposed to weather, deicing chemicals, and atmospheric pollutants, it must be protected. Hot-dip galvanizing has been successfully used to combat corrosion in bridges since the 1800s. Whether the superstructure of a traffic bridge, the backbone of a pedestrian crossing, or a beautiful truss igniting the landscape; hot-dip galvanized steel provides long-lasting maintenance-free protection for decades.

GALVANIZING PROCESS

Unlike paint coatings that form an adhesive bond with the underlying steel, galvanized coatings develop a metallurgical bond through the formation of a series of iron-zinc alloy layers. However, in order for these intermetallic layers to form properly, the steel must be prepared and processed in a specific sequence. The galvanizing process consists of three basic steps, namely surface preparation, galvanizing and inspection. Each of these steps, as discussed in the following, is important in obtaining quality galvanized coatings. The layout of a typical hot dip galvanizing line is shown in Figure 1.

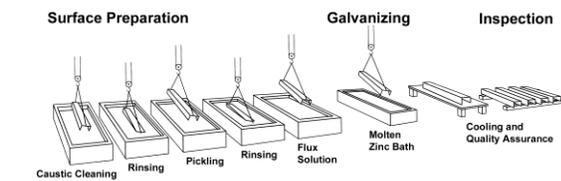


Figure 1. Galvanizing Process Schematic

SURFACE PREPARATION

It is essential that the material surface be clean and uncontaminated if a uniform, adherent coating is to result. Surface preparation is usually performed in sequence by caustic (i.e. alkaline) cleaning, water rinsing, acid pickling and water rinsing.

The caustic cleaner is used to clean the material of organic contaminants such as dirt, paint markings, grease and oil, which are not readily removed by acid pickling. Scale and rust are normally removed by pickling in hot sulphuric acid (at 65°C) or hydrochloric acid at room temperature. Sulphuric acid solutions typically contain 6-12% by weight of acid, while hydrochloric acid solutions are about 12 to 15% by weight of acid. Water rinsing usually follows caustic cleaning and acid pickling.

Surface preparation can also be accomplished using abrasive cleaning as an alternate to chemical cleaning. Abrasive cleaning is a mechanical process by which sand, metallic shot or grit is propelled against the material by air blasts or rapidly rotating wheels. This process physically dislodges rust and other materials from the surface of the steel and microscopically roughens the surface.

FLUXING

The final cleaning of the steel is performed by a flux. The purpose of the fluxing step is to remove any light iron oxide on the steel surface and to protect the steel from further oxidation until the steel is immersed in the zinc bath. The method of applying the flux to the steel depends upon whether the *wet* or *dry* galvanizing process is used. Dry galvanizing requires that the steel be dipped in an aqueous zinc ammonium chloride solution and then thoroughly dried. The drying prevents zinc metal from splashing out of the bath when the wet flux is immersed in the molten zinc, this is a safety

issue for the galvanizers. This pre-fluxing prevents oxides from forming on the material surface prior to the actual galvanizing step. In the wet galvanizing process, a layer of liquid zinc ammonium chloride is floated on top of the bath of molten zinc. The final cleaning occurs as the article being galvanized passes through this flux layer before entering the galvanizing bath.

GALVANIZING

The article to be coated is immersed in a bath (or kettle) of molten zinc maintained at a temperature of 435-460°C. Typical bath chemistry used in hot-dip galvanizing contains a minimum of 98% pure zinc along with a variety of trace elements or alloy additions. These additions, which could include lead (<1.2%), aluminum (< 0.005%), nickel (< 0.1%), and bismuth (< 0.1%), can be made to the bath to enhance the appearance of the final product or to improve the drainage of the molten zinc as the material is withdrawn from the zinc bath. Other metal such as tin ,copper, and cadmium can be in the zinc metal in trace amounts. In the USA, the bath metal is specified by ASTM Specification B6 (1).

As the cleaned steel passes into the molten zinc it is immediately wetted and a diffusion reaction between the zinc and the iron begins as it is heated to the temperature of the bath. This results in the formation of a series of iron-zinc alloys at the surface of the iron that commences quite rapidly but slows with time in the bath. The time of immersion in the galvanizing bath varies depending on the thickness and the chemical composition of the steel being coated. Thick steel sections take longer to galvanize than thin sections since the steel must be heated to the temperature of molten zinc before the galvanizing reactions can occur. However, the thickness of the coating does not substantially increase with longer immersion times.

At the completion of galvanizing, the articles are slowly withdrawn from the bath and the excess zinc at the surface is removed by draining, wiping, vibrating or (for small items) centrifuging. The metallurgical reactions that result in the formation and structure of the alloy layers continue after the articles are withdrawn from the bath as long as

their temperature remains near to the bath temperature. Freshly galvanized articles are normally cooled in either water or in ambient air immediately after withdrawal from the bath. Water quenching stops the alloying reaction by removing the residual heat from the article. This prevents the continuation of the alloying reaction that could, if allowed to continue, convert the free zinc layer into an iron-zinc alloy. When cooled quickly in air, a thin layer of pure zinc remains on the surface giving the freshly galvanized article a characteristic bright, shiny and smooth appearance. For large structural beams water quenching would not be recommended since this process will likely cause some distortion in the beam.

ZINC COATING

STRUCTURE

During the galvanizing process, a series of alloy layers form as a result of the metallurgical reaction between the molten zinc and the steel. The formation of these layers is influenced by a number of factors including the chemistry of the steel, the immersion time in the zinc bath and the bath temperature, the surface roughness of the base steel, and the rate of withdrawal of the article from the zinc bath. The cross section of a typical galvanized coating developed on steel with low silicon content (< 0.03%) is shown in Figure 2.

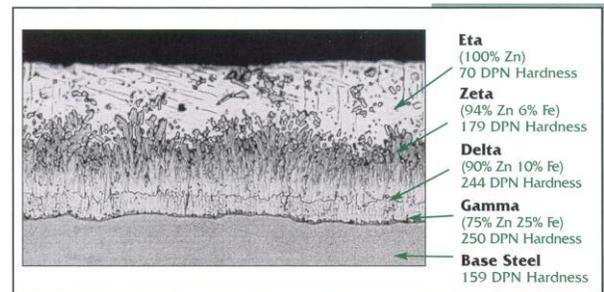


Figure 2. Typical Galvanized Coating Micrograph

The coating consists of a very thin gamma layer next to the steel substrate, a blocky delta layer and columnar growth of zeta crystals. These iron-zinc intermetallic layers are covered by a layer of pure zinc eta layer that remains on the surface as the article is withdrawn from the molten zinc bath.

The various alloy layers contain different amounts of iron, with the highest iron content in the layers closest to the steel. The outer zinc layer of the coating is formed on the surface of the part during withdrawal from the zinc bath and is essentially the same composition as the zinc bath. This outer layer gives the galvanized product its distinctive shine and bright grey appearance.

The outer pure zinc layer is very soft, and so can be easily scratched, but the underlying zeta and delta layers are somewhat harder than typical low carbon structural steels. This provides the coating with a significant abrasion resistance thereby allowing the coating to be used in situations where abrasive wear is to be expected. It also allows the galvanized article to be handled, transported and fabricated in much the same way as ordinary uncoated steel.

Galvanized coatings sometimes consist entirely of enlarged zeta crystals, due to the reactive nature of the steel where the silicon content of the steel to be galvanized causes the zeta alloy layer to grow constantly during the immersion of the steel in the galvanizing bath. Also, the zeta crystals have grown to the surface of the coating and have consumed the outer pure zinc layer as seen in Figure 3.

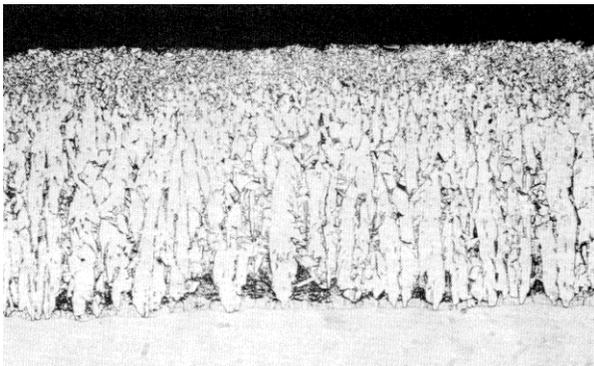


Figure 3. Reactive Steel Micrograph

This coating would have a dull gray surface appearance. Similarly, when galvanized steels are heated (annealed) at temperatures above about 430-450°C, the growth of the zeta phase is accelerated which can result in the complete disappearance of the eta layer at the surface. This appearance is very common in larger beams as the

silicon content of these beams contains high levels of silicon.

Although galvanized coatings may have a variety of microstructures, essentially no change occurs in the corrosion resistance of the coating. As previously noted, the extent of corrosion protection is a function of coating thickness, not coating structure. As such, the service life of bright, shiny coatings is similar to those with a dull gray appearance.

APPEARANCE

The surface appearance and the coating thickness of the galvanized coating can be affected by a number of variables including:

- the chemistry of the steel;
- the roughness of the steel surface (e.g. whether blast cleaned);
- the temperature of the galvanizing bath;
- the immersion time of the article in the galvanizing bath; and
- by control of the cooling rate after galvanizing.

Of all these factors, the chemistry of the steel has the greatest influence on the structure and appearance of the coating and the two major alloying elements in the steel that cause problems during galvanizing are silicon and phosphorus. Both these elements can act as catalysts during the galvanizing process resulting in rapid growth of the iron-zinc alloy layers of the coating. When the levels of silicon and phosphorus promote iron diffusion and cause thick coatings the steel is called “reactive”. The resulting galvanized coating is dull grey in color with a rough surface and may be quite brittle. The life of this coating is however proportional to its increased thickness and is unaffected by the appearance of the coating, provided the coating is sound and continuous.

Phosphorus, which is generally carried into steel from the raw materials used in iron-making, also has an adverse effect on the formation of the galvanizing coating. Phosphorus increases the strength and hardness of steel, but at the same time markedly reduces its ductility and impact

resistance. Accordingly, most structural and constructional steels normally specify a maximum phosphorus content of 0.04%, though actual levels are usually controlled to less than 0.025%. Phosphorus above 0.04%, working alone or in conjunction with silicon, can cause rapid development of the galvanized coating.

Variations in the thickness and appearance of galvanized coatings highlight one of the most significant problems faced by galvanizers when processing steels of uncertain origin and/or unknown chemistry, see Figures 4 and 5. While bright coatings are the preferred outcome when galvanizing, if reactive steels are galvanized the coating will usually be quite thick and grey in appearance. These variations become particularly obvious when different steels, some of which may be reactive, are mixed in the same galvanizing batch. Since the galvanizer cannot normally control the morphology of the finished coating on reactive steels, the appearance cannot be accurately predicted but this has no effect on the corrosion protection of the zinc coating.



Figure 4. Shiny Galvanized Coating



Figure 5. Dull Galvanized Coating

FABRICATION

The general fabrication of steel products to be galvanized (e.g. welding, cutting, punching, drilling etc) should ideally be done prior to galvanizing. Post-fabrication galvanizing provides coating protection to all edges and joints and takes full advantage of the corrosion protection afforded by the zinc coating. It also avoids unnecessary damage to the coating and minimizes the exposure of unprotected edges. Though damage to the coating can be repaired by applying zinc-rich paints, zinc metallizing or zinc solders, the repair is never as good as the original coating, nor will it last as long. There are, of course, many situations in which galvanized products need to be fabricated, formed or assembled either in the workshop or in the field. In these situations, some damage to the coating must be expected but with due care the severity of this damage can be reduced. The fabricator should thus be aware of the properties and the limitations of the coating.

WARPAGE AND DISTORTION

ASTM A384 (2) explains different types of potential distortion design issues that can occur while galvanizing. The most common distortion issue is the assembly of two different thicknesses of steel through welding. When these two steels are put into the galvanizing kettle and brought up to galvanizing temperature, the thermal expansion proceeds at a different rate for each thickness of material. This can put a considerable stress on the thinner material as it tries to expand more rapidly than the thicker material, but the welding together of the two materials does not allow for any movement separately. Since the thinner material cannot move near the weld joint, it often relieves the stress build-up by distorting away from the weld joint. The distortion of the thin steel can sometimes be removed after galvanizing, but other situations cannot be repaired.

Another design issue that can result in distortion is the asymmetrical assembly of steel pieces into a part to be galvanized, as in Figure 6. The design of the part in the picture includes a top flange from channel material, but has no corresponding bottom flange to make the design symmetric. This allows

the buildup of stress during the thermal expansion of the part in the galvanizing kettle to be relieved by distorting the entire piece from one end to the other, following the most likely rolling direction of the steel used for the web portion of this part.



Figure 6. Distorted Asymmetric Beam

Even symmetric assemblies can distort if they are constructed of very thin sheet steel (<1/4 inch thick). Steel that is thin and bent into a particular shape can distort during the galvanizing process as the thin steel expands during the few minutes the part is in the 850 F galvanizing kettle.

The high temperature induces a softening in the sheet steel and performs a stress relief of the mechanical stresses induced during the cold bending of the sheet. This stress relief can start a distortion of the part's shape in the galvanizing kettle. A temporary or permanent brace may be added to the design to prevent this distortion from occurring. The thin walled poles pictured in Figure 7 have a permanent brace welded to their wider end to prevent distortion of the walls of the pole during galvanizing. Some designs require an asymmetric look and need thin materials to fit the assembly of the part in its final application. The galvanizer should review any asymmetric design with his customer before attempting to galvanize the part. The earlier in the process of design the galvanizer can consult on the final design details, the less likely they will be to end up with a part that cannot be used after.



Figure 7. Temporary Bracing for Thin Walled Tube

For more details about distortion and design issues that can lead to distortion, review the information in ASTM A384 and study the American Galvanizers Association (AGA) Design CD for either Specifiers or Fabricators (3-4) on the AGA website to become aware of the many potential causes for distortion of steel parts during hot-dip galvanizing.

SIZE CONSIDERATIONS

Throughout North America, a variety of sizes of hot-dip galvanizing kettles are available, allowing a wide size-range of structural fabrications to be galvanized. Designing and fabricating in modules suitable for the available galvanizing facilities allows almost any component to be galvanized. For oversized fabrications, best practice suggests that they be designed in modules or sub-units and assembled *after* galvanizing. If this is not practical then there is the potential that the piece may be progressively dipped in the galvanizing bath.

When an item is too large for total immersion in the kettle of molten zinc but more than half of the item will fit into the kettle, it may be progressively dipped, sometimes referred to as "double-dipped."



Figure 8. Progressively Dipped Beam

When the need for progressive dipping is anticipated, adequate venting must be provided at both ends of the structure. When an article of small mass or asymmetric design is progressive-dipped, there may be a change of shape and/or movement from the centerline of the article. The thermal changes in the part are significant when a section of the part is immersed in the zinc metal and a section of the piece is outside the zinc bath. The thermal gradients in the part can cause warpage and distortion in the piece to be progressively dipped.

It is best to consult with your galvanizer before planning to progressive-dip.

CRACKING IN GALVANIZED STEEL

The weld area and surrounding heat-affected-zone (HAZ) can change the steel properties in the local area around the weld. This area can become a highly stressed location and can attract steel imperfections during the heating of the steel assembly. So, this area is experiencing stresses from the welding operation, steel impurities, and the two steel sections trying to move during the heating of the steel assembly. The ductility of the steel is usually sufficient to prevent anything from happening when all of these stresses combine; but when the conditions are above the yield stress of the material, the steel reacts by forming a small crack somewhere near the weld area.

The small crack can then expand as zinc and lead wick into the crack, pushing it into the surrounding steel material. The zinc cannot penetrate openings less than 3/32 in.; but in this case, as the crack opens under the heating of the steel, the zinc is pulled into the crack by wicking action and helps the crack expand and grow. Other low melting point metals like tin and lead can also be found inside the crack as they will also follow the crack opening. These low melting point metals will be found near the tip of the crack, since they stay molten for a long time after the part is removed from the heat source of the molten zinc in the kettle.

This whole process is known as liquid metal embrittlement (LME), but it does not mean that the steel parts are embrittled. The only embrittlement that occurs is the area around the weld and the HAZ where the small cracks can form. This same process has occurred many times with cope cut beams, where the cope area becomes the highly stressed region that attracts more stresses and can experience cracking at the 90 degree bend of the cope.



Figure 9. Cope Crack in Beam

What is really tough about the cope cracking issue is it does not happen all of the time, but only occasionally when the conditions are just right. An example of the size of the cope cracks is pictured in Figure 9. For cope cracking the frequency of occurrence is about 10%. This makes it very difficult to predict and to prevent. During the mid-1990's, ILZRO did a very thorough study (5) of the causes behind cope cracking. The principal conclusion of the study was that making a certain steel beam susceptible to this type of cracking required a number of contributing factors. There

are many different factors needed to exceed a threshold level before the steel would be susceptible to cracking. The most controllable factor was the residual stress in the area of the cope cut. This factor was reduced by applying a weld bead along the edge of the cope on both sides. The main benefit of this process was to reheat the area of the cope and relieve some of the residual stress in the area. This change to the fabricating procedures has lowered the occurrence frequency to less than 0.1%.

surface in contact with galvanized surfaces are ongoing.

What do you do about the piece that has cracked? Experience with cope cracking has shown the piece can be repaired and put into service. The crack is gouged out to about a ½ in. beyond the tip and the area is back filled with weld material. This repair is touched-up according to ASTM A780 (6) to provide corrosion protection. The part is then ready to be put into service if approved by the engineer of record. Past experience and inspection of cope cracks repaired using this process show the beams experience no further issues, many in place for over 25 years.

SLIP FACTOR OF GALVANIZED COATING

Galvanized coatings have been classified as Class A (slip coefficient of 0.30) with the requirement that the surface of the coating should be wire brushed to achieve this slip factor. The surface of the galvanized coating can actually be in one of two conditions; 1. Smooth and shiny indicating that the surface contains pure zinc metal or 2. Rough and dull indicating the surface contains iron/zinc intermetallic. Recent tests at the University of Texas in Austin showed that the slip factor for the shiny, smooth coating is 0.31 with no wire brushing and meets Class A. The slip factor for the dull, rough coating is 0.45 with no wire brushing. The slip factor for samples that have been wire brushed did not change for the shiny, smooth coating. On the other hand, the slip factor for the dull, rough coating came out lower after wire brushing. Most of the steel used for structural steel parts contains silicon in the quantity that will produce coatings with the rough, dull surface. Further testing of painted coatings over the galvanized coating and a metallized

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