GALVANIZING - 2022

Continuous hot-dip galvanizing – process and products.

Gary W. Dallin, P.Eng., Director, GalvInfo Center

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Introduction

Definition

Galvanizing is a process for rustproofing iron and steel by the application of a zinc coating. Three of the most-used processes for applying zinc to iron and steel are hot-dip galvanizing, electrogalvanizing, and zinc spraying. Most products are coated using the hot-dip process. It involves immersing steel into a bath of molten zinc, which is at a temperature close to 870°F [465°C], to form a metallurgically bonded zinc or zinc-iron alloy coating. This same hot-dip immersion process is also used to produce other coatings such as zinc-aluminum alloys.

Reason for galvanizing

Steel rusts (oxidizes/corrodes) when left unprotected in almost any environment. Applying a thin coating of zinc to steel is an effective and economical way to protect it from corrosion. Zinc coatings protect by providing both a physical barrier and cathodic protection to the underlying steel.

Barrier protection

The primary mechanism by which a galvanized coating protects is by providing an impervious barrier that does not allow moisture to contact the steel. Without moisture (the electrolyte) there is no corrosion. The nature of the galvanizing process not only ensures that the zinc coating is impervious to moisture, but adheres well to the steel with excellent abrasion and corrosion resistance.

Galvanized coatings will not crack or peel over time in the manner of other barrier coatings such as paint, even though they are reactive and corrode and erode slowly when exposed to atmospheric wet/dry cycles. Their service life is directly proportional to the coating thickness, and the corrosion rate of zinc in a given environment. It is therefore important to understand zinc's corrosion mechanisms and what factors affect its service life.

Freshly exposed galvanized steel reacts with the surrounding atmosphere to form a series of zinc corrosion products. In air, newly exposed zinc immediately reacts with oxygen to form a very thin zinc oxide layer. When moisture is present, zinc and its oxide react with water, resulting in the formation of zinc hydroxide. The final corrosion product is zinc carbonate, which results from zinc hydroxide reacting with carbon dioxide in the air. Zinc carbonate is a thin, tenacious, and stable layer that provides protection to the underlying zinc, and results in its low corrosion rate in most atmospheric environments. Because of this protective layer that forms on zinc in the atmosphere, its corrosion rate, depending on the climate, is 10 to 100 times slower than that of steel.

Galvanic (cathodic) protection

The second shielding mechanism is zinc's ability to galvanically protect steel. When steel substrate is exposed, such as at a cut edge or scratch, it is cathodically protected by the sacrificial corrosion of the zinc coating adjacent to the steel. This occurs because zinc is more electronegative (more reactive) than steel in the galvanic series, as shown in Table 1.

Table 1: Galvanic Series of Metals and Alloys

Corroded End – Anodic (electronegative)
Magnesium
Zinc
Aluminum
Cadmium
Iron or Steel
Stainless Steels (active)
Lead
Tin
Copper
Gold
Protected End - Cathodic or most noble (electropositive)

Note: Any one of these metals and alloys will theoretically corrode while protecting any other that is lower in the series as long as both form part of an electrical circuit and an electrolyte solution is present.

When zinc-coated steel is in an oxidizing environment, zinc gives up its electrons before iron does. In practice, this means it will not be undercut by rusting steel because the steel cannot corrode when adjacent to and in electrical contact with zinc. Any exposure of the underlying steel, because of severe coating damage or at a cut edge, will not result in corrosion of the steel unless a large area has been exposed or until the nearby zinc has been consumed.

The distance over which the galvanic protection of zinc is effective depends on the environment. When completely and continuously wetted, especially by a strong electrolyte, e.g., seawater, relatively large areas of exposed steel will be protected as long as any zinc remains. In air, where the electrolyte is only superficial or discontinuously present (such as from dew or rain), only smaller areas of bare steel can be protected. The “throwing power” is nominally about 0.125 in [3.2mm], although this can vary significantly with the type of electrolyte.

Service life

Zinc corrosion rates correlate directly with two major factors; time of wetness, and concentration of air pollutants. If the surface stays wet for long periods then the protective films do not form and corrosion proceeds at an increased rate. The effect of wetting on zinc's corrosion rate depends on the type of moisture. For example, while the moisture from rainfall may wash away zinc's corrosion products, that formed by condensation can usually evaporate and leave the corrosion products in place. Corrosion only occurs when the surface is wet.

The pH of aqueous solutions that contact zinc, have a significant effect on its corrosion rate. At pH values below 6 and above 12 the corrosion rate increases substantially. Many industrial atmospheres contain sulfur in the form of sulfur dioxide that contributes to acid rain that can have a pH of less than 6. Figure 1 illustrates the effect of aqueous pH on the corrosion rate of zinc.

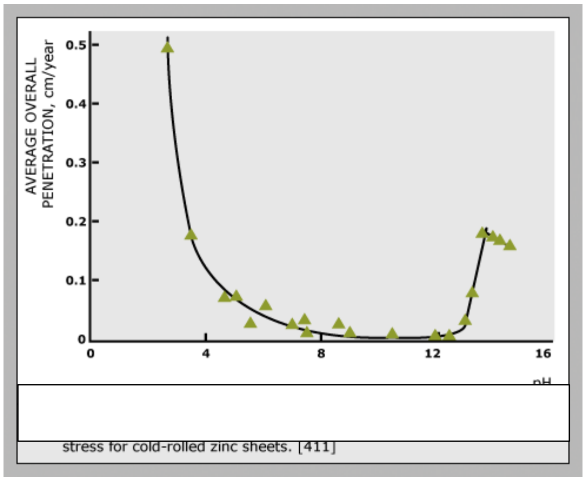


Figure 1: The effect of pH on the corrosion rate of zinc

Chloride environments have far less effect on zinc's corrosion rate than sulfur compounds, but because chlorides can be present in coastal marine and wind-blown road salt environments, they will likely be the most frequent concern necessitating extra corrosion protection. Nonetheless, galvanized parts exposed outdoors can remain rust free for many years, and the two basic reasons are the relatively stable zinc carbonate film that forms on the zinc surface, and the sacrificial protection provided by the zinc.

The service life of zinc-coated steel is therefore dependent on the conditions of exposure and on the coating thickness. The relationship of these factors is shown in Figure 2.

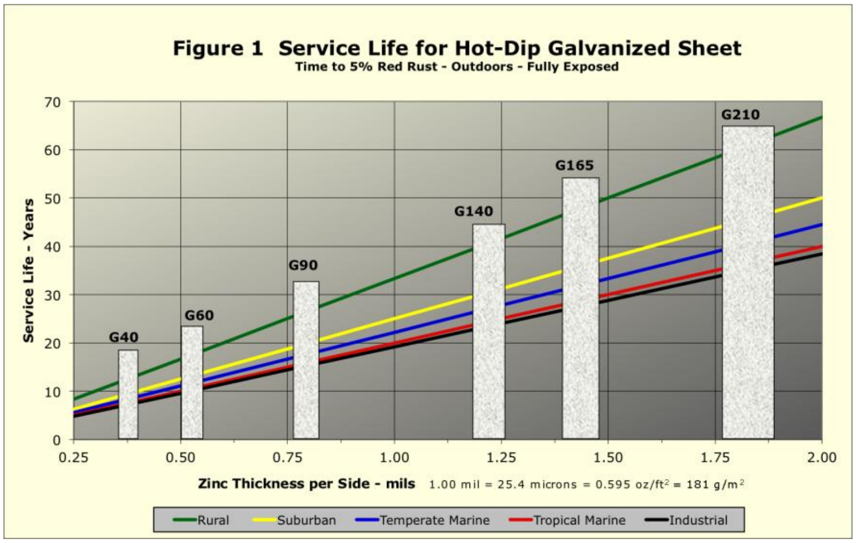


Figure 2: Service life of galvanize in various environments as a function of zinc coating weight

Note that the zinc corrosion rates shown in Figure 2 are based on data 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.

The corrosion rate of a zinc coating in the indoor atmosphere of, say, a residential house, is generally very low. A ten-year study of steel framing in residential buildings was undertaken by the NAHB Research Center and sponsored by the International Zinc Association. It measured zinc and zinc-alloy coating corrosion rates of steel framing samples in four different home environments in the U.S.A. and Canada (Miami, FL; Leonardtown, MD; Long Beach Island, NJ; and Hamilton, ON). Corrosion was minimal from all four sites for all sample types. The extrapolated coating life expectancy for G60 [Z275], based on the average mass loss, ranged from 300 to over 1000 years. For semi-exposed locations in aggressive environments, G60 [Z275] still extrapolated to over 150 years of coating life.

Galvanizing Methods

Hot-dip galvanizing

This is a process by which an adherent, protective coating of zinc or zinc alloy is developed on the surfaces of iron and steel products by immersing them in a bath of molten zinc. The hot-dip process is used to produce most zinc-coated steel.

General (Batch) galvanizing

The oldest method of hot-dip galvanizing is the batch process, and which continues to be used for fabricated steel items such as structures, pipe, and fasteners. It involves cleaning the steel articles, applying flux to the surface, then immersing the articles in a molten bath of zinc to develop a thick, zinc-iron alloy coating. A typical hot-dip coating produced by the batch process consists of a series of alloy layers. Starting from the base steel, each layer contains a higher proportion of zinc until the outer layer, which is relatively pure zinc, is reached. Total thickness of the coating can be from 1.4 mils [35 μm] to 3.9 mils [100 μm]. The names of the layers proceeding outwards from the steel are: gamma (Γ), delta (δ), zeta (ζ), and eta (η). Table 2 gives the properties of these layers.

Continuous galvanizing

The method of applying zinc coatings to steel sheet is continuous hot-dip galvanizing. Coils of cold rolled (or hot rolled) steel sheet are charged to the entry end of a continuous processing line, unwound, joined end to end one after the other, then passed through a cleaner, an annealing furnace, then a bath of molten zinc bath at speeds up to 600 fpm [183 mpm]. As the steel exits the molten zinc bath, gas "knives" wipe off the excess coating from the sheet to obtain the specified zinc thickness. The coating is left to freeze as traditional galvanize (GI), or can be thermally treated to convert it to galvanneal (GA), which is a zinc-iron alloy. The coated sheet is then cooled to ambient temperatures, leveled and/or skin-passed, passivated, perhaps oiled, then recoiled for shipment to the fabricator. This process will be described in greater detail later and is the subject of the greater part of this article.

Table 2: Properties of alloy layers of hot-dipped galvanized steels

			Melting Point				
Layer	**Alloy**	**Iron, %**	**°C**	**°F**	**Crystal Structure**	**Diamond Micro hardness**	**Alloy Characteristics**
Eta (η)	Zinc	0.03	419	787	Hexagonal	70-72	Soft, ductile
Zeta (ζ)	$FeZn_{13}$	5.7-6.3	530	986	Monoclinic	175-185	Hard, brittle
Delta (δ)	$FeZn_7$	7-11	530-670	986-1238	Hexagonal	240-300	Ductile
Gamma (Γ)	Fe_3Zn_{10}	20-27	670-780	1238-1436	Cubic	------	Hard, brittle
Steel Base	Iron	99+	1510	2750	Cubic	150-175	------

Electrogalvanizing

Very thin formable zinc coatings, ideally suited for deep drawing or painting, can be applied to steel sheet products by electrogalvanizing. Zinc is also electrolytically deposited on other steel products such as wire and pipe. The coating is thin and uniform and has excellent adherence. It is free of the zinc crystals present on hot-dip galvanize and is bonded to the steel substrate by interatomic forces. The coatings are composed of pure zinc and have a homogeneous structure. (It is also possible to produce electrogalvanize coatings of zinc-nickel and zinc-iron). Electrogalvanize coatings are generally not as thick as those produced by hot-dip galvanizing, although some product is made with heavier coating weights. One feature of electrogalvanizing is that it is done cold and does not alter the mechanical properties already present in the steel.

Zinc spraying and other methods

Steel can be galvanized using zinc spraying (metallizing), which consists of projecting atomized particles of molten zinc onto a prepared surface. This process is usually performed on-site to cover welds, ends, and rivets. Other methods of galvanizing include sheradizing and painting with zinc-rich paint.

Other hot-dip coatings

The continuous hot-dip process is also used to apply other metallic coatings, including 55% Aluminum-Zinc Alloy-Coated (Galvalume™), Zinc 5% Aluminum Alloy-Coated (Galfan™), Aluminum Coated (Aluminized), and Zinc-Aluminum-Magnesium Alloy-Coated.

Continuous Hot-Dip Galvanizing Lines (CGLs)

The balance of this article will focus on continuous hot-dip galvanizing, including lines that produce high value-added products such as sheet for exposed auto panels. Figure 3 shows the layout of a typical modern hot-dip galvanizing line capable of producing such products. This, and other similar lines, unwind full-hard cold reduced coils, weld them end to end, pass the strip through the line to be cleaned, annealed, coated, surface conditioned, inspected, oiled, and rewound into GI or GA coils. Some lines also convert heavier thickness, pickled, hot rolled coils into coated sheet.

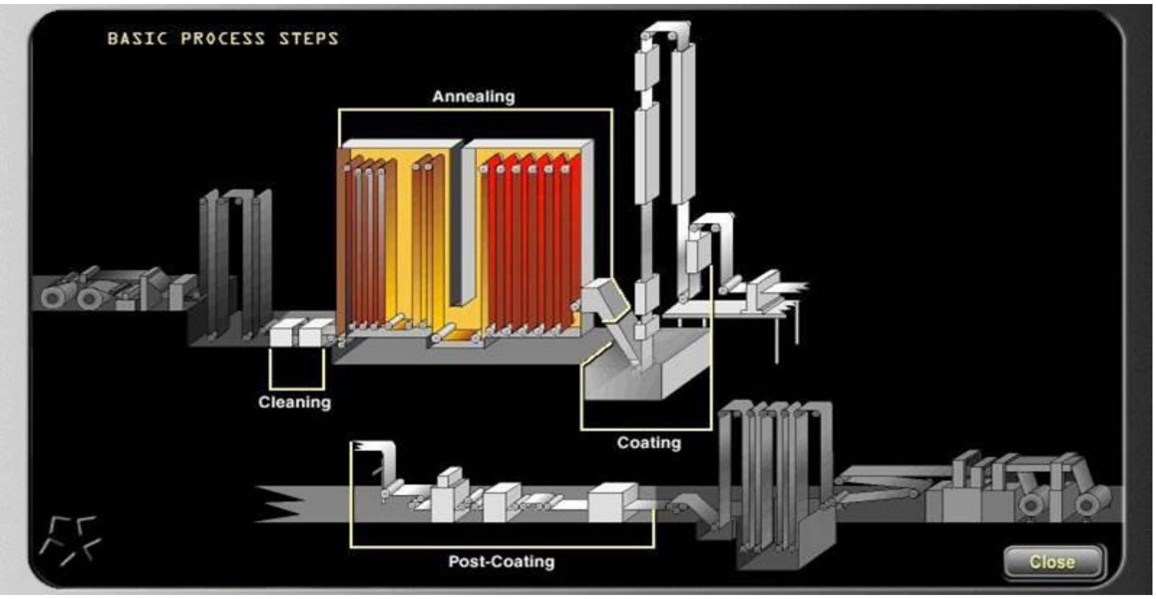


Figure 3: Modern Hot-Dip Galvanizing Line

A few CGLs still use the original continuous line method of charging pre-annealed and skin passed cold rolled coils and applying a flux to the surface before entering the zinc bath. Most facilities, though, are “hot” lines that anneal the strip in-line. A current list of North American metallic hot-dip and electrolytic continuous coating lines is available at www.galvinfo.com

Substrate for galvanizing

Substrate to produce hot-dip galvanize can be categorized into the following major groups:

- Commercial Steel (CS) - low carbon steel
- Forming Steel (FS) - low carbon steel
- Structural Steel (SS) - carbon steel
- Deep Drawing Steel (DDS) - extra low carbon or ultra low carbon steel
- Extra Deep Drawing Steel (EDDS) - ultra low carbon stabilized steel
- High Strength-Low Alloy (HSLAS) - micro-alloyed low carbon Steel
- Advanced High Strength Steels (AHSS) - alloyed and control cooled low carbon steel
  Includes solution hardened (SHS) and bake hardening (BHS) steel

CS and SS use low carbon and carbon steel. Carbon levels range between 0.04% and 0.15%, with manganese from 0.2% to 1.0%, depending on the product being made. The substrate is cold rolled sheet with anywhere from 50 to 80% reduction in thickness from hot rolled sheet.

FS typically uses carbon levels of 0.04-0.08%, with manganese at about 0.25%. In order to obtain better response to annealing, cold reduction is between 60 to 80% and the coating line is slowed to allow longer annealing time to increase grain size.

DDS and EDDS are generally made from ultra-low carbon stabilized steels, although some DDS is made using extra low carbon (0.015-0.020%) steel. EDDS, and to some extent DDS, are produced to be fully stabilized (non-ageing) after annealing and coating.

HSLAS typically is made from micro-alloyed low carbon steel. The primary alloying element used is Nb.

AHSS is produced using higher levels of alloying elements and carefully controlled annealing and cooling cycles. This class also includes low carbon SHS and BHS steels.

Ultra low carbon stabilized steel

The presence of carbon (C) and nitrogen (N) in steel results in higher mechanical properties, age hardening, and deterioration of the r-value (resistance to thinning). To deal with this, liquid steel is processed through a degasser to remove C and N. They are reduced to levels low enough that the remainder can be “stabilized” by additions of small amounts of titanium (Ti) and niobium (Nb). These elements are strong carbide and nitride formers, taking C and N out of solution in iron. The C and N are removed from the interstices between the iron atoms, hence the somewhat misleading term, “Interstitial-Free” (“IF”) steel. It is non-ageing with no yield point elongation, meaning fluting and stretcher strains are never a problem, since there is no free C and N.

IF steel made using only Ti is very common and is used to produce the best mechanical properties for deep drawing. This type of IF steel is very reactive in a zinc bath and is usually coated only as GI.

Another popular type of IF steel is stabilized with both Ti and Nb. The synergy of these two elements allows complete stabilization to be achieved at lower levels of each element. Depending on the relative amounts of Ti and Nb, IF such steel needs to be annealed at a higher temperature during processing and has slightly inferior mechanical properties to the Ti only type; except that the former has better planar anisotropy, i.e., Δ r is smaller. (r-value measures the ability to of steel to work harden without thinning and varies by the direction in which it is measured). Also, Ti-Nb type IF is less reactive in zinc and is usually employed when producing GA.

Interstitial-free stabilized steels are ideal for directly producing DDS and EDDS hot-dip products. Since all the C and N have been taken out of solution, the steel is almost pure alpha iron. During heating and cooling it does not undergo phase transformations so can be cooled fast in the furnace without being affected by the hardening that comes into play when continuous annealing low carbon steel. Also, during the coating and galvannealing operations, the strip is reheated above the overaging temperature. If low carbon steel were being used, C and N in solution would cause hardening and enable strain ageing to occur. With IF steels, the cooling, and GA reheating is irrelevant, as C and N are not available to become involved in hardening and ageing reactions.

One type of EDDS made using stabilized steel is actually a high strength steel with minimum yield strength of 30 ksi [205 MPa]. It is made using phosphorous additions of up to 0.06% and combines good formability with high strength, producing good dent resistance on exterior panels. This alloy is a type of solution-hardened steel (SHS).

Fully stabilized, ultra-low carbon IF steel is susceptible to a phenomenon known as cold work embrittlement. Compression strain makes the steel prone to crack propagation due to an embrittlement of the grain boundaries resulting from the complete absence of carbon. The problem is solved by the addition of as little as 2 PPM of boron (B), which strengthens the grain boundaries. Unless treated with B, these steels should not be used in load bearing, structural end uses.

Some of the advantages of ULC stabilized steel are:

- Superior stamping, forming, drawing performance,
- Part consolidation - reduce numbers of dies required to make a part,
- Free of strain ageing,
- Improved coating adhesion for galvanize products;

While some of the disadvantages of ULC stabilized steel are:

- Very soft - difficulty shearing, punching,
- Sheet that has poor dent resistance,
- Susceptible to cold work embrittlement,
- Higher rolling loads when Nb present,
- Difficulty in spot & resistance welding,

High strength steel

For many years galvanize with 80-ksi [550 MPa] yield strength has been produced using a “full hard” (unannealed or recovery annealed) method (ASTM A653, Grd 80 [A653M, Grd 550]). This product has limited ductility and is only used for roll-formed building siding.

Over the years there have been various approaches to making formable high strength steels. Initially the focus was on combining high yield strength with good elongation. During the last three decades, much work has been aimed at producing advanced automotive coated steels with good formability, combined with high tensile strength and lower yield/tensile strength ratio. The driving force behind this continuing technology development is to produce steels that enable production of fuel-efficient vehicles.

High strength steel (HSS) sheet can be produced by several methods:

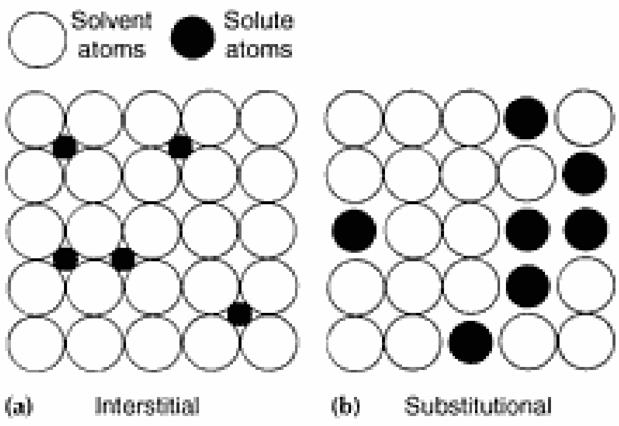
- ❑ Standard HSS – widely available and used today in both structural and automotive applications. Included are the high strength low alloy steels (HSLAS). One or more of the following strengthening methods are utilized to produce these types of steels:

- Solid solution strengthening (for HSS)
    - Interstitial
    - Substitutional
- Precipitation hardening and grain refinement (for HSLAS)

- ❑ Advanced high strength steels – a continually evolving class of high strength, formable steels produced using higher alloy levels combined with specialized in-line thermal treatments.

The **solid solution strengthening** method is the traditional approach and achieves high strength with moderate formability. The **interstitial** approach uses elements such as carbon and nitrogen that stretch the ferrite lattice. This mechanism is usually combined with **substitutional** elements such as manganese, silicon, and phosphorous, which replace iron atoms, also stretching the ferrite lattice.

Figure 4:
Interstitial vs. Substitutional Alloying



These two mechanisms, shown in Figure 4, can be used to produce galvanized steels with yield strengths up to about 55 ksi [380 MPa] with reasonable formability. Steel of this type has a characteristic low yield to tensile (Y/T) ratio. They are generally used for structural applications. Other steels (described below) with low Y/T ratios (<0.75) are gaining favour in automotive applications to take advantage of their crash energy absorption properties.

The **precipitation hardening** method of producing HSLAS with low carbon steel uses alloying elements, such as V, Nb, and Ti, to combine with C and/or N to form very small carbide/nitride precipitates. These particles harden the steel by preventing or altering dislocation movement, the mechanism by which steel yields. The precipitates also act as **grain refiners** by pinning the recrystallization interfaces, delaying recrystallization until the carbides grow, resulting in a much smaller ferrite grain size. The yield strength increases since it is inversely proportional to ferrite grain size. Vanadium is not used as a **micro-alloying** element for galvanize because VN precipitates dissolve at the continuous annealing temperatures used, the N combines with Al, and the precipitates are lost. Vanadium additions are used mostly for uncoated HSLAS produced by batch annealing where lower annealing temperatures are used. Niobium at levels as low as 0.005% is effective because of its high atomic weight. Nb-C precipitates do not dissolve at continuous annealing temperatures, so are available for both precipitation hardening and grain refinement. These techniques are used to produce HSLAS with yield strengths from 40 to 60 ksi [275 to 410 MPa]. The Y/T ratio of these steels is high (>0.8) and they have lost favour for automotive applications because of this.

New types of high strength coated steels have been, and continue to be developed for automotive applications. They are referred to as Advanced High Strength Steels (AHSS). To produce these steels, higher levels of alloys are used combined with more complex and controlled heat treatments in the CGL furnaces. The result is better formability at a given strength level and, in some cases, post-forming strengthening. The most common types of AHSS are: Dual Phase (DP), Multi Phase (MP) or Complex Phase (CP), and Transformation Induced Plasticity (TRIP) steels. Recent developments have concentrated on third generation (3G, GEN3) steels with ultimate tensile strengths (UTS) of up to 1200 MPa. These grades have increased levels of retained austenite compared to TRIP steels produced by complex in-line heat treatments, and can have strong bake hardenability up to 160 MPa.

Figure 5 shows the relationship between the various families of high strength steels in terms of total elongation (formability) and tensile strength. (See also Fig. 19).

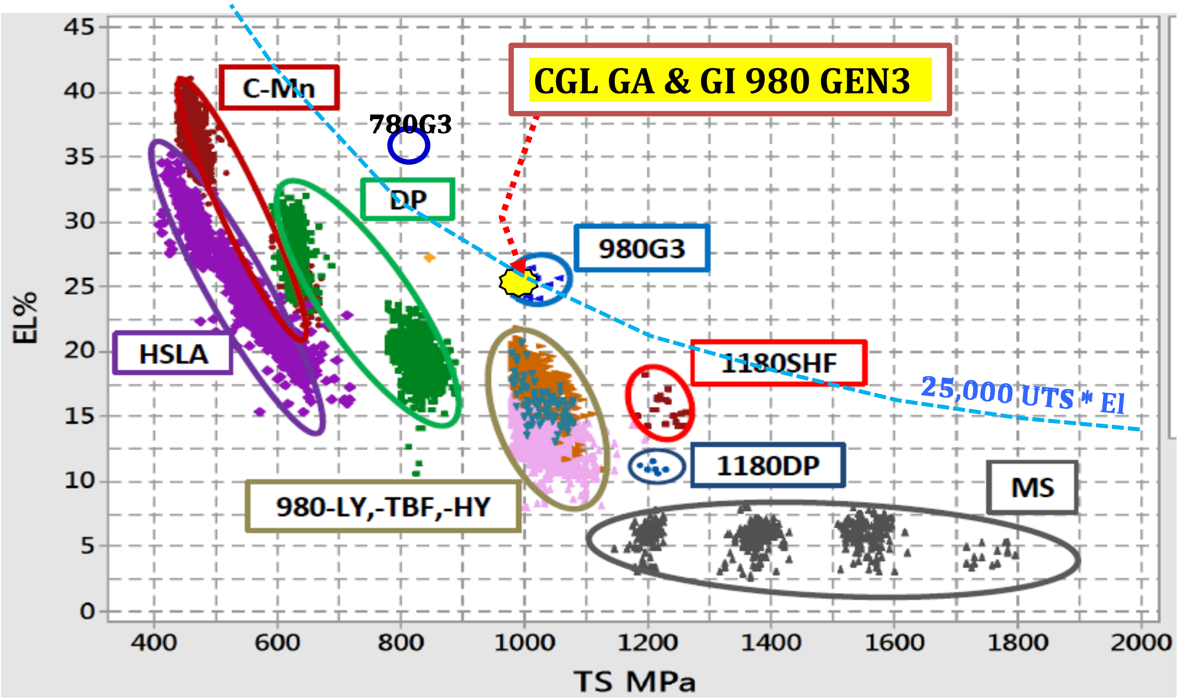


Figure 5: Characteristics of Advanced High Strength Steels

The galvanizing process

Referring to the galvanizing line diagram in Figure 3, the continuous hot-dip galvanizing process is as follows:

Preparation of black coils

Black coils, usually full hard cold rolled steel, are placed on one of two entry reels. The lead end is cropped to remove any off-gauge or damaged steel. The end is cropped square and is mash seam welded to the tail end of the previous coil. On modern lines a direct current welding machine takes about 1.5 minutes to complete the weld. A hole is punched in the centre of the strip to allow tracking of the weld through the line.

While the entry end of the line is stopped, the process section is kept running using the strip that is stored in the vertical accumulator. Some lines use horizontal accumulators located under the furnace section.

Cleaning

Full hard coils charged to continuous coating lines will always have some degree of oxide, rolling oil, grease, and fine steel particle contaminants present on their surface. Before the strip reaches the zinc pot the soils must be removed or reduced to an insignificant amount. The cleaning operation begins this process.

Liquid alkali cleaning, which can be combined with a high-current-density assist, is an important part of making high quality galvanize and galvanneal. It removes residual rolling oils and iron fines from the surface by cleaning in hot alkali (some lines have an electrolytic assist), with scrub brushes, followed by rinsing and hot air drying. This cleansing of the surface prior to annealing contributes towards excellent coating adhesion, optimum appearance and better paintability. It also removes loose iron-bearing debris from the surface that could get carried through to the zinc bath, forming pot top dross or surface dross on the strip.

Alone, or in combination with liquid cleaning, some hot-dip lines use direct flame cleaning. The strip is heated in a multi zone, direct-fired, non-oxidizing furnace, which volatilizes the organic surface contaminants and can reduce small amounts of iron oxide to iron. The furnace zone temperatures are typically in excess of 2300°F [1260°C] to maximize the potential for reducing the oxides on the strip. It is important to not have a highly oxidizing atmosphere to prevent the oils from burning and leaving behind a carbon residue.

Annealing and cooling

A HDG galvanizing line furnace is required to: heat the steel sheet to the required temperature/time cycle to develop the required strength and ductility; provide conditions that remove thin oxide layers that may be present; and provide a surface that will react correctly with zinc when the strip enters the coating bath.

Hot dip galvanizing lines use vertical or horizontal, radiant tube annealing furnaces with multi independently monitored combustion zones for precise and uniform temperature control. The heat resistant alloy radiant tubes are equipped with high efficiency burner systems. The vertical design minimizes strip contact and provides more efficient heating of the strip compared to horizontal designs. Depending on the size, these furnaces have as many as eight heating zones and a soak zone. Annealing temperatures vary from 1330°F [720°C] for commercial steels, to 1550°F [845°C] for EDDS ultra low carbon grades. The atmosphere in the furnace is a very dry, controlled hydrogen-nitrogen mixture meant to continually reduce all iron oxide on the steel surface back to pure iron so as to provide a surface that will alloy properly with zinc.

Usually, following the heating/soaking zone is a set of hot bridle rolls to provide the tension control to minimize shape distortion, and maintain the low-tension operation necessary when producing EDDS. Next is a rapid jet cooler, which can cool the strip at rates up to 40 °C [100 °F] per second as required for bake hardenable and AHSS steels. Some lines have large furnace rolls (5 ft. [1525 mm] in diameter) following the fast cooling section. This is important to prevent the increase of mechanical properties in ULC steel by repeated bending over small rolls. A second hot bridle roll can be located at the exit end of the furnace, to assist in keeping the strip flat and stable at the coating knives for enhanced coating weight control. This is needed to meet the very tight limits on coating weight variability specified by automotive producers. Figure 6 shows an example of heating and cooling steel temperature ranges for various products.

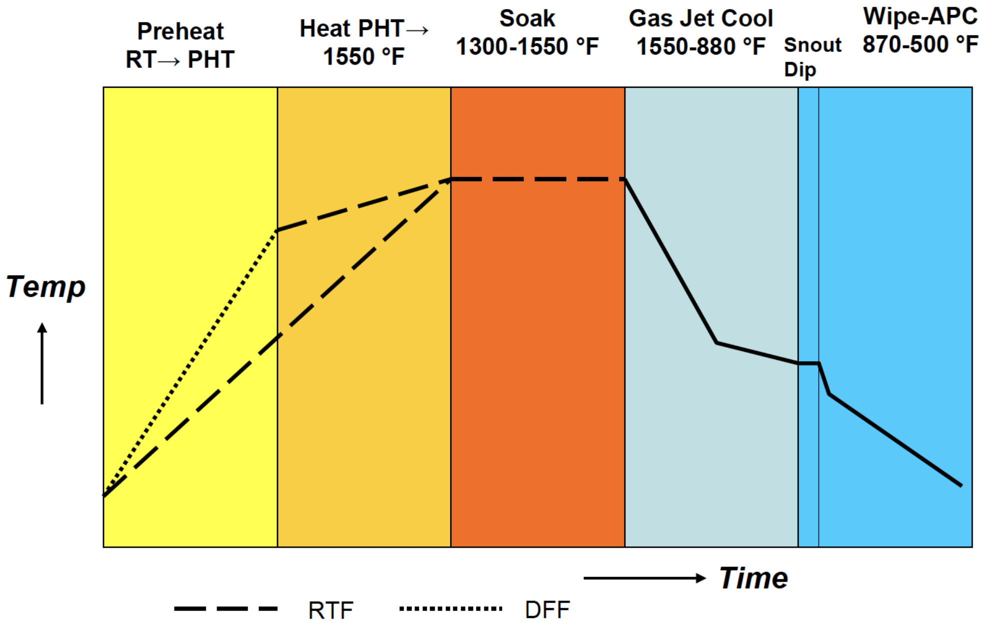


Figure 6: Example of a Heating Profile

Zinc bath management and alloying reactions

Zinc pots on modern continuous galvanizing lines are ceramic lined vessels and typically hold about 200 - 350 tons of liquid zinc, although some have capacities up to 500 tons. They are actually large metallic reactors. The purpose of the large volume of liquid zinc is to provide superior stability of both bath chemistry and temperature, two of the most important variables in making high quality GI and GA. It also minimizes the effect of any bottom dross. Submerged in the zinc is a sink roll and twin stabilizer rolls, the latter of which act to equalize the zinc distribution across the width of the strip by controlling the passline of the strip as vertically exits the bath. Most CGL lines today use lead-free zinc, resulting in galvanize with a spangle-free, smooth appearance.

To produce high surface quality coatings with the proper composition and appearance, stable bath composition and temperature, quiescent conditions, and efficient control of dross build-up are required. Most CGLs maintain a zinc temperature of between 865-870°F [463-466°C]. Aluminum is required in the zinc bath to inhibit the zinc-iron reaction. Pre-alloyed zinc “jumbo” ingots, containing anywhere from 0.20% to 1.00% Al, are used to avoid undesirable aluminum variations. Controlling bath chemistry by using only Al-free zinc jumbos, and 10% Al brightener bar additions, creates large Al fluctuations and contributes to dross formation. For this reason, many CGLs now control bath Al content via the choice of the Al content in the zinc jumbos. Computer programs are now available to manage the free or “effective” Al in the bath, resulting in better coating quality, less dross generation, and improved CGL productivity and product quality. On modern lines, robots are increasingly being used to skim off top dross, and instruments are available to monitor bath chemistry in real time.

As steel strip passes through a zinc bath, various reactions occur at the steel/liquid zinc interface. These reactions are governed by what is depicted in Figure 7, which is the zinc-rich corner of the Zn-Al-Fe phase diagram. It provides the means by which to manage the zinc bath. The yellow lines show the solubility limits of both Fe and Al in zinc, in this case at 860˚F [460˚C]. Without the presence of Al, the reaction would produce a relatively thick, brittle Fe-Zn alloy. As Al is added to the bath, the solubility limit of Fe is lowered. Overall, Al reacts faster with Fe than does Zn, quickly producing a temporary and very thin, adherent Fe-Al-Zn alloy layer on the steel. Nevertheless, enough Fe does dissolve into the zinc before the Fe-Al-Zn layer finishes forming to quickly saturate the zinc with dissolved Fe. To produce galvanize with good zinc adhesion, coating lines must operate in the green area of Figure 7, with total Al levels above 0.14%. Aluminum acts as a very strong and much needed inhibitor to the Zn-Fe reaction. The Al available to control the reaction (effective aluminum) is only that dissolved in the zinc (lower left black area) but not the portion combined with Fe.

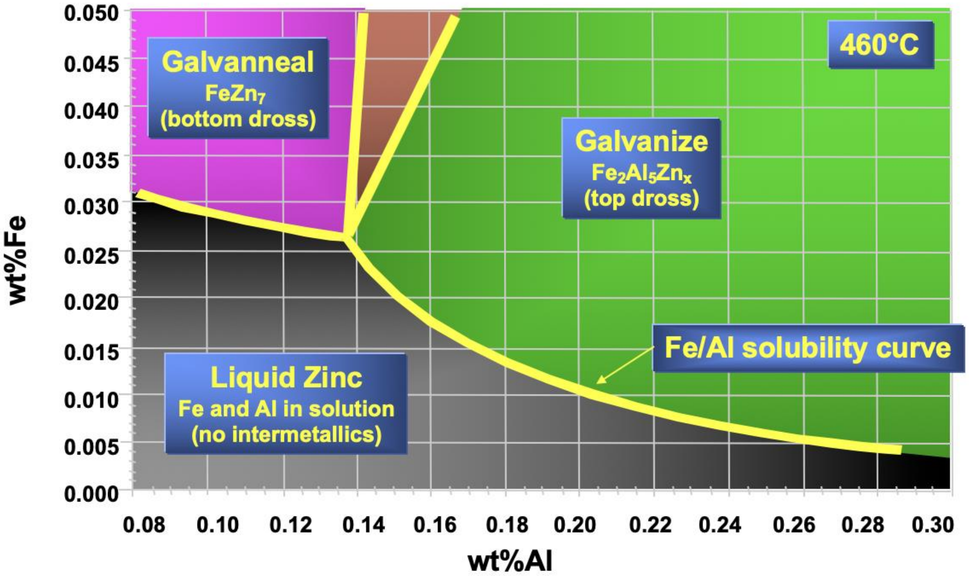


Figure 7: Iron-Aluminum Solubility Curves

As explained above, the goal is to form ternary Fe_2 $Al_{5-X}Zn_X$ intermetallics at the steel interface. This intermetallic also forms dross particles in the zinc melt, has a density less than that of zinc, so floats to the bath surface as part of the top dross. Binary intermetallics ($FeZn_7$) will only form if the Al falls below 0.14%. These have a density greater than zinc and sink to form bottom dross. By the proper use of pre-alloyed zinc ingots the formation of $FeZn_7$, and thus bottom dross, can be virtually eliminated. Also, as can be seen in the formula for top dross, it is about 45% Al by weight. Additions of high Al (10%) alloy ingots to the bath results in most of the Al reporting directly to the top dross, and leaving the bath on the surface of the strip. Having a clean strip surface entering the bath, free of iron debris, is also important in minimizing dross formation.

Control of the steel/zinc reaction has a direct affect on the coating quality in terms of its adherence, formability, weldability, uniformity, and appearance. As covered above, when Al is at the correct level, the metallic reaction forms a very thin, interfacial, ternary alloy layer on the steel with a composition of 45% Al, 35% Fe, and 20% Zn ($Fe_2Al_{5-X}Zn_X$). Note again that this layer has the same composition as top dross, is the reason for the excellent adherence of the zinc to the steel, and only forms when full Al inhibition is in effect. See Figure 9 for an electron microscope image of this alloy layer. Full inhibition occurs when the effective Al in the bath is at or above 0.14%. When effective Al is below 0.14%, binary $FeZn_7$ intermetallics can form (partial inhibition), which are brittle and can lead to poor coating adherence. Effective Al levels above 0.14% produce adherent coatings but will result in a zinc overlay with slightly higher Al content due to the amount of Al in the interfacial layer. At 0.14% effective Al, the overlying zinc coating contains about 0.20% Al. Higher coating Al may result in spot weldability problems, the more so the higher the Al. Bath effective Al levels of higher than 0.18% should be avoided if this is an issue for the end user. It is also important to control the strip temperature as it enters the zinc bath. Ideally the strip temperature should be one or two degrees C above the liquid zinc temperature. Too great a variation either way can result in changes to the amount of Al in the coating, and can interfere with proper interfacial alloy formation.

Coating weight [mass] control and measurement

In the zinc pot, the moving strip passes around a rotating, submerged sink roll and is redirected vertically to exit the bath below the coating knives. Stabilizer and corrector rolls, just under the surface of the zinc, help control strip shape and vibration, allowing a stable, flat strip to pass between the knives. Typical gas knives, one on each side of the strip, employ a low-pressure, high-volume approach to delivery of the wiping medium. Figure 8 depicts the gas wiping process on one surface of the sheet.

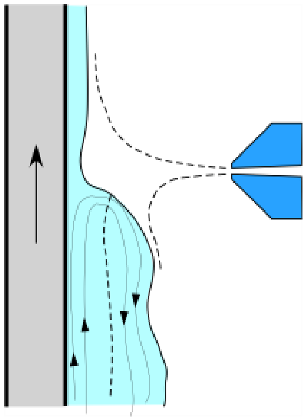


Figure 8: Depiction of gas wiping process

Pressure is the principal control parameter for coating mass (weight) control, although height, distance to the strip, and angle of the knives are also adjustable. Automatic coating weight controls using artificial intelligence technology have been installed on some lines to produce consistent, steady state, coating weight with a low standard deviation.

Traditionally, the gas knives use air. Some lines use nitrogen gas, the benefits of which are questionable, plus it has a higher cost.

After the strip has been cooled to ambient temperatures, a twin-head x-ray fluorescent gauge utilizing a 2 in. [50 mm] focused beam repeatedly scan across the width of the strip. The gauge provides a continuous read-out of zinc thickness (weight) of both top and bottom surfaces for coating weight control purposes.

Galvanize (GI) versus galvanneal (GA)

If the zinc coating is left to freeze after the gas wiping operation, it forms a “traditional” GI coating, the thickness of which is a function of the action of the coating knives. GI has a bright, metallic lustre and is usually applied at coating weights of G40 [Z120] and heavier. As most CGL lines today use lead-free spelter, the spangle size is small (<0.5mm) and difficult to discern. In the past, lead and/or antimony were added to the bath to produce large, flowery spangles. With the very small spangle produced by a lead-free bath, it is much easier to make an extra smooth product by temper passing. Figure 9 shows an electron microscope image of the cross-section of a GI coating and illustrates thick, free zinc eta (η) above the very thin (~0.1 μm), ternary $Fe_2Al_{5-X}Zn_X$ interfacial layer.

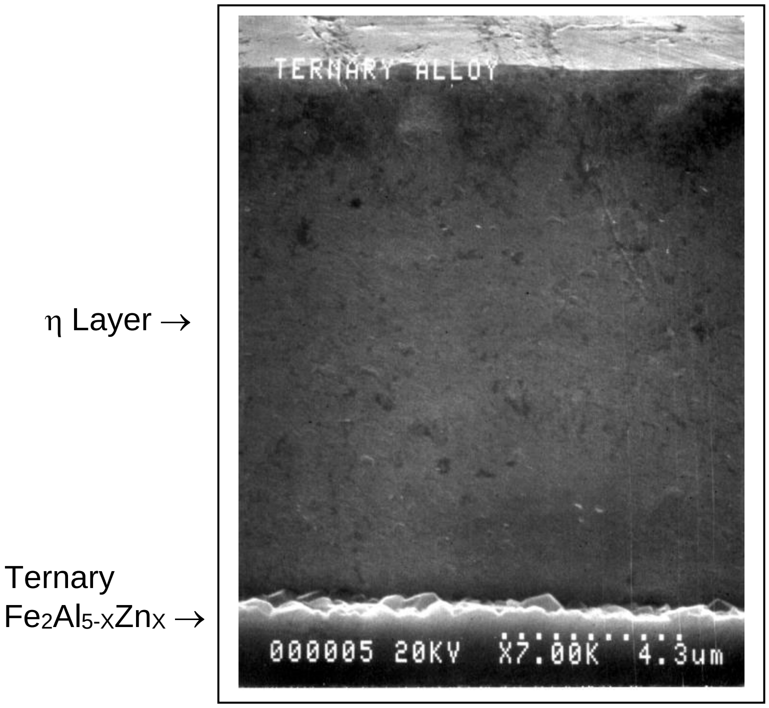


Figure 9: Cross section of galvanize (GI) coating (magnification X 7000)

Reheating the strip to a temperature of up to1100°F [590°C] immediately after leaving the coating knives produces galvanneal. The zinc is still liquid when the strip enters the galvanneal furnace. The reheating restarts the zinc/iron diffusion reaction and breaks down the inhibition layer that formed when the strip was in the zinc bath. After 5 to 10 seconds a dull grey matte coating is created which has a bulk iron content of 9 to 12%. A cross-section of the coating structure is shown Figure 10.

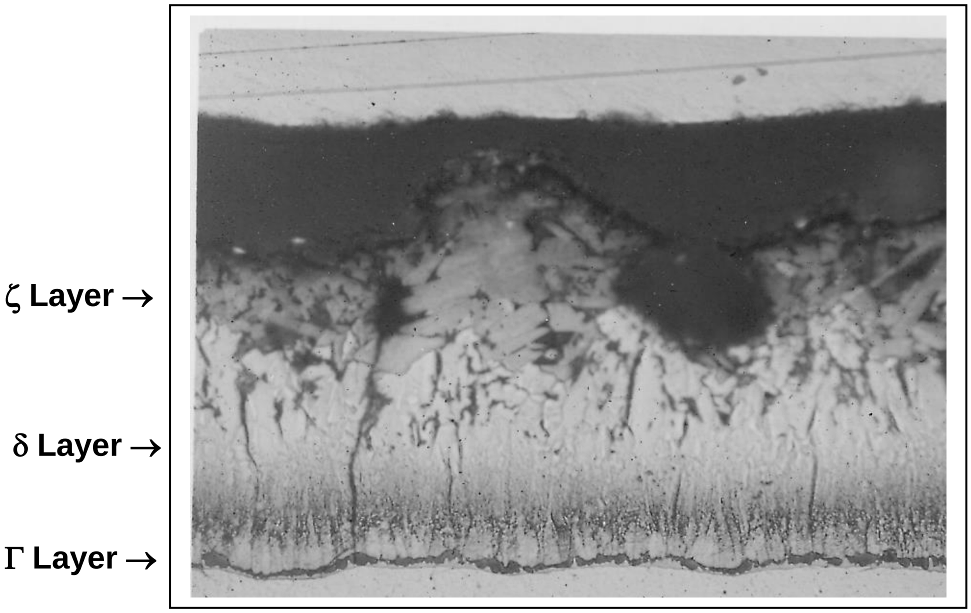


Figure 10: Cross section of galvanneal (GA) coating (magnification X 1000)

The layers that form, from the steel substrate outward, are gamma (Γ), delta (δ), and zeta (ζ) – similar to those that form in batch galvanizing, except no eta (η) layer is present. The compositions of the intermetallics in GA coatings are shown in Table 3.

Table 3: Composition of Galvanneal (GA) Layers

Layer	%Fe	%Al
Zeta (ζ) $FeZn_{13}$	5.2 – 6.1	0.7
Delta (δ) $FeZn_{10}$	7.0 – 11.5	3.7
Gamma (Γ) Fe_3Zn_{10}	15.8 – 27.7	1.4

The reactions start at the steel interface and are dependent on:

- Galvannealing time and temperature
- Bath Al
- Steel grade

- A higher Al content requires higher temperature and/or longer time to produce optimum GA coatings. Also, stabilized IF substrate reacts faster than ULC or plain carbon substrate. Amongst IF substrates, Ti stabilized reacts faster than Ti-Nb stabilized.
- On modern CGLs the reheating of the strip to make galvanneal is done using induction furnaces. Typically, the furnace has three induction zones, which reheat the strip from about 870°F [465°C] to as high as 1100°F [590°C] in a few seconds. Induction furnaces, combined with soaking and cooling zones, provide the means to do this in a controlled, fast, and efficient fashion, resulting in a coating with good appearance and adherence. Conversion to a galvanneal coating is a diffusion reaction between zinc and iron and occurs mostly while the coating is still liquid. The use of difficult to control gas-fired furnaces has fallen out of fashion. Induction galvannealing is easier to control than convection and/or radiation galvannealing as the heat comes from inside the strip.
- Many automakers prefer GA to galvanize because of its extremely good paintability and appearance, plus its excellent corrosion resistance under automotive type paints.
- GA is rarely used in unpainted end uses as it contains 10% iron, and the coating thickness is only about one third that of G90 [Z275]. It does not have good corrosion resistance in the unpainted state.
- Coating weight [mass] and coating thickness, of both GI and GA are shown later in this article in the section on Galvanize Properties.
- Iron content and coating weight [mass] are displayed both numerically and graphically in real time during the production of every coil to confirm coating uniformity. Controlling the iron level between 9 and 12% on GA is an important parameter to produce good coating adhesion resistant to powdering. The coating mass and percent iron data is stored in a data base for quality control purposes.

Post treatments

Temper passing

In-line temper rolling is an important part of producing exposed quality coated sheets. It eliminates an off-line operation that would be cost increasing, and imparts a carefully controlled surface finish, mechanical property control, and good flatness.

The 4-high design is common and incorporates tension bridle rolls before and after the temper mill to allow extensions up to 2% to achieve the required surface finish and mechanical properties. Work roll bending is incorporated for optimum shape control. A wet rolling practice prevents surface contamination and zinc pick-up. On most lines, load rather than extension controls the temper mill. Figure 11 depicts an in-line temper mill.

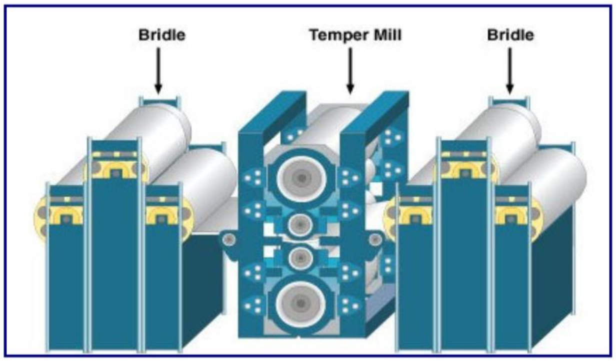
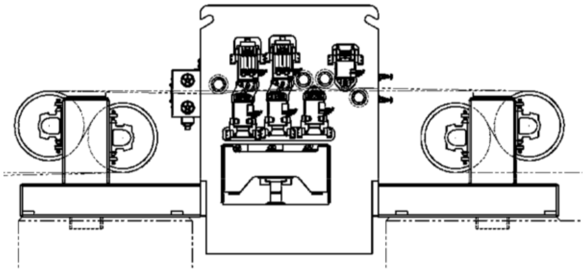


Figure 11: In-line temper mill

Leveling

A tension leveler (Figure 12), usually located immediately after the temper mill, provides superior flatness while maintaining precise control of elongation so as to prevent fluting on carbon steel product. The presence of intermediate bridle rolls between the temper mill and leveler permits control of elongation, independent of the temper mill mode. Extensions of up to 1.5% are attainable with such levelers.

Figure 12: In-line tension leveler



Chemical treatment

For non-automotive end uses, the next step in the CGL process is for the strip to be given a chemical treatment. The purpose is to passivate the surface to impart resistance to the formation of "wet storage stain" or “white rust”, terms traditionally used in the galvanizing industry to describe the white zinc corrosion product that sometimes forms on the galvanized steel surfaces during storage and transport. If freshly unpassivated galvanized steel becomes wet with moisture trapped between contacting surfaces, which restricts access to free-flowing air, zinc hydroxide quickly forms. This is a white (sometimes grey to black), non-protective corrosion product. Zinc hydroxide can form during a single incident of wetting, by rain or condensation. However, once areas affected with light white rust are exposed and allowed to dry, there is minimal harmful effect on the service life of galvanized steel. If the damp, restrictive conditions continue, then zinc corrosion may proceed rapidly down to the base steel. Most galvanized sheet product receives some form of surface passivation treatment to retard the formation of wet storage stain. For many years these treatments contained chromium in the form of the Cr^{+6} ion, which is very effective in delaying the formation of white rust for periods up to six weeks.

Unfortunately, Cr+6 is toxic substance, and its use is now prohibited in many jurisdictions. Suppliers have developed trivalent chrome (Cr^{+3}) and non-chrome bearing chemical treatments. Some non-chrome treatments involve the use of phosphoric acid and other non-toxic heavy metals.

Passivation solutions of any type are not applied to sheet intended for automotive end uses as they interfere with phosphatability, paint adherence, and spot weldability.

Some hot-dip lines are now applying clear organic coatings (some with added passivation chemicals) by in-line roll coating to prevent handprint or black scuffing marks during product manufacturing by users. These treatments were first developed for aluminum-zinc hot-dip coatings, which are particularly susceptible to this problem.

Inspection

The strip then passes through the inspection station, which can incorporate horizontal and vertical and/or top and bottom visual surface inspection. The area is equipped with both fluorescent and strobe lighting. Some lines have automatic inspection devices to assist the human inspectors in assessing surface quality.

Oiling and recoiling

An electrostatic oiling unit is used to apply a light, consistent, precisely controlled film of either a rust preventative oil or single phase prelube to both surfaces of the sheet. Immediately after oiling the strip is recoiled on a mandrel to produce coils to the customers' ordered weight. Unpassivated sheet for automotive end use generally receives a light oil application.

Products

Most galvanize is produced to either ASTM specifications or Automotive specifications. ASTM standards are used by most customers and are also referred to by many automotive documents.

ASTM standards

The following standards for zinc-coated steel-sheet products are commonly used in industry:

A924/A924M - Standard Specification for Steel Sheet, Metallic-Coated by the Hot-Dip Process

This standard covers the general requirements that apply to hot-dip coated steel sheet in coils and cut lengths. The common requirements for all types of hot-dip metallic-coated steel sheet, such as product dimensional tolerances for thickness, width, flatness, etc. are contained in this standard.

A653/A653M - Steel Sheet, Zinc-Coated (Galvanized) for Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process

This standard covers steel sheet, zinc-coated (galvanized) or zinc-iron alloy-coated (galvannealed) by the hot-dip process. This standard covers the most commonly used type of coated-steel sheet within the metal-construction industry. It is often prepainted for use as exterior roll formed building panels.

A755/A755M - Steel Sheet, Metallic-Coated by the Hot-Dip Process and Prepainted by the Coil Coating Process for Exterior Exposed Building Products

This standard covers steel sheet metallic-coated by the hot-dip process and coil-coated with organic films for exterior exposed building products. The substrate is available with several different metallic coatings. Paint coating systems supplied under this standard shall typically consist of a primer coat covered by various types and thicknesses of topcoats.

A common non hot-dip galvanize standard is:

A879/A879M - Steel Sheet, Zinc Coated by the Electrolytic Process

This standard covers steel sheet in coils and cut lengths that are zinc-coated by electrodeposition. The electrolytic zinc-coated sheet covered by this standard is produced with a coatings varying from a light (thin) coating mass to relatively heavy masses. The zinc coating is used to provide some enhancement in corrosion resistance compared with cold-rolled steel sheet. For most applications, the product is painted. It is not typically used for outdoor applications where high corrosion resistance is required.

Other metallic zinc-bearing hot dip coatings are:

A792/A792M - Steel Sheet, 55% Aluminum-Zinc Alloy-Coated by the Hot-Dip Process

This standard covers 55% aluminum-zinc alloy-coated steel sheet in coils and cut lengths. This product is intended for applications requiring high corrosion resistance, or heat resistance, or both.

A875/A875M - Steel Sheet, Zinc-5% Aluminum Alloy Metallic-Coated by the Hot-Dip Process

This standard covers steel sheet, in coils and cut lengths, metallic-coated by the hot-dip process, with a zinc-5 % aluminum alloy coating. The coating is produced as two types: zinc-5% aluminum-mischmetal alloy or zinc-5% aluminum-magnesium alloy.

The material is intended for applications requiring corrosion resistance, formability, and paintability.

Each of the above-listed standards contains the requirements that are specific to the type of coating covered in the document. For example, Standard A653 [A653M] contains the coating-weight designators G60 [Z180], G90 [Z275], etc.) for hot-dip coated galvanized (zinc-coated) steel sheet. Also, each of the standards contains the requirements for the different steel designations (CS, FS, DDS, SS, etc.) that are available with the specific types of coatings listed in the document.

Other ASTM Standards for Hot-Dip Coated Steel Sheet that are Commonly Used by Industry

In addition to the product standards, there are several other ASTM standards relating to hot-dip coated steel-sheet products that are frequently referenced by industry.

These include:

A90/A90M - Standard Test Method for Weight of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings

This test method covers procedures for determining the weight or mass of the coating on steel sheet and other articles on which the coating is zinc or a zinc alloy including the zinc-iron alloy coating, the 55% aluminum-zinc alloy coating, and the 5% aluminum-zinc alloy coating. This is considered a destructive test in that the coating is physically dissolved from the steel, and the weight of coating is determined by the weight loss during the stripping operation.

A754/A754M - Standard Test for Coating Weight of Metallic Coatings on Steel by X-Ray Fluorescence

This test method covers the use of x-ray fluorescence for determining the coating weight of metallic coatings on steel sheet. The test method is used for "on-line" measurements of coating on continuous production lines. It provides the capability to determine the coating-weight distribution throughout a coil during production on a real time basis.

Galvanize properties

Mechanical

Table 4 gives typical ranges of selected mechanical properties of various galvanize products.

Table 4: Typical Mechanical Property Ranges – Selected Galvanize Products

Product	YS (ksi)	El % (in 2")	R_m value	n value
ASTM A653 CS Type A (no min C)	25/50	>20	-	-
Type B (min C 0.02)	30/50	>20	-	-
Type C (rephos)	25/60	>15	-	-
	25/45	>26	1.0/1.4	0.17/0.21
	20/35	>32	1.4/1.8	0.19/0.24
	15/25	>40	1.6/2.1	0.22/0.27
Auto EDDS (not TR) (stabilized IF)	17/23	42.5/48.0	1.62/2.1	.245/.260
Auto EDDS (TR for AE) (stabilized IF)	18.5/26.0	41.2/51.2	1.5/2.0	.225/.254
Auto EDDS (TR for AE) (stab. IF rephos)	27.1/36.0	33.6/41.2	1.7/2.0	.20/.25
Auto HSLAS Grd 50 (Nb added)	52.5/64.0	26.9/35.3	-	-

Adherence

Adherence of GI coatings is generally not an issue. As long as the steel surface is oxide free entering the bath, and the Al level properly controlled, a good ternary interfacial alloy layer is formed and lead-free zinc will not even crack on the outside of a "zero T" bend. GI coatings withstand roll forming and stamping operations very well.

Coating adhesion is one limitation of GA. The coating can powder or flake off in the dies, resulting in poor stamping performance and surface problems. Powdering is an intra-coating failure creating fine, powdery coating particulate. It results whenever coating undergoes a compressive strain and is affected primarily by coating mass (weight) and coating iron content. Increased levels of either will result in increased powdering. A coating mass of 55 g/m^2 or lower will pass most automotive powdering tests. Some powdering tests require an iron content of 10.5% or less to pass.

Flaking of GA is a failure of the bond between the steel and the coating, creating relatively large (0.5 to 2 mm) sheet-like particles. It occurs during bending/unbending strain, followed by a shear stress on the coating, such as present along the bead in a draw die. Flaking can result from either a weakened coating-steel bond (due to dirty steel, over-alloyed coating, or heavy temper rolling), or an increased transmission of strain to the coating-steel interface (resulting from free zinc in the surface).

Adherence and bare spot issues can occur with some of the highly alloyed AHSS grades due to the strong affinity of the alloying elements for oxygen in the annealing furnace. Special operating practices are needed to avoid these problems.

Figure 13 shows a schematic of the difference between powdering and flaking.

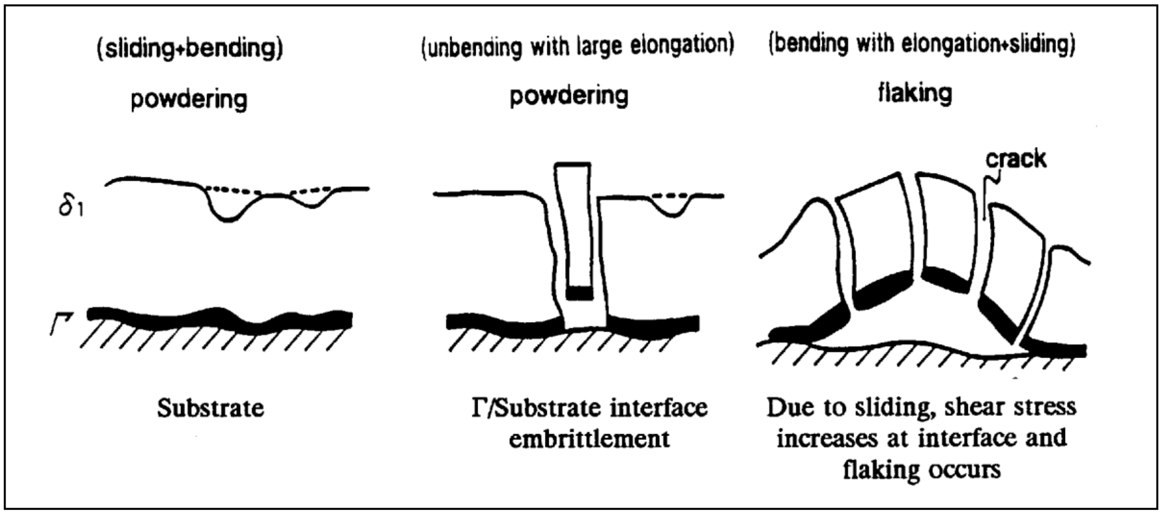


Figure 13: Schematic – Powdering versus Flaking on Galvanneal

Coating weight [mass] versus thickness

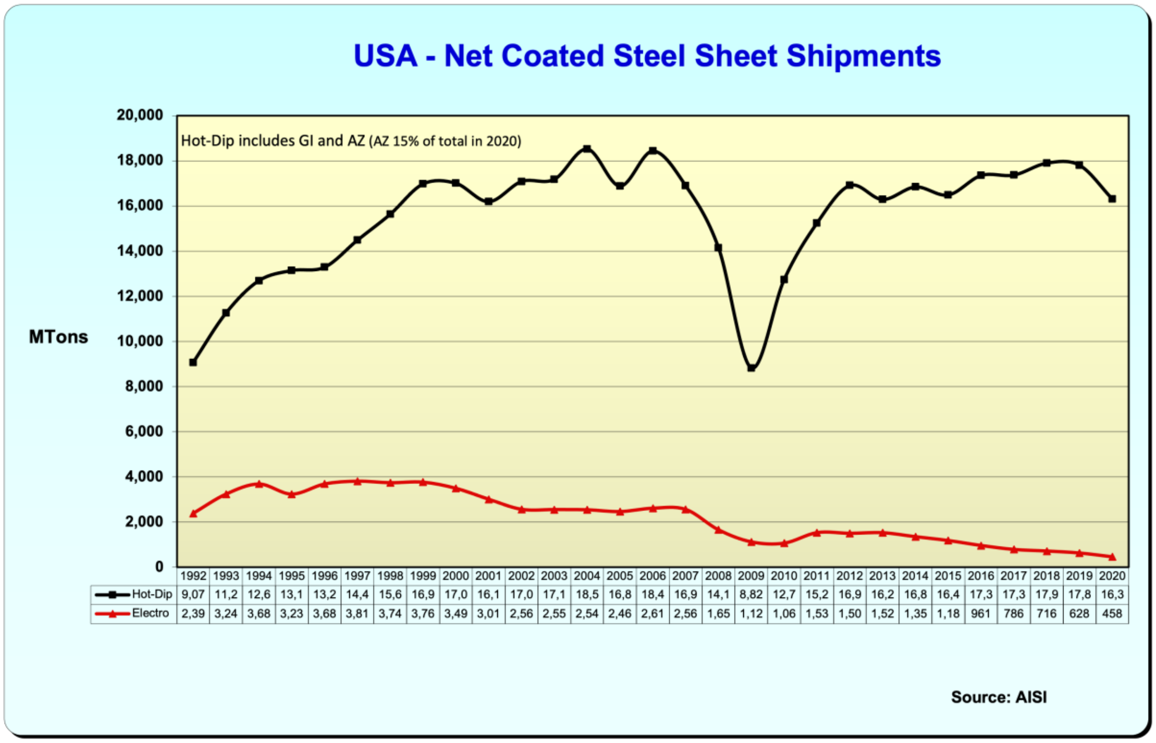
Table 5 shows typical hot-dip galvanize coating mass [weight] and thickness for various coating types and designations. This information is used when computing the required cold roll thickness of the steel substrate.

Table 5: Coating Thickness of GI and GA for Various Coating Designations

Coating		Mass-g/m² [Weight-oz/ft²]		Nominal Thickness (Total Both Sides)	
Type	**Designation SI [Imp]**	**Minimum (Per Side)**	**Nominal (Both Sides)**	**mm**	**in**
GI (Zinc)	Z600 [G185]	204 [0.64]	650 [2.13]	0.0916	0.0036
	Z275 [G90]	94 [0.32]	293 [0.96]	0.0413	0.0016
	Z180 [G60]	60 [0.20]	200 [0.66]	0.0282	0.0011
	Z90 [G30]	30 [0.10]	110 [0.36]	0.0155	0.0006
	70G70G - GM	70 [0.23]	160 [0.52]	0.0225	0.0009
	98G98G - GM	100 [0.33]	230 [0.75]	0.0324	0.0013
	MS6000-66 - DC	100 [0.33]	230 [0.75]	0.0324	0.0013
	60G60G - Ford	60 [0.20]	140 [0.46]	0.0197	0.0008
GA (Zinc-Iron)	ZF180 [A60]	60 [0.20]	200 [0.66]	0.0282	0.0011
	ZF120 [A40]	36 [0.12]	140 [0.46]	0.0197	0.0008
	ZF75 [A25]	24 [0.08]	100 [0.33]	0.0141	0.0006
	40A40A - GM	40 [0.13]	90 [0.29]	0.0127	0.0005
	50A50A - Ford	50 [0.16]	120 [0.39]	0.0169	0.0007
	MS6000-44A - DC	45 [0.15]	100 [0.33]	0.0141	0.0006

Markets

Zinc and zinc-alloy coatings on steel offer substantial improvements in corrosion resistance, not only for automobile bodies, but also for appliances, commercial and residential buildings and other general construction applications. As a result, there has been a large increase in the production and applications of zinc-coated steels. In the United States, the volume rose from 9.3MM tpy in 1990 to over 18MM tpy in 2004 & 2006 (Figure 14), dropped off during 2008-10 and has now recovered and is holding at over 16MM tpy as of 2021. To meet this demand, there are 77 operating lines in North America as of early 2022. Coincident with this large growth, market pressures on price and quality, and the ever-increasing need for efficiency, have led to significant improvements in the hot-dip sheet product quality, and in techniques for using coated steels.



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
■ Hot-Dip	9,07	11,2	12,6	13,1	13,2	14,4	15,6	16,9	17,0	16,1	17,0	17,1	18,5	16,8
▲ Electro	2,39	3,24	3,68	3,23	3,68	3,81	3,74	3,76	3,49	3,01	2,56	2,55	2,54	2,46

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
■ Hot-Dip	18,4	16,9	14,1	8,82	12,7	15,2	16,9	16,2	16,8	16,4	17,3	17,3	17,9	17,8	16,3
▲ Electro	2,61	2,56	1,65	1,12	1,06	1,53	1,50	1,52	1,35	1,18	961	786	716	628	458

Source: AISI

Figure 14: United States Galvanized Steel Shipments

Automotive – General

Since zinc-coated steel was first used in North American vehicles in the late 1950's, the quantity per vehicle has grown to about 850 lbs. [385 kg]. Most of the unexposed parts are fabricated from either hot-dip galvanized (GI) or hot-dip galvannealed (GA). Many exposed or skin panels are made from GA, while some use GI. Experience indicates that all products provide satisfactory corrosion protection, providing vehicle designs are appropriate, and the phosphating and painting systems are properly controlled.

It is unlikely that the usage per vehicle will increase from today's levels because of the present satisfactory corrosion performance. A more likely scenario is a small reduction due to more formable high strength steel and because of the increased use of tailor welded blanks, all of which will be described later in this section. The impact of these activities results in lighter vehicle weight along with improved crash protection for passengers.

Many developments are taking place aimed at reducing the cost of vehicles, improving structural performance, fuel economy, durability, quality, and safety.

A very close relationship has developed between the automotive design groups and the steel suppliers whereby steel industry personnel participate in the design of new vehicles. Pre-competitive efforts are pursued through the AISI and the Auto/Steel Partnership. Examples of programs are formable ultra-high strength steels, hot press forming, and improved fatigue resistance. Individual companies provide support to a specific vehicle program using computer-aided services and extensive forming trial support. The end result is more reliable stamping performance and the optimum steel selection.

The success of this activity can be seen in the chart in Figures 15 & 16, which show that, even though the overall use of steel in automotive has fallen by ~25% over the last 4 decades, the use of galvanize has risen by a factor of over 6 and is the largest market for this product in the USA.

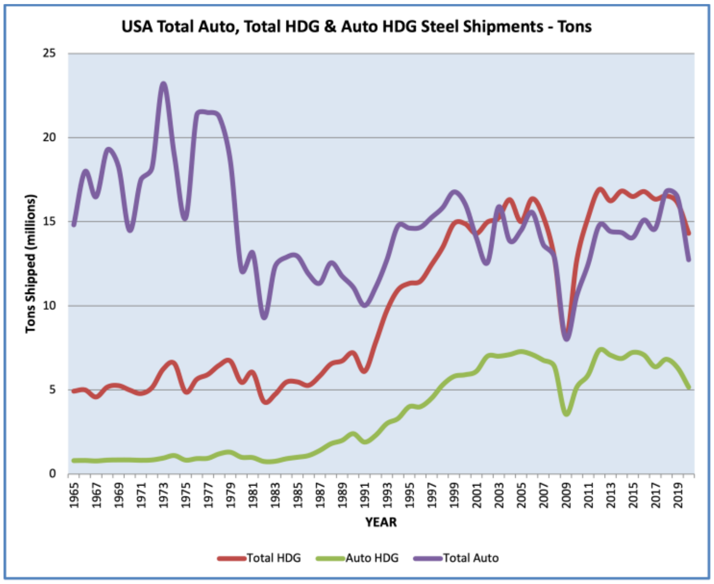


Figure 15: Use of HDG by automotive industry

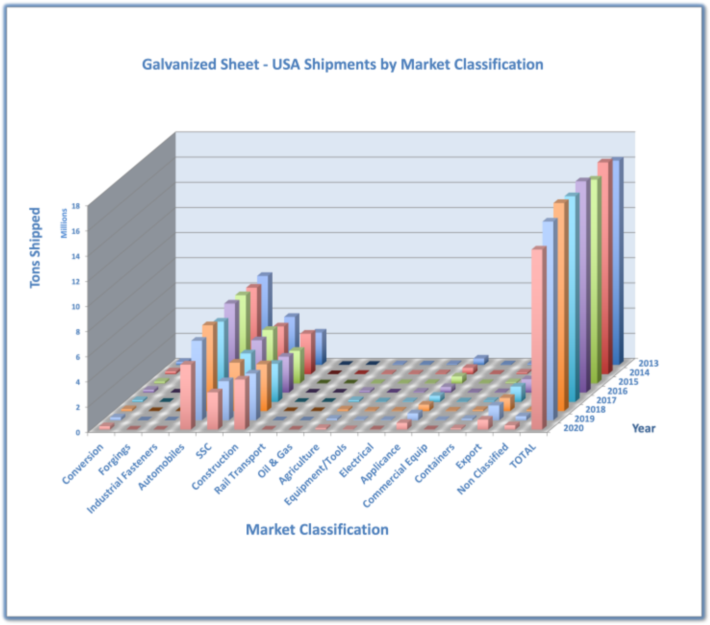


Figure 16: Automotive industry largest galvanize steel market in USA

Automotive – High strength and advanced high strength steels (AHSS)

Weight reduction, improved crash resistance, and improved damage resistance are some of the benefits of high-strength steels. Usage is steadily increasing. For instance, using ultra-low-carbon, vacuum-degassed steel and controlled alloying additions, partially stabilized steel can be produced with a limited amount of solute carbon after precipitation reactions are complete.

Bake hardenable steel (BHS) uses carbon strain aging to augment the yield strength of formed automotive panels, improving dent resistance or permitting some gauge reduction. The strain comes from normal forming and the aging is accelerated by the paint baking treatment. BHS contains enough supersaturated solute carbon that the aging reaction typically adds 4 to 8 ksi [27 to 55 MPa] to panel yield strength.

This approach to providing high strength panels has the advantage of presenting formable low yield strength material to forming operations to avoid panel shape problems due to elastic deflection associated with initial yield strengths exceeding 35 ksi [235 MPa]. BHS is the practical consequence of new manufacturing technologies, which permit control of supersaturated solute carbon in a range which is high enough to provide a useful amount of accelerated strain aging, without aging during transport/storage after being temper rolled. The BHS product produces panels free from stretcher strains at least 2 or 3 months after its production. Figure 17 illustrates the concept of bake hardening, with BH representing the flow stress increase on baking. This chart also represents the typical strain and baking conditions for automotive panels.

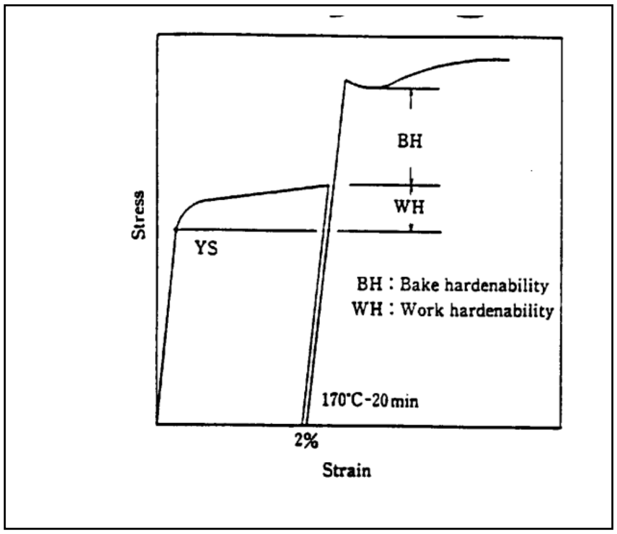


Figure 17: Increase in Yield Strength from Work and Bake Hardening

When producing BHS on a CGL, the important part of the process is trapping solute carbon by fast cooling through the carbide precipitation range, and avoiding cementite precipitation by quickly passing through the over aging zone to the pot entry temperature.

All automobile companies are committed to lowering of CO_2 emissions from their products. Weight reduction is an integral part of achieving this; hence they depend heavily on AHSS multiphase steel technology. The added requirement for vehicles to perform well in collisions requires steels with tensile strengths in the 590-1180 MPa range. These grades are produced as both Dual Phase (DP) and Transformation Induced Plasticity (TRIP) coated sheet. DP steels for processing in CGLs include hardenability elements such as Mn, Cr, Si, B, N and Mo, and microalloying elements such as V, Nb and Ti. Rapid cooling and isothermal holding are required during continuous annealing to achieve the required mechanical properties. Figure 18 illustrates the tensile properties of some of these steels. The much larger area under the stress-strain curve of AHSS steels is an important property that allows them to absorb considerably more crash impact energy compared to HSLA steels.

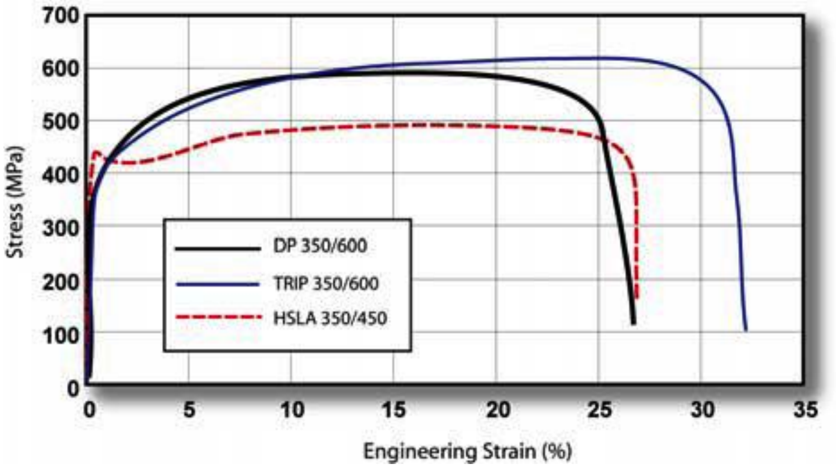


Figure 18: Tensile behavior of AHSS

In the AHSS category, another class known as Ultra High Strength Steels (UHSS) with tensile strengths in the range of 700 to 1600 MPa are available. These steels have lower formability, however, so programs are in place to develop Third Generation (3G, GEN3) AHSS with ultra-high strength and formability, as shown in Figure 19. Use of such steels will permit an additional 10% mass reduction of automotive body assemblies.

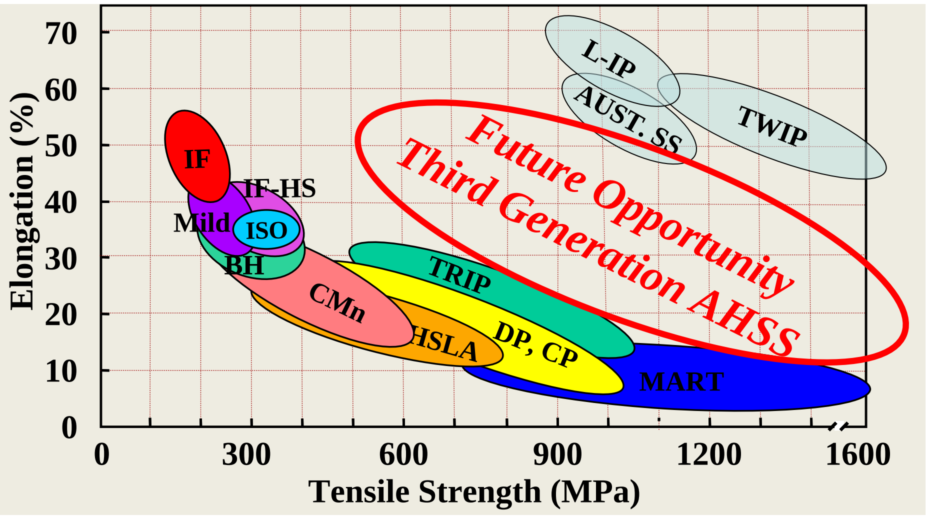


Figure 19: Future growth of AHSS – 3rd Generation

Taylor welded blanks and laser welding

Conventional vehicle body construction is achieved by joining together large numbers of stamped parts, each one of which is formed from a blank of a single material. This results in thicker components than needed in many areas and zinc coatings in areas where they are not needed. Tailor welded blank technology has developed to address these inefficiencies. Welding (usually by lasers) dissimilar materials together makes blanks. The composite blanks can be made from different metal thicknesses, coated and uncoated steels, or steels of different strength levels. The result is thick steel only where needed, higher strength only where needed, and enhanced corrosion resistance only where it warrants the extra protection.

Advantages of the process are: reduced vehicle weight, reduced vehicle cost, improved structural performance, reduced material usage, fewer parts, elimination of reinforcements, fewer spot welds, and lower assembly costs. Recognition of these benefits has led to a very rapid growth in the adoption of this technology, such that virtually every new North American car incorporates tailor welded blanks.

Figure 20 shows a tailor welded blank for a side ring made from five pieces, and a cross-section of a typical laser weld joining two sheets of significantly different thickness. Laser welds are very strong and stand up well during forming.

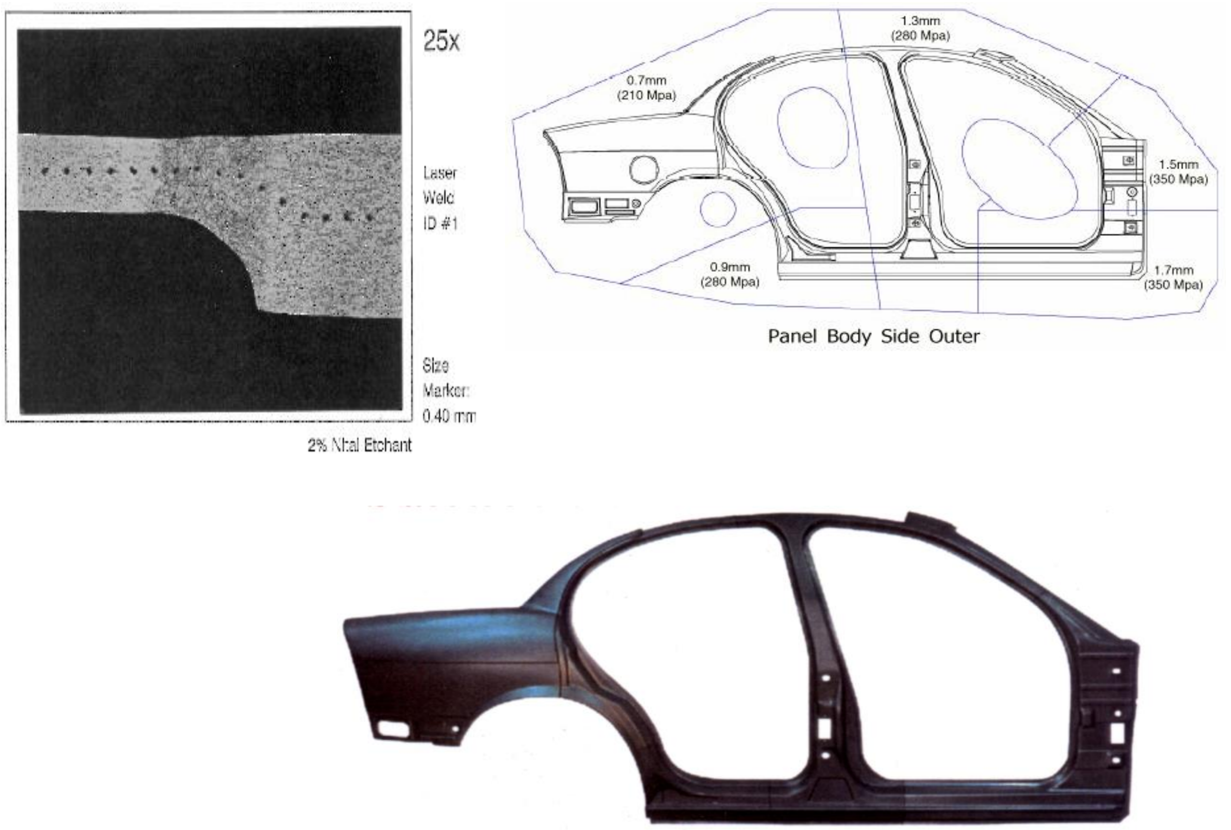


Figure 20: TWB side ring – blank and finished part; cross section of laser weld

Since one of the major performance attributes of a vehicle is rigidity as measured in bending and torsion, continuously welded joints, as opposed to spot welded joints, offer much greater resistance to elastic deformation. Laser welding is gaining acceptance, therefore, as a method to increase rigidity, and usually to achieve weight saving as an added benefit, since thinner steel can be used without loss of rigidity when such welds are employed. Laser welds also offer cost savings because much smaller flanges are needed.

Hydroforming

Hydroforming is another technology that offers the chance to reduce weight, the number of parts, and improve structural integrity. In this process (see Figure 21) tubing is pre-formed by bending, inserted in a die, filled with water, and then formed to fit the die cavity by application of pressure to the water. Complex shapes can be readily produced with this process. The result is fewer parts, less welds, cross section changes that can be achieved without welding pieces together, and superior structural performance. Since, in many cases, there is also a cost saving, the process has been adopted by the automotive industry for engine cradles, rails, cross members and other structural parts.

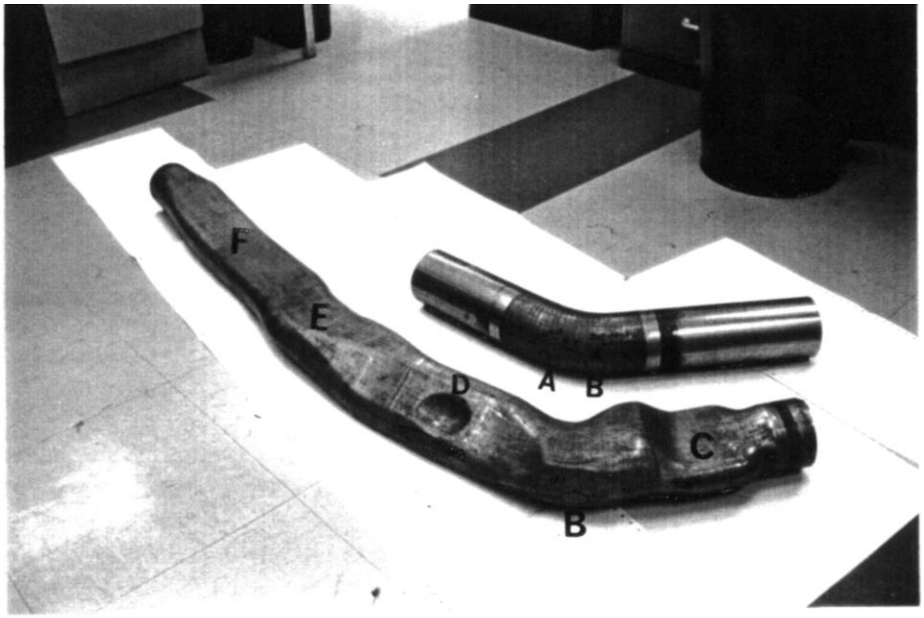


Figure 21: Section of Pre-bent Tube and Hydroformed Engine Cradle

Construction

Prepainted hot-dip galvanized steel is also extensively used in the construction industry. Much of the product is prepainted for appearance and durability. Gradual shifts in the mix of paint types used for external building cladding by the construction industry continue to occur as cost and performance change. North America remains different from the rest of the world because of its extensive use of silicone modified polyesters (SMP). The polyester trend is driven by cost considerations. In addition, vinyl plastisols have excellent barrier characteristics, which make their use valuable for highly corrosive environments, but high cost and sensitivity to high levels of UV, limits application to specialized applications, usually in northern latitudes. The use of fluorocarbon paint systems is more dominant in the U.S. south due to their improved UV stability.

The corrosion resistance of painted galvanized steels is strongly influenced by the chemical and physical stability of the interface between the zinc surface and the organic coating. Zinc phosphate has been found to be very effective as a pretreatment in limiting underfilm corrosion.

Prepainted galvanize for exterior applications is usually made using G90 [Z275] substrate to provide maximum corrosion resistance, especially at cut edges, and is generally temper passed to produce a smooth surface. The spangle-free galvanize made today is easy to temper pass and results in a smooth, even appearance after painting. As a rule, galvanneal is not used to produce prepainted sheet steel. The coating is hard compared to G90 [Z275] and forms an extremely strong bond with factory applied paints. When subsequently formed, e.g., in a roll former, the GA coating, not being able to powder freely, tends to shear and break away from the substrate, taking the paint coating with it.

Appliance

In North America, the use of hot-dip galvanized sheet for home laundry products and other appliances has been constant over the last decade, as shown in Figure 16. Improved corrosion resistance compared with cold rolled sheet is the reason for this, allowing longer lasting appliances and increased use in humid climates. Galvanized steel offers very clear advantages for prepainted parts in that the zinc coating helps to minimize sheared-edge corrosion that are known to occur with cold rolled sheet.

Some manufacturers are using galvanized steel and applying paint to the exterior side only; thus, saving paint costs. Automated paint lines for powder coating of flat blanks are especially viable for this option. Additional paint savings are realized by the ability to apply much more uniform paint thicknesses when painting flat blanks rather than post-painting formed parts.

The presence of zinc coating on the steel means that total reliance on the paint for corrosion resistance is not necessary and reduced paint thicknesses can be tolerated. Prepainting; either coil painting or blank painting of flat panels can achieve these reduced paint thicknesses much more readily.

To accommodate the fabrication of galvanized steel sheet into formed parts using very small radii bends, it has been necessary to modify the tooling used for forming. These changes, when combined with uniform, light zinc coating weights and non-spangled product, are allowing the fabrication of parts with bend radii as tight as zero t, without degradation of the corrosion resistance in the vicinity of the tension bend.

Steel suppliers are also cooperating with the appliance manufacturers during design to ensure that, not only are the best materials chosen in their most economical form, but that fabrication and assembly is thoroughly investigated to minimize problems during production.

Summary

It can readily be seen that galvanized steel sheet is a product that is growing in use in many different market areas, has and continues to undergo improved manufacturing methods, and is offering tightly controlled characteristics in the continuous effort to supply value for customers.

Additional information can be found on the topic of zinc-coated steel sheet at www.galvinfo.com .

References

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