Current Issues in Coating Mass Control for Zinc-Coated Steel

Gary W. Dallin, Frank E. Goodwin, International Zinc Association

Introduction

Galvanized sheet is a widely available product used by many different industries, including construction, automotive, appliance, electrical hardware, drainage, and HVAC. While there is a wealth of data and information about the corrosion rate of zinc in the myriad environments in which these products are used[1,2], the zinc coating mass specified and ordered is sometimes not suited for the end use. This may be because corrosion principles are not fully understood, or a low coating mass is ordered to lower purchase costs. Early failure can result if coatings are too thin for the application.

Designers of products made from galvanized sheet must know the corrosion severity of the intended service environment, the design life of the product, and what constitutes a failure in order to wisely decide on the required zinc coating mass. Questions to be answered include: Is it an outdoor or indoor environment? Will the product be boldly exposed or sheltered? What are the expected times of wetness? Is exposure to chlorides, sulfates, and nitrates involved? Are local microclimates, e.g., heavy industry, a factor? For indoor applications, will the environment be controlled? In the case of buildings, is animal confinement or an indoor pool or some other moisture source involved? Do all parties understand the expected service life and what will be considered a failure, e.g., first appearance of red rust, or perforation of the steel substrate? What will be the consequences of failure? Once the above, and perhaps other, questions have been answered, the corrosion rate of the zinc can be estimated. Combined with the required design life, the required minimum coating mass can easily be calculated.

Determining the required coating mass for a given product is therefore not generally a difficult task, since the service life of a galvanized coating is a linear function of whatever environment in which it is placed. Notwithstanding this, and due to cost reduction demands from users of galvanized sheet, there is growing demand to produce thinner zinc coatings[3]. This demand is sometimes at odds with the capability of zinc to meet the service life needed for the intended environment. While there are many products that do not need thick zinc coatings due to relatively benign service conditions or short one-time usage, some thin zinc coatings do find their way into end products where early failure is almost guaranteed. Such applications may not only be a waste of steel substrate, which would have a much longer service life if coated with a thicker zinc coating, but also a waste of the production resources used to manufacture them in the first place. It is quite likely false economy, as it will not minimize life-cycle costs, i.e., an alternative with a higher initial cost may be economically justified by reductions in future costs (for example, operating, maintenance, rehabilitation, or replacement) when compared to an alternative with lower initial costs but higher future costs[4].

Continuously galvanized steel sheet is produced on coating lines that use gas wiping to remove the excess liquid zinc that is drawn up from the molten bath by the moving strip.

Gas wiping is an efficient process that has been continuously improved for many decades, and is now at the stage where it can closely control the final coating thickness at line speeds from 50 to 200 m/min with low maintenance requirements and reasonable investment costs[5]. To produce thinner coatings, though, gas pressure must be increased and the gas knives moved closer to the moving strip, which can rapidly bring the process near its operational limits. In these cases, line speed must be reduced to achieve a thinner coating. Even then, each coating line has a minimum zinc thickness, below which it is physically not possible to wipe. Needing to run slower than rated line capacity lowers line productivity and increases operational costs[6]. Purchasers expect thinner coatings will reduce the product price, but in fact the production cost may increase.

The optimal coating mass for a particular product made from galvanized sheet is therefore a balance between the required service life, the service environment, and the ability of a zinc coating line to produce that coating mass at a reasonable cost. If a thin coating is the right product for a particular end use, then the selling price may have to be higher to offset lower coating line productivity, or it may be less costly to apply more zinc than the end use requires. These considerations must be taken into account by the buyer and could influence what coating mass will be ordered.

Coating Thickness Designation Systems

Most world standards for galvanized sheet, including ASTM International standards, do not directly use thickness to specify zinc coatings. The simple reason is that it is very difficult and expensive to directly and accurately measure the thickness of zinc on coated sheet, as the coating is usually a small fraction of the total coated sheet thickness. In the case of even a single coil of galvanized sheet, if thickness is measured manually (and even if accurately done), it is but one very small point on a large surface area, with no assurance that the result is representative of the overall coil. A more representative method is to use a destructive, weight-strip-weigh technique to measure all the zinc on a larger surface area of sheet. That is the main reason galvanized sheet standards specify the coating in terms of mass [weight] per unit area.

The industry does use sophisticated and expensive x-ray and radioisotope fluorescence devices, both on-line and off, that directly senses zinc thickness. On-line equipment requires considerable expertise to operate. These units continuously measure the coating thickness as the strip passes by, which is crucial to being able to control the amount of zinc deposited. They must regularly be calibrated via the weigh-strip-weigh technique, though. Also, the real time results provided are mathematically converted to mass [weight] per unit area for purposes of assessing compliance with ASTM and other specifications.

The most widely used ASTM zinc-coated sheet standard is A653/A653M[7], which covers hot-dip galvanized products. One of the coating designation systems in this standard uses descriptors such as G90. The “G” means the coating is galvanize (zinc), and the number refers to the *weight* of zinc on the surface of the steel sheet in inch-pound (Imperial) units, e.g., G90 = 0.90 oz/ft^2 total both sides. The second (M version) system in the standard is SI (Metric), which uses descriptors such as Z275. The "Z" means the coating is galvanize (zinc) and the number refers to the *mass* of zinc on the surface of the steel sheet in g/m^2, e.g., Z275 = 275 g/m^2 total both sides. The relationship between these two systems is: 1.00 oz/ft^2 = 305 g/m^2. When converting these values to thickness, the calculation uses the density of zinc.

For consistency and simplicity, the balance of this paper will use the SI system (*mass*) when describing zinc coatings.

Service Life Data

In the atmosphere, the corrosion rate of a zinc coating varies widely depending upon many environmental factors. For example, "time of wetness" is an important issue that affects corrosion rate, e.g., outdoor applications in a dry climate like, for instance, Dubai are very different from locations that experience high annual rainfall or extended foggy periods. Also, the presence of impurities such as sulfates, chlorides, and nitrates can dramatically affect corrosion rate. The presence of these compounds is quite often a function of localized microclimates (heavy industry, salt spray from major roadways or a sea coast, etc.). Other variables, including the amount of oxygen present in the electrolyte, and the temperature of the environment are important determinants for predicting product life.

Figure 1 shows calculated corrosion rates for six different North American cities in each of five climate categories. The corrosion rates shown are estimates based on models using data from environmental databases. The life expectancy (to 5% red rust) lines are not based on actual measured zinc consumption rates. They reflect calculated outdoor corrosion rates produced using the Zinc Coating Life Predictor (ZCLP). This software was developed by Teck Metals Ltd., and can be found at in the GalvInfo Library – Additional Information section[8]. It performs calculations based on statistical models, neural network technology, and an extensive worldwide corrosion database. The calculated corrosion rates used to generate this chart are averages for six different North American cities in each of the five climate categories. Six common ASTM A653M coating mass "bars" have been overlaid on the chart. For each bar, the left edge is an assumed one-half of the minimum allowed triple spot test coating thickness, and the right edge is one-half the maximum TST thickness that would typically be produced. To determine the corrosion rate for a specific locale, the documented actual environmental data for the ZCLP can be looked up and input onto the software[9].

Although the corrosion rate can vary considerably depending on local environmental factors, as Figure 1 shows, the life of a zinc coating is a linear function of coating mass for any specific environment, i.e., to achieve twice the life for any specific application, twice the coating mass is required. As is also is seen in this chart, when the per side coating thickness is much below 10 microns, outdoor service life is less than 10 years, making the use of such thin coatings an unwise choice.

Note that the zinc corrosion data given in Figure 1 is from after circa 1975, when aggressive pollutants such as sulfur dioxide began to decline from their higher levels of the mid 20th century. The service life of galvanize in, say, urban industrial areas is now longer than it was 40 to 60 years ago. On the other hand, corrosion rates in marine environments are not so much changed, since the rate of zinc loss is governed more by the amount of deposited sea salt than airborne pollutants.

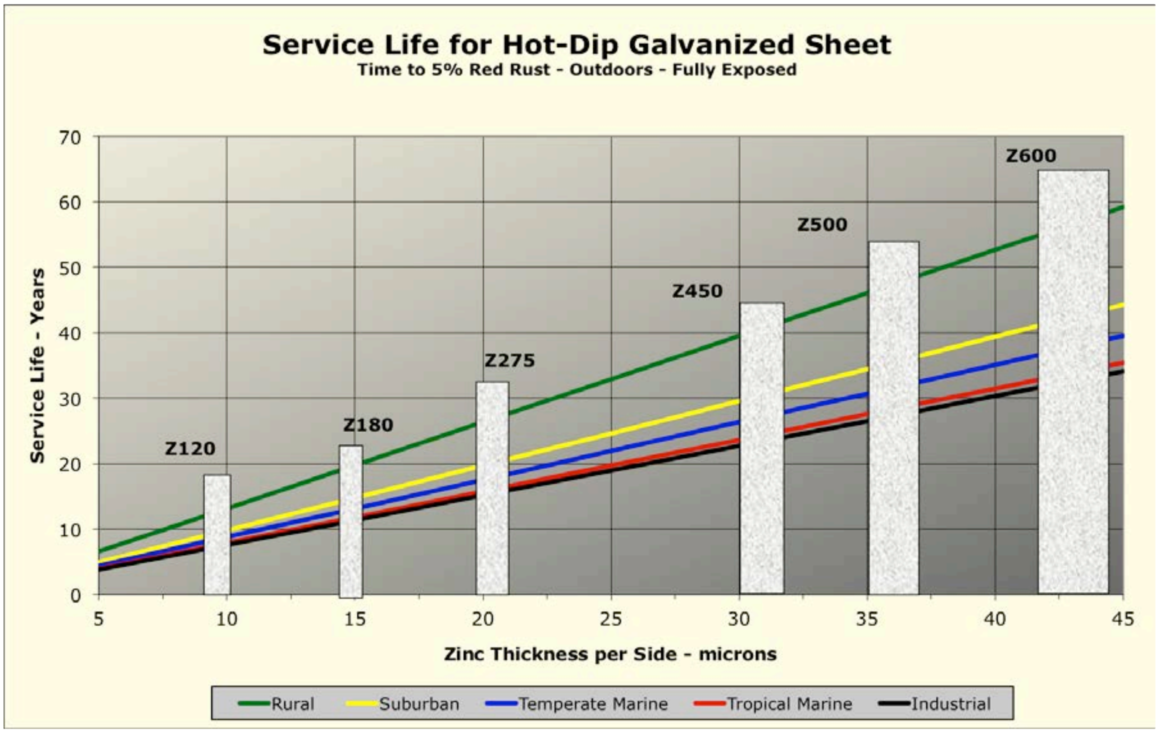

Figure 1. Service life chart for hot-dip galvanized sheet

In addition to The Coating Life Predictor, the books by Zhang[10] and Porter[11] are excellent sources for additional and more detailed information on the corrosion behaviour of zinc-coated steel, not only in the atmosphere but indoors, in waters and aqueous solutions, in soil, under paint, in concrete, and in organic and inorganic chemicals. In some environments, the rate of corrosion is so high that galvanized steel is not the preferred product. Generally, such applications are in environments that are either very acidic or very basic.

Design vis-à-vis Service Conditions

"*Mistakes in plant design are the most frequently cited (58%) cause of corrosion failure in chemical-process industries*"[12]. While this quote does not refer directly to products manufactured with galvanized sheet, design plays just as important role in their corrosion failures.

Reference 12 lists a number of general principles necessary for successful design. Those most applicable to products made with galvanized sheet are; minimize attack time, restrict galvanic cells, protect against environmental cells, and design for inspection and maintenance. As pointed out earlier in this paper, zinc coatings corrode uniformly at known rates in atmospheric, and most other environments, so the coating thickness needed to last for the design life of an application can easily be calculated. The best designs take advantage of the uniform corrosion of zinc and avoid creating conditions where accelerated localized attack can result.

When zinc is exposed to wet/dry weather cycles it forms a very thin, protective zinc oxycarbonate patina[13]. However, a very small amount of zinc is dissolved by rainwater and removed during each wetting event. This is the primary reason why zinc coatings are eventually consumed. In designing a structure, it is important to ensure that the entire exposed surface (roof elevation, side wall, etc.) always "sees" the same weather as uniformly as possible across the entire surface area. If some portion of, say, a roof receives extra water, draining from some higher, non-zinc coated surface, then that extra water also takes its share of zinc (in addition to that taken by the rain that fell directly on it). The end result is the area of impingement has its zinc coating removed at a higher rate.

In designing a building, or any other structure that is subject to weather, avoid configurations where water drains incompletely and/or pools. When it is subjected to long periods of wetness, the protective zinc oxycarbonate patina layer breaks down, increasing the zinc corrosion rate. Well-designed structures clad with galvanized sheet have good drainage and dry uniformly and quickly after a rain event. This minimizes the chance of localized severe corrosion hotspots.

Zinc corrosion in soil involves different chemical reactions than is the case in air. It is a very complex topic, due mostly to the myriad soil types and conditions that exist. Some soils are very corrosive to zinc. To avoid such situations, design so that galvanized sheet on buildings is kept away from the ground. When galvanized sheet is used for products, such as drainage pipe, that will be in an underground environment, the coating mass is almost always Z550 or thicker.

Galvanized sheet used to clad some commercial and industrial buildings, and many farm buildings, is sometimes the only separation between the inside and outside "climate", i.e., there is no inner wall or ceiling structures separated from the outer wall by insulation, etc. This is the case in many animal confinement buildings, where it can become warm and humid inside. When it is cold outside, condensation can form on the inside of the wall and roof panels. If ventilation is not good, condensate can be present for long periods, accelerating corrosion of zinc coatings. Animal waste decomposition products, e.g., sulfides, ureas and amines, become dissolved in the condensate and cleaning water, adding to the corrosivity of the environment[14]. The solution is to have a building design, including insulation, which has adequate ventilation to both remove gaseous decomposition products and prevent moisture buildup and condensation inside the structure.

The above discussion touches on just a few design issues relating to successfully using galvanized sheet. Sometimes, even with the right coating mass, problems can arise. Using a coating thinner than required in order to save some material costs up front can only compound design errors, bringing on an even earlier failure.

In Table 1 are shown one producer's recommended minimum coating mass to be used for a variety of common galvanized sheet applications[15].

Recommended Minimum Coating Mass – Galvanized Sheet

Product	Coating Designation				
	Z275	Z180	Z120	Z100	Z90
Ducting - Indoor	Use if desired	Recommended minimum	X	X	X
Ducting - Exposed	Recommended minimum	X	X	X	X
Expanded Metal	Use if desired	Use if desired	Use if desired	Recommended minimum	X
False Ceilings & Accessories	Use if desired	Use if desired	Use if desired	Use if desired	Recommended minimum
Portable Building Frames	Use if desired	Recommended minimum	X	X	X
Purlins & "C" Framing	Recommended minimum	X	X	X	X
Steel Doors & Frames	Recommended minimum	X	X	X	X
Electrical Conduit Pipes	Recommended minimum	X	X	X	X
Cable Armor	Use if desired	Use if desired	Recommended minimum	X	X
HVAC Components	Recommended minimum	X	X	X	X
Junction Boxes	Use if desired	Recommended minimum	X	X	X
Studs & Runners	Use if desired	Use if desired	Use if desired	Recommended minimum	X
Electrical Cable Trays	Recommended minimum	X	X	X	X
Metal Furniture	Use if desired	Use if desired	Recommended minimum	X	X
Water Tanks	Recommended minimum	X	X	X	X
BBQ Pans & Single Use Drums	Use if desired	Use if desired	Use if desired	Recommended minimum	X

Recommended minimum (dark green) **Use if desired** (light) **X Not recommended**

Table 1 Suggested coating mass application chart for galvanized sheet

Gas Wiping Process

The gas wiping process that is used to apply zinc coatings has many practical advantages: it is simple, requires low maintenance and has a low operational cost, a large process window, and low energy requirements. The sheet vertically exits the bath at high speeds, dragging out more zinc than is needed for the coating. The higher the line speed or the liquid viscosity, the higher the amount of liquid entrained by the moving strip. Gas knives employ low-pressure/high-volume gas streams (in most cases air, but sometimes nitrogen) that impinge against both sheet surfaces. The gas flows through piping to two knife boxes positioned parallel and adjacent to each side of the strip. It escapes through precisely designed and machined slot openings placed about 10 to 12 mm from the traveling strip. The resulting gas jet acts as a knife, stripping the excess molten zinc and forcing it back in the direction of the coating bath surface[16]. It is not the peak pressure of the gas hitting the sheet that generates the wiping force but the maximum pressure gradient and the shear stresses developed on the entrained liquid film. For line speeds over 100 m/min and coating thicknesses below 20 μm, the final thickness depends linearly on the nozzle to strip distance when it is over 7 times the nozzle opening[17].

Typically, a moving strip 10 to 11 mm away from the knife will have a coating weight variation of about 10%. Because of the limited effect of the distance when it is below 7 times the nozzle gap, wiping infinitely close will not lead to an infinitely thin coating[18].

The pressure dependence is asymptotic as shown is Figure 2. Therefore, for thin coatings, a large increase in pressure only slightly reduces the thickness. The increase in gas flow with increasing pressure does result, however, in more splashes, a higher resolved force on the strip, higher noise levels, and a higher rate of skimmings formation.[19]

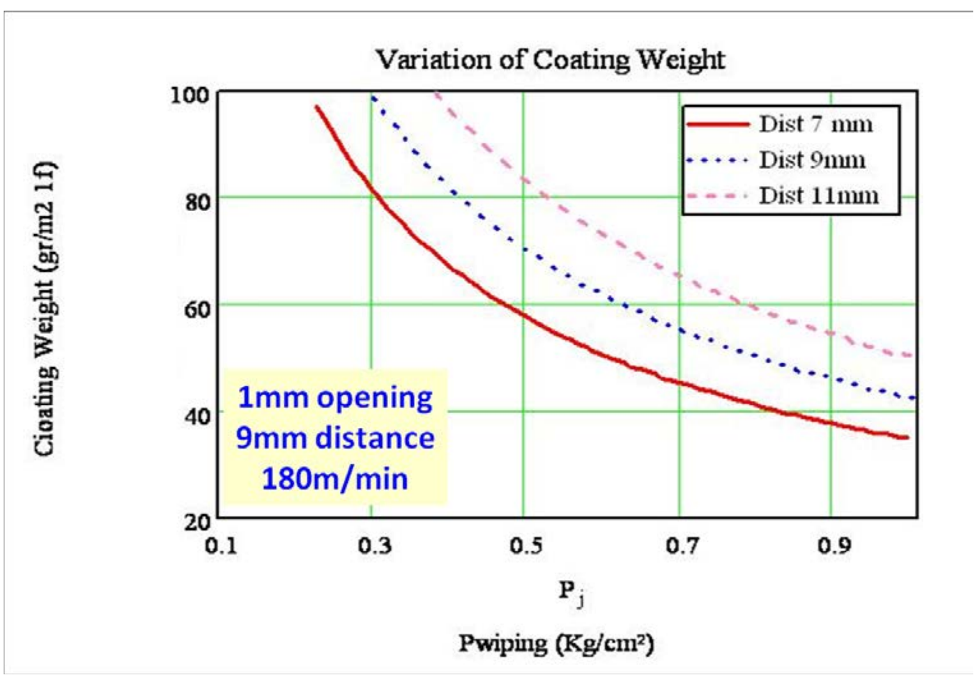

Figure 2 Effect of knife pressure on coating mass [weight] (from ref. 3)

Figure 3 shows that the minimum coating physically achievable at 180 m/min is 32 g/m^2/side, considering a wiping distance of 6 mm and a nozzle opening of 0.8 mm. Wider nozzle openings are less efficient due to the limit of 7 times the gap for the nozzle to strip distance.[20]

Distance	Mini Coat Th(µm/gm²)
8mm	6.65-43
7mm	5.8-38
6mm	5.0-32
5mm	4.15-27

Figure 3 Effect of knife distance on coating mass [weight] (from ref. 3)

The nozzle to strip distance cannot be kept safely below 7-8 mm, since the risk is too high of the strip touching the nozzles due to strip vibration and/or not perfectly flat sheet.[21]

When the nozzle to strip distance is below 6 to 7 times the nozzle opening, the coating thickness will decrease only slightly, if that. It is generally accepted that below this wiping distance the risk of the knives touching the strip is too high, especially on wide material, and that the minimum nozzle opening should be 0.8mm.[22]

Thin coatings on thin sheet are expensive to produce. The present best per side industrial practice is about 35 g/m^2 (5 µm) at 120-130 m/min, 52 g/m^2 (7.3 µm) at 160-170 m/min, and 72 g/m^2 (10 µm) at 180-190 m/min.[23] With the present best wiping practice, a 50 g/m^2 becomes cheaper than a 35 g/m^2 on thin sheets due to the needed reduction in the line productivity to reach thin layers. The minimum galvanizing cost is in the range of 52 to 72 g/m^2/side.

Figure 4 is a "Cost Map"[24] (per ton of GI) for a galvanizing line based on the limits shown beside the map. For the 35 g/m^2 coating (where processing speed should be high) to produce it requires running at the speed used to produce 50 g/m^2, which is the most economical coating mass at 180 m/min.

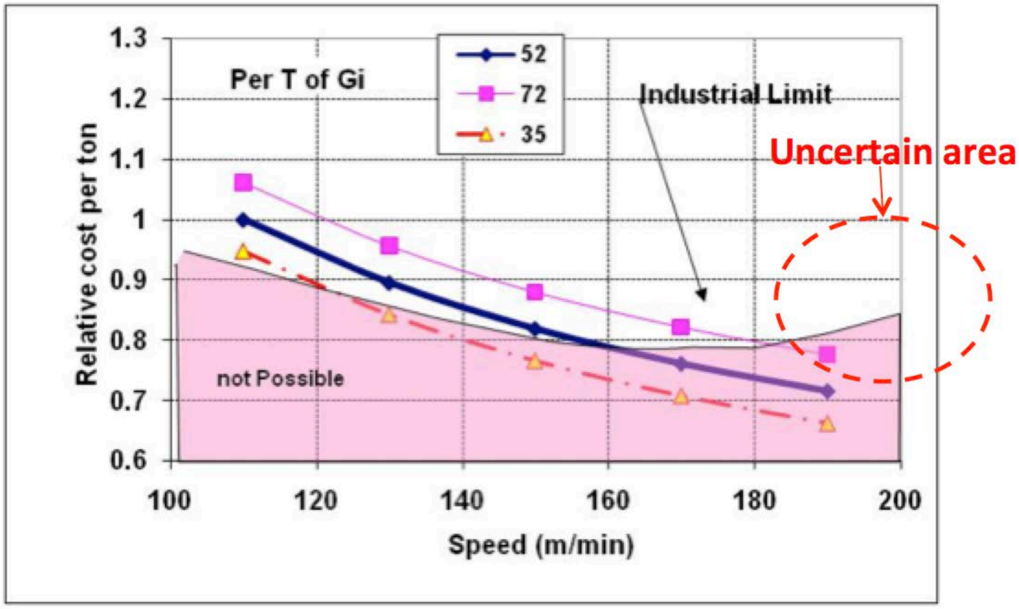

Figure 4 Relative cost map for GI based on physical limits identified (from ref. 23)

This shows that thin coatings on thin sheet are expensive to produce[25], so it would be more economical to give away extra zinc so as to increase line productivity. Every continuous galvanizing line should develop a cost map for the particulars of that line. Marketing staff would then know the sheet thickness range of when it even makes sense to offer a 35 g/m^2 (5 μm) per side coating, versus when to decline such orders, or add a surcharge to offset the reduced productivity.

There are a number of quality issues associated with producing thin zinc coatings while running at high line speeds.

With air wiping, thin coatings are more sensitive to imperfections such as bright spots. At line speeds below 50 m/min for Pb-Sb free bath and Al > 0.21%, an "edge effect" is observed. It is the result of transverse shrinkage of the back flow due to the liquid surface tension. An accumulation of oxides is observed on the edges, some of which are entrained by the strip through the wiping knives.[26]

The gas wiping process also has a physical limit related to a splashing phenomenon. The air knife can become inefficient, requiring an immediate line slow down to allow the exploding back flow to remain on the sheet. Over a certain line speed a back flow explosion cannot be avoided, as it is independent of the final film thickness. That line speed limit is close to 200-230 m/min for zinc.

Narrow nozzle openings are very sensitive to dust, zinc splashes, and scratches, all of which can lead to jet (blower) lines. In practice, an opening below 0.8 mm is very difficult to operate.[27]

The amount of dross produced is also a large concern when producing thin coatings at high line speed. When total gas flow from the knives is too high, the level of dross becomes unacceptable. It has been observed that the amount of dross created per square meter increases when wiping increases, which is the case for thin coatings at high line speed. In the case of zinc containing 0.25% Al run at 130 m/min it was observed that the dross created was 25 to 30 g/m^2 for both sides. At 80 m/min the amount of dross dropped to 12 to 15 g/m^2. Dross must be removed during top drossing of the bath to avoid entrainment in the coating and surface defects on the final product. Top dross removal for lines running at 150-180 m/min can correspond to a loss of 24 to 27% of the charged zinc[28]. This is an appreciable loss. The amount produced is not significantly reduced by N_2 wiping.

Prepainted Galvanized Sheet

Coil coated steel sheets are widely used in building, automotive, and appliance industries. Their superior corrosion stability is explained by the synergistic protection provided by metallic and organic coatings.[29] Besides defects such as scratches that occur during transport, processing, installation, product service life, the cut edges of prepainted panels are usually not treated. Paint delamination at cut edges is a principle reason for the failure of coil coated steel sheets.

The aim of the study in reference [26] was to investigate the role of the metallic coating thickness on long-term cut edge protection of coil-coated products. Paint delamination from cut edges of coil coated materials was followed as a function of exposure time at a marine test site for seventeen hot dip galvanized materials differing in the thickness of zinc coating (7–20 µm) and steel substrate (0.2–2.5 mm). Results are shown in Figure 5.

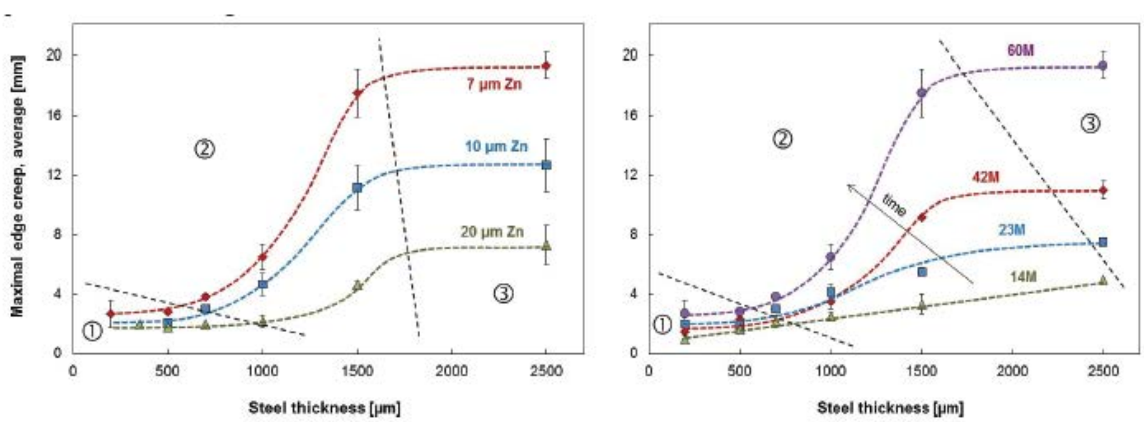

Figure 5 Effect of steel thickness on paint delamination as a function of coating thickness and exposure time (from ref. 26)

The study concluded that edge creep increases with decreasing zinc thickness and increasing steel thickness. For steel substrates over 0.75 mm, any reduction in coating thickness below Z275 (20 mm) leads to an accelerating drop in service life due to edge creep. For steel thickness less than 0.75 mm, the effect of zinc thickness in protecting against edge creep was not so pronounced.

In the case of prepainted galvanized sheet, zinc supports the paint, protecting against under-film corrosion. The thicker the zinc the slower the underfilm corrosion proceeds, so the longer the protection time. This is even more the case as the steel substrate thickness decreases. As paint costs from 5 to 25 times more than Z275 coatings per unit area, using thinner zinc coatings in exposed environments is an ineffective and wasteful use of resources, particularly in cases where the steel thickness is above 0.75 mm. Once the zinc layer is gone, the paint is if little value in protecting the steel.

These field performance results indicate that a Z275 coating is strongly advised for all exterior prepainted sheet applications, except for the potential use of Z180 in cases where the climate is dry and the environment no more aggressive than urban.

Even though there are no documented corrosion studies on prepainted sheet used in indoor applications, one supplier[30] recommends a Z120 product is the minimum zinc coating mass that should be used, with the exception of ceiling accessories where a Z100 will suffice.

There is one painted, hot-dip, zinc-iron alloy-coated product, with a relatively thin coating equivalent to about a Z100, that when painted after forming, has excellent underfilm corrosion resistance. The coating is known as galvanneal, which has about a 10% bulk iron content, with no free zinc. It cannot be formed after painting as the paint will delaminate because of the hard zinc-iron alloy coating substrate, so is not suitable for prepainted products. While it will show cosmetic brown corrosion in a few hours when wet in its unpainted state, when post painted it behaves equivalent to somewhere between a Z180 and Z275 product with respect to underfilm and creep back corrosion, both in accelerated testing and in field service. The reason for galvanneal's good corrosion resistance is attributed to the ability of paint to bond extremely well to the microscopic zinc-iron crystals on its surface, and the electrochemistry of its coating[31].

In Table 2 shows recommended minimum coating mass to be used for a variety of common prepainted galvanized sheet applications.

Recommended Minimum Coating Mass – Prepainted Sheet					
Product	Climate	Substrate Coating Designation			
		Z275	Z180	Z120	Z100
Roofing & Cladding (Single Skin)	Dry	Use if desired	Use if desired	Recommended minimum	X
	Urban	Use if desired	Recommended minimum	X	X
	Marine/Aggressive	Recommended minimum	X	X	X
Sandwich Panel (Double Skin)	Dry & Urban	Use if desired	Recommended minimum	X	X
	Marine/Aggressive	Recommended minimum	X	X	X
Automatic Doors	Dry & Urban	Use if desired	Recommended minimum	X	X
	Marine/Aggressive	Recommended minimum	X	X	X
K Span (Quonset Buildings)	Dry & Urban	Use if desired	Recommended minimum	X	X
	Marine/Aggressive	Recommended minimum	X	X	X
Lighting	Indoors	Use if desired	Use if desired	Recommended minimum	X
Ceiling Accessories	Indoors	Use if desired	Use if desired	Use if desired	Recommended minimum
Internal Partitions	Indoors	Use if desired	Use if desired	Recommended minimum	X
Shelves	Indoors	Use if desired	Use if desired	Recommended minimum	X
Cold Rooms	Indoors	Recommended minimum	X	X	X

Recommended minimum   Use if desired   X Not recommended

Table 2 Suggested coating mass application chart for prepainted galvanized sheet

Conclusions

Zinc is a significant cost component of galvanized sheet, increasingly so the thinner the sheet, therefore it is understandable why cost-minded users want thinner coatings.

The coating thickness of galvanized sheet determines its life. To select the proper coating mass it is important to know and understand:

- The expected service life of the end use.
- The particulars of the service environment and the coating mass needed to meet the service life – always keeping in mind that atmospheric corrosion resistance of zinc-coated products is a direct function of the coating thickness, and the selection of coating designations too thin for the application will result in almost linear reduced corrosion performance of the product.
- Cost curves for each coating line so that the coating mass having the minimum cost is known, e.g., somewhere in the range of 52 to 72 g/m^2/side for zinc coatings
- For prepainted sheet, the importance of enough zinc being present on the substrate to minimize under-film corrosion and outlast the expensive paint coating layers.

In conclusion, thinner coatings can come with hidden costs, so the following points should always be considered when deciding on the required coating mass.

- There is a wealth of knowledge about the corrosion rate of zinc in most environments. When this is not taken into account, or ignored, it is false economy to sacrifice service life to save the relatively small up front zinc cost of a too thin coating mass. Certainly, using less than 120 g/m^2 for outdoor applications is unwise, both from a product life cycle cost and a sustainability standpoint.
- Line productivity is largely dependent on speed, and at a given line speed there is a minimum coating thickness limit. Running slower to obtain thinner coatings decreases productivity and increases costs that cannot be recovered unless the selling price is raised.
- While coating extras, regardless of zinc thickness, have always been charged in the case of thin sheet to cover the extra cost of the higher proportion of zinc in the coated product, when a lower than rated line speed is required to produce thin coatings, additional surcharges should apply rather than discounts.
- Thin zinc coatings can sometimes be more expensive, and in some instances, impossible to produce.
- In the case of prepainted galvanize sheet, zinc supports the paint, protecting against under-film corrosion, so zinc should be thick enough to outlast the life of the paint cover.

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