

ZINC COATINGS

PROTECTING STEEL



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Galvanized steel offers a unique combination of high strength, light weight, corrosion resistance, aesthetics, recyclability and low cost that is unmatched by any other material

1. Introduction

For over a century, zinc has enhanced the longevity and performance of steel. Zinc coatings provide the most effective and economical way of protecting steel against corrosion.

Zinc-coated or galvanized steel offers a unique combination of

- high strength
- formability
- light weight
- corrosion resistance
- aesthetics
- recyclability
- low cost

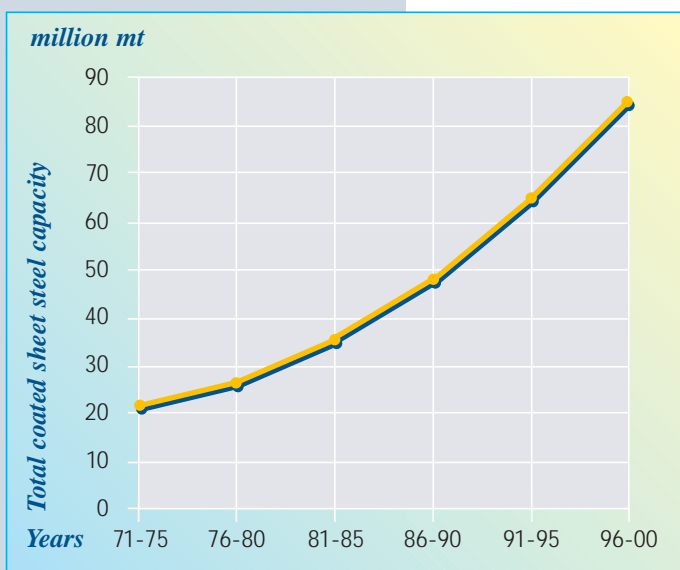
that is unmatched by any other material. For this reason, galvanized steel sheet is an ideal material for a multitude of building and manufacturing applications - from automobiles to household appliances to residential, commercial and industrial construction.

Corrosion is estimated to cost an industrialised country's economy at least 4% of GDP each year. Recognising this fact, together with the known strength, economy and durability of zinc-coated steel sheet, manufacturers and consumers are today demanding a higher content of zinc-protected sheet in durable goods and building products, a trend that has been growing steadily over the last 15 years.

Today there are over 550 continuous galvanizing lines worldwide and additional capacity is planned in response to growing demand.

This brochure describes the continuous galvanizing process, products, coating performance and the environmental characteristics of zinc coatings. Other zinc coatings in addition to continuous galvanizing are also briefly discussed.

Total coated sheet steel capacity 1970 - 2000, in millions of metric tons



Source: Cominco Ltd

"Zinc is an essential element in the environment. The possibility exists for both a deficiency and excess of this metal. For this reason, it is important that regulatory criteria for zinc, while protecting against toxicity, are not set so low as to drive zinc levels into the deficiency area."

**United Nations Programme on Chemical Safety
– Environmental Health Criteria Zinc**

2. Environmental Performance of Zinc Coatings

Zinc-coated steel is an environmentally responsible choice.

New research is shedding light on the role of essential elements such as zinc in the environment. Zinc is an integral part of our environment and exists naturally in rock, soil, air and water. Zinc is also an essential element for all life, from humans and animals to plants and micro-organisms.

Nature makes use of essential elements such as zinc for various biological processes. Organisms take up the zinc they need from their surrounding environment and their development is optimal when cellular requirements for zinc, and other essential elements, are satisfied. When uptake is too low, deficiency occurs and adverse effects may be observed.

When determining the environmental impact of zinc coatings, the local impact as well as the macro, long-term effect should be considered. While small quantities of zinc wash off from coatings exposed to the outdoor environment, this zinc is usually not bioavailable and has little impact on the surrounding ecosystem. On a macro scale, the excellent corrosion protection provided by zinc coatings greatly improves the durability and life cycle of steel products, thus conserving valuable natural resources.

Natural background levels of zinc in the environment

Air (rural)	0.01 - 0.2	µg/m ³
Soil	10 - 300	mg/kg
Parent rocks	2 - 1500	mg/kg
Ore bodies	5 to more than 15 percent	
Open ocean	0.001 - 0.06	µg/l
Coastal seas	0.5 - 1	µg/l
Lowland rivers	5 - 30	µg/l
Mountain rivers	< 10	µg/l
Large lakes	0.09 - 0.3	µg/l
Streams in mineralized areas	> 200	µg/l

Source: Van Assche et al (1996)

Recommended daily zinc intake (U.S. recommended dietary allowance in milligrams per day)

Infants	0 -1 yr.	5
Children	1 - 10 yrs.	10
Men	11 - 51+ yrs.	15
Women	11 - 51+ yrs.	12
Pregnant		15
Lactating	1st 6 months	19
	2nd 6 months	16

Source: NRC (USA, 1989)



The proportion of recycled zinc in new zinc products is more than 30 percent

All types of zinc-coated steel products are recyclable. Both the technology and recycling capacity have been developed in response to environmental awareness and the need for cost-effective, alternative supplies of raw material for the steel and zinc industries. Once steel is galvanized, zinc becomes part of the steel recycling circuit. The Electric Arc Furnace (EAF) is the principal recycling route for zinc-coated steel, producing new steel and zinc that return to the market place.

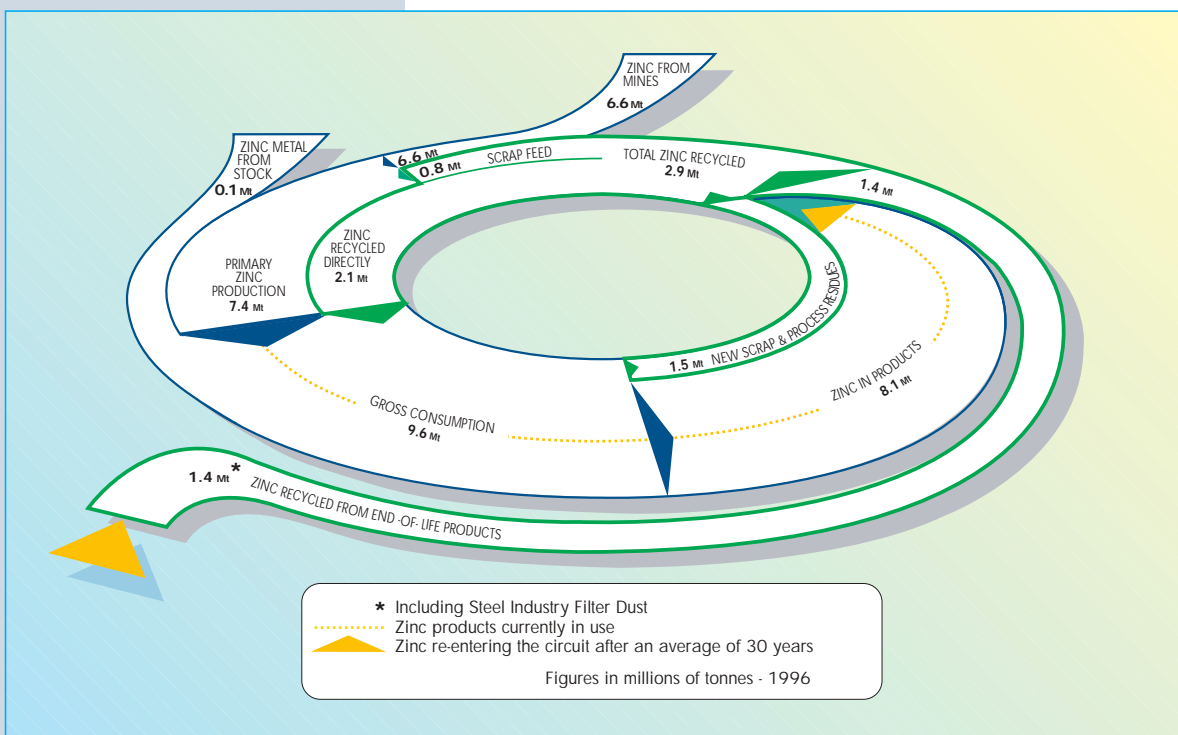
Zinc-containing EAF dust is treated and the zinc recovered in the form of zinc oxide, which is in turn used for producing zinc, which is then re-used for galvanizing. This closed-loop recycling route is widespread today in industrialised countries. New cost-effective treatment technologies continue to be developed with the aim of maximising zinc recovery. Today, 80 percent of the zinc available for recycling is indeed recycled.

Galvanized steel is recycled from three sources:

- scrap arising during the production of galvanized sheet
- scrap generated during product manufacturing and installation
- end-of-life products, whose availability for recycling is a function of product life-span, for example: 12-15 years for cars versus 25-100 years for building products.

The amount of galvanized scrap steel available for recycling has been rising over the last ten years. The majority of galvanized steel sheet, however, is still in the marketplace in the form of cars, appliances and building products although more and more is now becoming available for recycling. Building product applications - the largest market for galvanized steel sheet - remain in service for many years before recycling. It is only recently that some of the lower life-span galvanized products, such as automobiles, have started entering the recycling circuit. Over the next ten years, the supply of zinc-coated steel scrap is expected to increase by more than 50%, with the highest increase coming from the automotive sector.

The zinc recycling circuit



Source: Zinc Recycling - The General Picture. IZA-Europe 1999

Zinc coatings protect steel by providing a physical barrier as well as cathodic protection

The coating weight required depends both on the service life needed and the exposure conditions

3. Technical Performance of Zinc Coatings

There are many factors to consider when selecting the most appropriate zinc coating. In addition to corrosion protection, the coating's formability, adherence, appearance and cost should also be considered. These factors will be discussed to provide guidance on selecting the correct zinc coating for a given application. All zinc coatings, like the steel they protect, are recyclable.

3.1. Corrosion Resistance

When left unprotected, steel will corrode in almost any environment. Zinc coatings protect steel by providing a physical barrier as well as cathodic protection for the underlying steel. It is important that the correct zinc coating is specified to provide optimal performance under the exposure conditions to which the coating will be subjected.

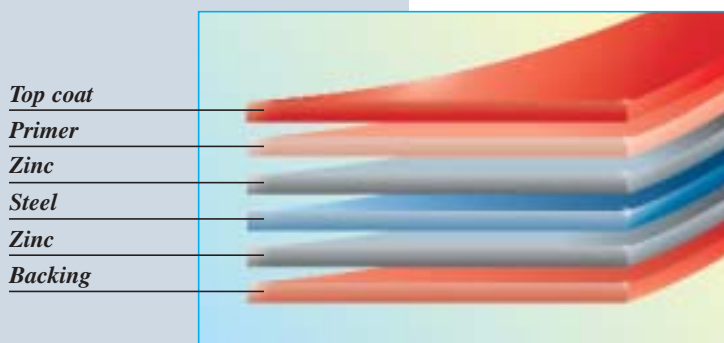
3.1.1. Barrier Protection

Zinc coatings provide a continuous, impervious metallic barrier that does not allow moisture to contact the steel. Without moisture, there is no corrosion, except in certain chemical atmospheres. The effectiveness of zinc coatings in any given environment is directly proportional to coating thickness. Coating life is determined by the coating corrosion rate, itself a function of many factors such as time, composition of the atmosphere and the type of coating.

In situations of outdoor exposure, the acidity level of rain will influence the zinc corrosion rate. With indoor exposure - ventilation ducts, floor decks and steel framing, for example - moisture may also be present. In industrial indoor situations, the atmosphere may be corrosive. Thus the type and weight of coating required depends both on the service life needed and the exposure conditions.

Corrosion resistance of coatings can also be improved by using a zinc alloy coating, such as Galfan® or Galvalume®, or by applying paint top coats. These two methods, individually or together, are recommended for exposed sheet applications where enhanced corrosion protection is required.

Painted galvanized steel



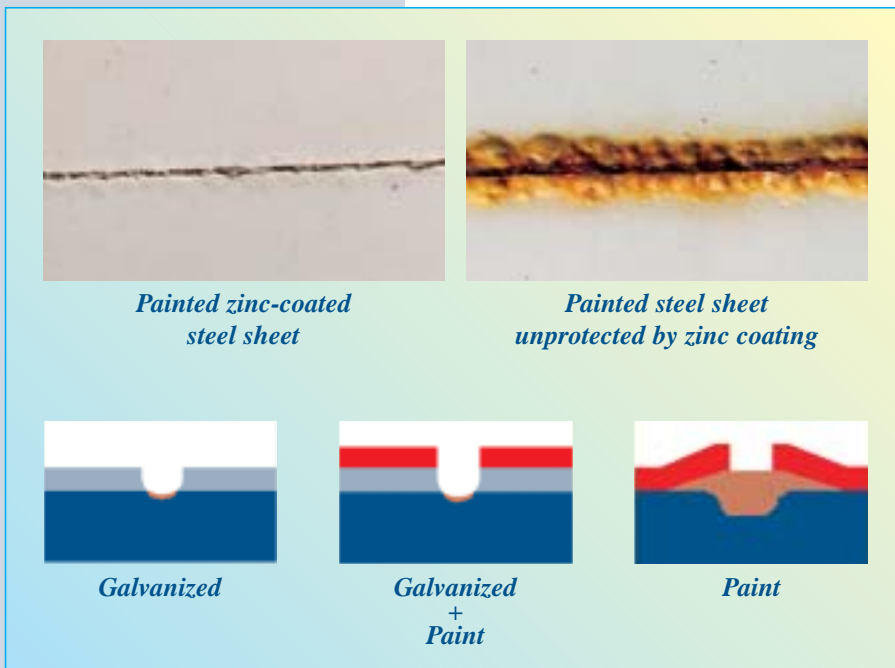
Galvanized steel



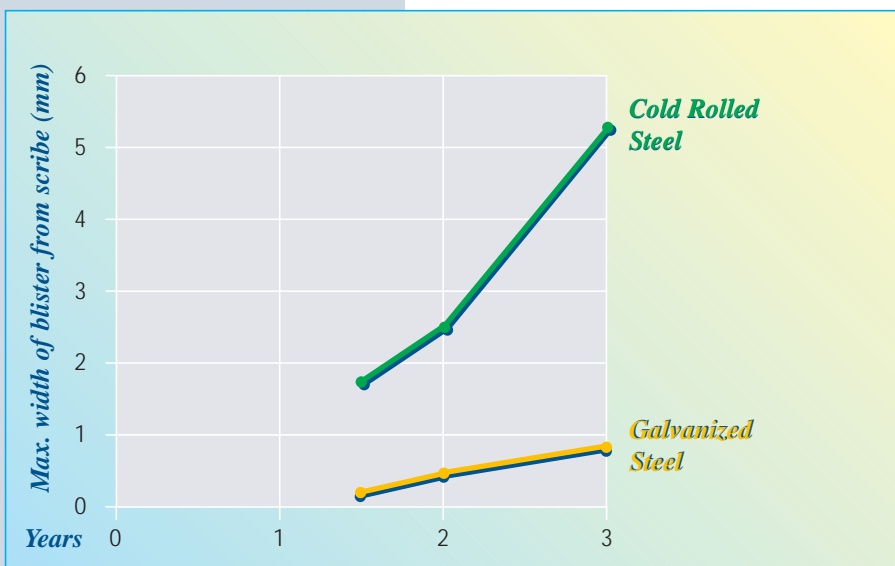
**Zinc coatings
extend the
life of
paint coatings**

3.1.2. Cathodic Protection

Another outstanding protection mechanism is zinc's remarkable ability to galvanically protect steel. When base steel is exposed, such as at a cut edge or scratch, the steel is cathodically protected by the sacrificial corrosion of the zinc coating adjacent to the steel. In practice, this means that a zinc coating is not undercut because the steel cannot corrode adjacent to a zinc coating. This contrasts with paint and aluminum coatings where the corroding steel progressively undercuts the surrounding barrier film. The extent of this cathodic protection is determined by the type of coating, its thickness and that of the underlying steel, as well as by the area of damage.



Cathodic protection.
When painted zinc-coated steel is scratched, zinc protects both the underlying steel from corrosion and the overlying paint coat from lifting.



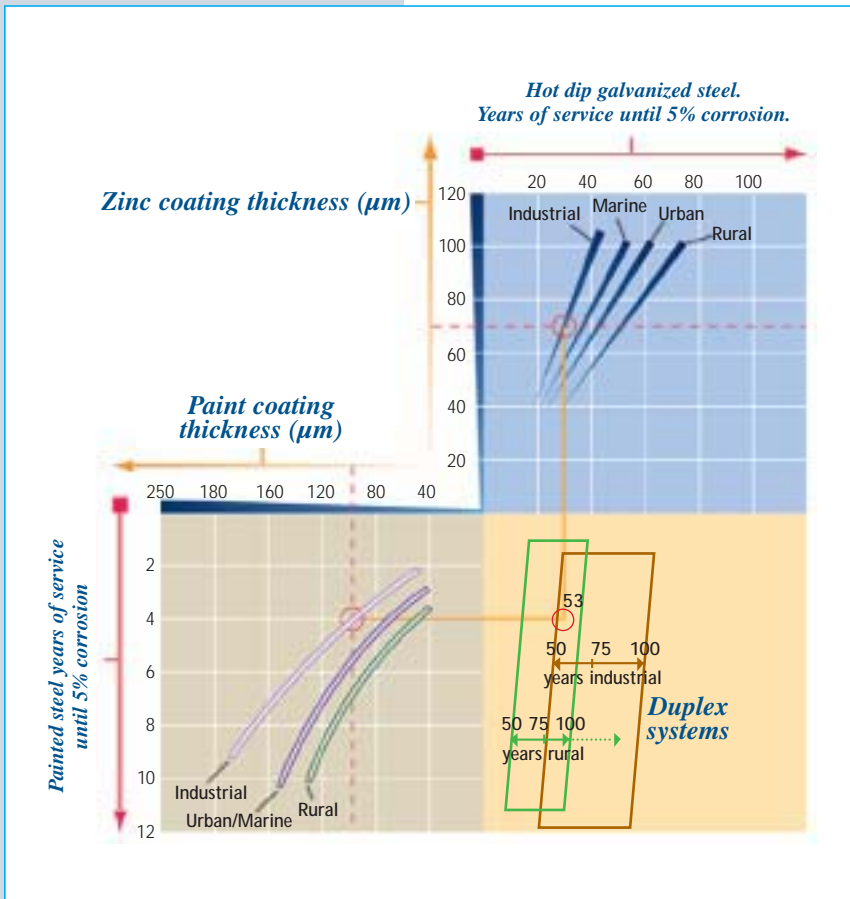
Growth of corrosion of painted cold-rolled and painted galvanized steel sheets used for car body outer panel.

3.1.3. Painted Zinc Coatings

Zinc coatings are easily painted. The term "duplex coating" is used for galvanized and painted steel parts, whereas the term "coil coating" or "pre-painting" is used for continuous galvanized and painted steel sheet. Paint acts as a barrier protecting the underlying zinc coating. Zinc is an excellent substrate for paint coatings because if the paint film is broken, zinc's high corrosion resistance prevents undercutting of the paint film. Even if the coating damage does reach the steel base, zinc's cathodic action will prevent the steel from corroding. Zinc's ability to extend the life of paint coatings is what makes pre-painted galvanized steel sheet such a durable product that continues to extend its market share in commercial and residential roofing and cladding applications.

Combigram of duplex systems.

The zinc and steel industries have for many years conducted both research and field trials on the performance of various combinations of painted and coated sheet steel. The result of this extensive base of information is that existing performance can be predicted for a wide range of atmospheric conditions. In the example shown for a highly corrosive industrial atmosphere, a 70 µm galvanized coating plus a 100 µm layer of paint will provide a coating life of over 50 years. Similar evaluation can be made for other coating combinations and atmospheric conditions.



Source: Stichting Doelmatig Verzinken / Progalva

3.2. Formability and Adhesion

The formability and adhesion of continuous galvanized zinc coatings are excellent and in most cases match the formability of the underlying steel. The formability of galvanized steel - which is defined as the resistance to cracking and loss of adhesion of the zinc coating during forming - is inversely proportional to coating and steel substrate thickness. There are, however, some coatings that are more ductile than others, an important consideration for deep draw stamping applications. It is therefore necessary to balance the requirements for corrosion resistance and formability .

Photo: Cockerill-Sambre



Photo: Cockerill-Sambre



Photo: Cockerill-Sambre



Photo: Sollac

Zinc coatings can differ in appearance depending on customer needs and consumer preferences

3.3. Surface Appearance

Zinc and zinc alloy coatings can differ in appearance depending on customer needs and consumer preferences. Galvanized coating finishes can vary from extra smooth and featureless to a flowery "spangle" pattern. Galvanneal (Zn-Fe) coatings have a matt grey appearance. Electrogalvanized coatings have the smoothest finish among zinc coatings and provide the best substrate for a high quality paint finish.

There are standards covering all aspects of surface appearance - coating finishes, surface qualities (from regular to best quality) and surface treatments (chemical passivation, oiling) - all targeted to enhance further processing.

3.4. Assembly

Assembly refers to the technique of joining galvanized sheet steel products, mainly to themselves. In any application, the joining method should suit the metallic coating and will be determined either on the basis of its performance or the properties and characteristics of the galvanized product.

There are several effective joining methods:

Welding is the most common method of joining steel products. Resistance welding is a technique that uses resistance to the flow of electrical current to generate heat and thereby join two materials. Pre-finished galvanized steel can be spot welded if the zinc coating is not too thick to enable the welding current to pass from one electrode to the other. This technique is often used in the downstream sectors.

Mechanical fixing methods such as screws, rivets, self-piercing rivets and lock forming can be used for a wide range of steel substrate, zinc coatings and applications.

Adhesive bonding has become more popular and can also be allied to mechanical fixing. The range of adhesive systems is wide and the selection depends on numerous variables such as surface condition, adhesion, strength and cure speed.



Photos: Galvazinc Association

4. Continuous Galvanizing

4.1. Products

Starting from high purity zinc, alloying elements can be added to produce galvanized coatings with different properties. These products can be used in a wide variety of applications and climates. The family of continuous galvanized coatings includes galvanized, electrogalvanized, galvanneal, Galvalume® and Galfan® coatings.

Galvanized

A pure zinc coating that is the standard continuous galvanized product typically used in building panels, steel framing, agricultural and automotive applications, as well as in numerous other functions. It has good surface finish and adhesion properties.

Electrogalvanized

Steel sheet with an electroplated zinc coating that has an ultra-smooth surface finish which is desirable for surface critical parts such as automotive exterior body panels. The coating thickness for electrogalvanized sheet is typically lower than for a hot-dip galvanized product. Electrogalvanized coatings generally use pure zinc although alloy coatings (Zn-Fe, Zn-Ni) are also commercialised.

Galvanneal

A zinc-iron alloy coating with improved paintability, weldability and drawability, Galvanneal is used in the automotive industry because of its improved manufacturing performance in models which use lighter and stronger grades of steel.

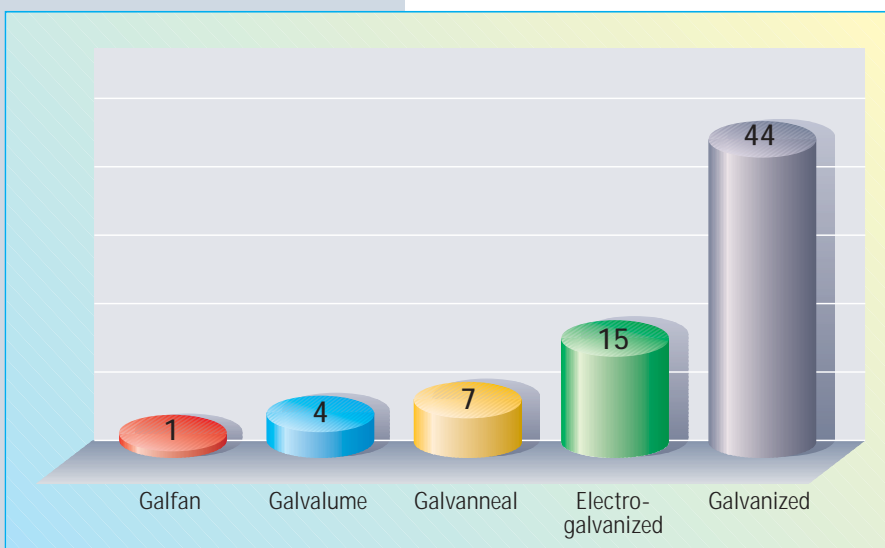
Galvalume®

Galvalume is a zinc-55% aluminum alloy coating with superior corrosion resistance for applications without severe forming. It is widely used for painted and unpainted building panels and roofing and for higher temperature applications in vehicle powertrain and heat-reflective components.

Galfan®

Galfan is a zinc-5% aluminum coating with superior corrosion resistance when formed. It is used for painted building panels and for severely formed components, such as automotive parts and domestic appliances intended for corrosive environments. Galfan coated steel is noted for its outstanding coating adhesion, making it ideal for deep drawn and "zero-thickness" bend applications.

Continuous galvanized zinc coatings and amount of steel coated 1998 (million metric tonnes)



Source: ILZSG / IZA

**Recent advances
in galvanizing
technology and
paint systems
enable new
profiled products
to be made**

4.2. Aesthetics

Galvanized steel sheet can also be painted for improved corrosion protection and aesthetics. The most cost-effective and best quality painting method is continuous coil coating or pre-painting. This allows for exact preparation of the galvanized surface prior to coil coating. Painted galvanized sheet is roll-formed to give profiles specified by the customer. Recent advances in galvanizing technology and paint systems enable pre-painted galvanized sheet to be roll-formed with striking patterns, allowing architects new roofing and cladding possibilities for industrial, commercial and residential buildings. For example, roll forming and stamping are now used to make tile roofing, offering a product with much lower weight and cost than the traditional material.

A wide variety of paint systems are available to meet the performance requirements of a given application. Today's automobiles have a perfect body finish that combines a high degree of aesthetic appeal with high standards of corrosion protection. Roll formed pre-painted sheet for building, cladding and roofing presents three main assets - the aesthetic appearance of sharp profile, long life and favourable economics.

Roll forming of pre-painted sheet gives a lower cost than painting after forming. Domestic appliances combine severe forming with guaranteed corrosion protection to meet the requirements of modern design.



Photo: BHP Steel

Steel sheet suppliers can provide advice on the most appropriate system for individual needs.



Photo: Segal



Photo: BHP Steel



Photo: BHP Steel

4.3. Standards

Around the world, standards such as ISO, ASTM and JIS are available to assist in the specifying and purchase of galvanized steel sheet. The table below lists some of the more popular coating weights available in each product standard. For details of local standards, please refer to your steel supplier.

Range of Commonly Available Coating Weights

Product	Designation	Coating Weight (oz/ft ² /2-sides)	Coating Weight (g/m ² /2-sides)	Thickness (one side-inches)	Thickness (one side-μm)
Galvanized	G40 or Z120	0.40	120	0.0003	8
	G60 or Z180	0.60	180	0.0005	13
	G90 or Z275	0.90	275	0.0008	20
	G200 or Z610	2.00	610	0.0017	43
Electrogalvanized	6G/6G	0.13	40	0.0001	2.5
	20G/20G	0.40	120	0.0003	8
	40G/40G	0.80	245	0.0006	16
Galvanneal	A40 or ZF120	0.40	120	0.0003	8
	A60 or ZF180	0.60	180	0.0005	13
Galvalume®	AZ50 or AZ150	0.50	150	0.0008	20
	AZ60 or AZ180	0.60	180	0.0010	24
Galfan®	GF60 or GF180	0.60	180	0.0005	13
	GF90 or GF255	0.90	255	0.0008	20

**Steel
protected
with zinc
resists decay,
corrosion,
termites,
fire, wind, floods
and earthquakes
better than
any other
construction
material**

4.4. Applications

The major uses of galvanized steel sheet are construction and vehicle and appliance manufacturing. Globally, galvanized sheet is a major constituent in the 50 million vehicles and over 40 million appliances produced each year, as well as in countless commercial and industrial buildings. A growing market is galvanized steel framing and roofing for residential buildings.

Today, there are over 550 continuous galvanizing lines worldwide and additional capacity is planned in response to growing demand.

Zinc-coated steel resists decay, corrosion, termites, fire, wind, floods and earthquakes better than any other construction material. For this reason, it is being used more and more in commercial and residential construction.

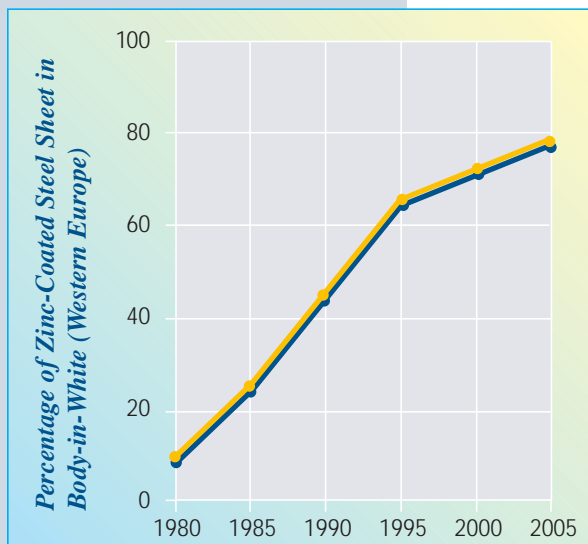
Common uses of coated steel sheet

Coated Product	Applications	Key Attributes
Galvanized	Steel framing Heating, ventilation, AC Corrugated culverts Roof and floor decking Pre-painted building panels Agricultural storage bins Autobody inner panels	Formability and durability Range of coating thickness Strength and speed of installation Paintability Cost effective
Electrogalvanized	Autobody outer panels Computer cases	Surface finish, weldability Electro-magnetic shielding, surface finish
Galvanneal	Autobody outer panels Pre-painted appliance wrappers	Weldability, paintability, formability
Galvalume®	Bare and painted roofing and siding	Corrosion performance for bare coating Paintability
Galfan®	Pre-painted architectural panels Automotive equipment	Corrosion performance Very good formability and paintability

Photo: BHP Steel



The growth in auto industry use of zinc-coated steel sheet



Source: IZA-Europe



Photos:
Galvazine Association





Photos: Cockerill-Sambre, Cominco, Galvazinc Association, Usinor

The existence of cost-effective recycling routes contributes favorably to the global cost of zinc-coated steel products

4.5. Economics

Zinc-coated steel sheet offers a unique combination of strength, durability, formability, recyclability and cost. Recyclability is a key selection criteria for specifiers. The existence of cost-effective recycling routes contributes favorably to the global cost of zinc-coated steel products.

The use of galvanized sheet for automotive body panels allows today's automakers to guarantee up to 12 years' corrosion resistance, while adding only a fraction of a percent to the cost of the vehicle. The cost-benefit ratio represents outstanding value for the consumer. The same applies to building panels - galvanized coil coated products are now available with up to 50 year performance warranties. The improved performance and added value generated by zinc coated steel sheet is vastly superior to the small additional production cost. Durability, aesthetics, longterm stability of surface appearance and low maintenance are all significant advantages for the final user.

In the construction industry, galvanized steel decking combined with high-speed concrete pouring allows faster construction, thereby lowering construction costs.

Commercial and industrial washing machines can operate every day around the clock thanks to galvanized steel sheet casings that resist wear and tear from exposure to soaps, bleaches and chemical solutions.

Galvanized steels can be stamped and formed using existing steel manufacturing equipment, thus avoiding the need for costly new tooling - in this way, galvanized steel contributes to manufacturing economies.

Thicker coatings are more expensive than thinner coatings and zinc alloy coatings are more expensive than galvanized coatings. In both cases, however, these premium products give higher performance. The extra cost involved is small when compared to improvements in performance. Choices are best made by matching coating performance to application needs.

Galvanized steel is a value-added product that allows the use of steel sheet in applications where uncoated steel could not be used. Zinc coatings help expand the markets for steel.



Continuous galvanized steel is made under precise, factory-controlled processes

4.6. The Process

Globally, some 70 million tonnes of galvanized steel are produced each year in continuous galvanizing lines.

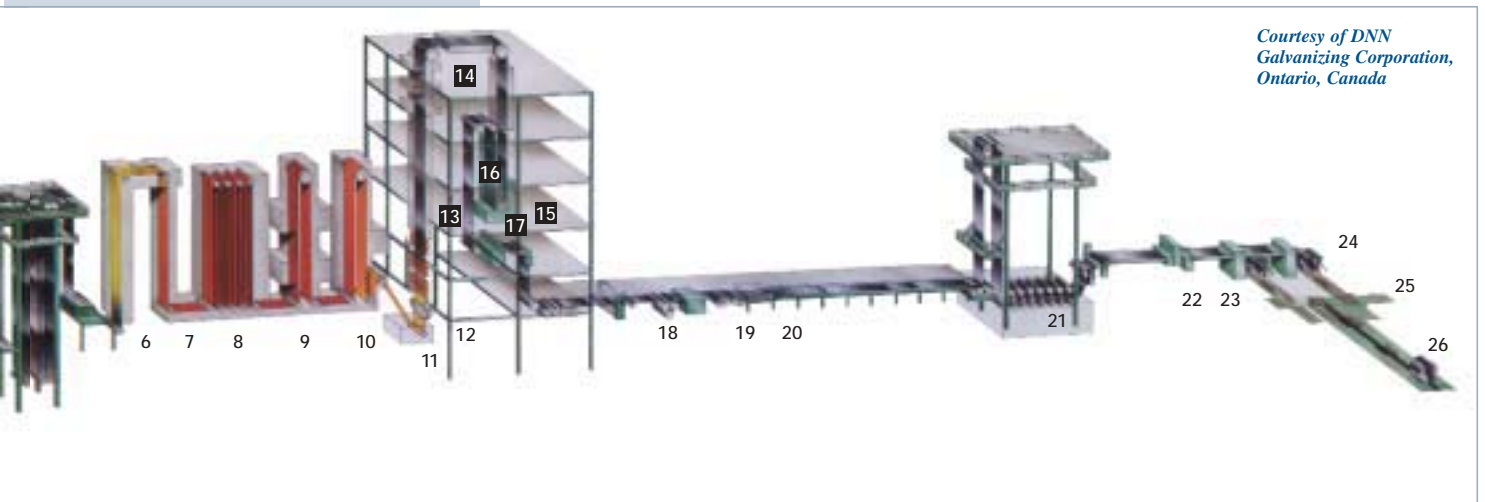
Continuous galvanized steel is made under precise, factory-controlled conditions during which flat rolled steel coils are upgraded to high-quality, zinc-coated steel using high-speed continuous lines that control not only the coating quality but also the strength and formability of the steel product. Zinc is applied either by dipping in molten zinc or by electroplating.

In the continuous hot-dip galvanizing process, coils of rolled steel are continuously unwound and fed through cleaning and annealing sections before entering a molten zinc bath at speeds up to 200 metres per minute (650 feet/minute). As the steel exits the molten zinc bath, gas "knives" wipe off the excess coating from the steel sheet to control coating thickness. The steel strip then undergoes a series of mechanical or chemical treatments. Depending on customer requirements, the coated sheet steel can be passivated, oiled and recoiled, and cut to length and palletized before shipment to the fabricator. All galvanized coatings are metallurgically bonded to the steel they protect. This ensures coating adhesion - critical for manufacturing processes that stamp, roll or draw the steel into its final product shape.

Electrogalvanized coatings are produced by electroplating zinc or zinc alloys onto steel in a continuous process. The major use of electrogalvanized coatings is autobody outer panels, although other automotive structural components such as inner panels, doors, housings and appliances are also produced from this material.



Photo: Cockerill-Sambre



Continuous Hot Dip Galvanizing Line

Key

- | | |
|---------------------------|----------------------------------|
| 1. Entry Gauge | 14. Tower Roll Clean |
| 2. Double Cut Shear | 15. Quench Tank |
| 3. Welder | 16. Water Cooling Dryer |
| 4. Cleaning | 17. Coating Weight Gauge |
| 5. Entry Looping Tower | 18. Temper Rolling |
| 6. Preheat Furnace | 19. Tension Leveller |
| 7. Direct Fired Furnace | 20. Skinpass Mill Dryer |
| 8. Radiant Tube Furnace | 21. Delivery Looping Tower |
| 9. Gas Jet Cooling | 22. Electrostatic Oiler |
| 10. Controlled Cooling | 23. Flying Shear |
| 11. Zinc Pot | 24. Tension Reel |
| 12. Air/Nitrogen Wiping | 25. Coil Cars |
| 13. Galvannealing Furnace | 26. Scale and Automatic Shipping |

Every year, some 10 million tonnes of steel products are protected by the general galvanizing process

5. Other Zinc Coatings

5.1. General Galvanizing

General Galvanizing, also known as Hot Dip Galvanizing, After-Fabrication Galvanizing or Batch Galvanizing, refers to the galvanizing of fabricated or manufactured steel items. The fabricated steel article is cleaned and then dipped into a molten zinc bath, either on racks for small items or individually for large items.

Zinc coatings from this process are five to ten times thicker than continuously galvanized coatings and can offer long term outdoor protection in most environments. This resistance can vary from 20 years in an industrial site to over 65 years in a rural environment.

General galvanizing provides fabricated steel items with excellent protection against corrosion. The nature of the immersion process provides good edge protection and complete coverage of the outer surface area as well as inner protection of hollow parts. In general, a zinc coating of at least $60-70\mu\text{m}$ is applied. Every year, worldwide, more than 10 million tonnes of steel products are protected against corrosion by the general galvanizing process.



Photo: Stichting Doelmatig Verzinken



Photo: Galvazinc Association



Photo: Progalva

5.2. Particulate Applied Zinc Coatings

Zinc can also be applied to steel by zinc metallizing, or by adding zinc dust to paint systems.

5.2.1. Metallizing

Zinc metallizing, or thermal spraying, is a process by which zinc wire, or powder, is fed into a spray gun, melted and sprayed onto a work piece. Melting is accomplished either by combustion in an oxygen-fuel gas flame, or by an electric arc that is created between two zinc wires. The resulting metallic coating is slightly porous with a lamella or layered structure. Metallized coatings can be applied at high thickness (100–200 μm) which makes them ideal for long-term corrosion protection.

5.2.2. Mechanical Plating

This process is used primarily for small (<0.5kg) threaded work or other close tolerance items. The parts to be plated are tumbled together with zinc powder and glass beads in water. The tumbling action causes the glass beads to hammer the zinc onto the part. This process eliminates the possibility of hydrogen embrittlement of high strength fasteners. Coating thickness is controlled by time and quantity of zinc powder added.

5.2.3. Sherardizing

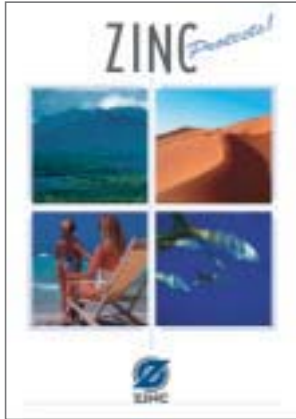
Sherardizing is a diffusion controlled process which produces a zinc iron alloy coating. Small fabricated articles are charged in a drum with zinc powder and sand. The drum is rotated at a temperature below the melting point of zinc, typically 380°C, for up to 3 hours. Uniform, hard, abrasion resistant coatings can be formed on complex parts.

5.2.4. Zinc-Rich Paint

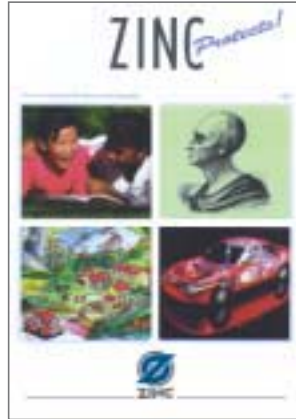
Zinc-rich paint typically contains over 77% zinc in the dry film and benefits from the barrier and cathodic protection provided by zinc. Zinc-rich paints are classified as organic, or inorganic, depending on the binder used. They can be applied by brush or spray and must always be applied over a properly prepared steel substrate.

Publications on Zinc from IZA

To order, please email IZA (email@iza.com) or fax: +32.2.7760089.
 For more information about zinc and zinc coatings, visit
www.zincworld.org



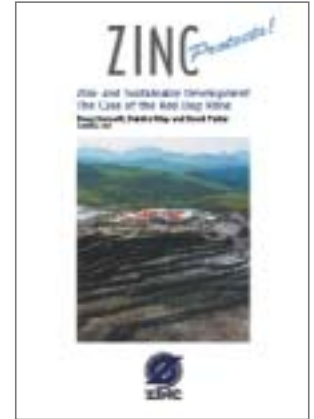
Zinc - The IZA Annual Magazine 1997



Zinc - The IZA Annual Magazine 1998



The Role of Zinc in Child Health



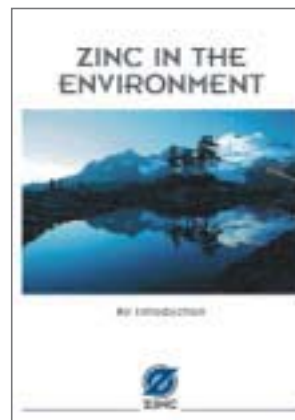
Zinc and Sustainable Development - The Red Dog Mine



Zinc Recycling - The General Picture
 (English, French, German, Spanish)



Zinc Recycling - Zinc Coated Steel
 (English, French, German, Spanish, Italian)



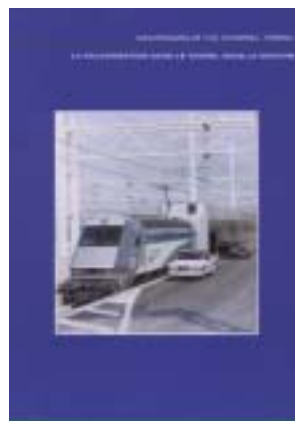
Zinc in the Environment - An Introduction
 (Also available in French, German and Spanish)



Zinc and Sustainable Development



Zinc in Public Infrastructure - Applications for the 21st Century
 (Also available in Spanish)



Galvanizing in the Channel Tunnel
 (English - French)



Pocket Guide to World of Zinc
 (New edition in 2000)

International Zinc Association (IZA)

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- . communicating zinc's value to society
- . promoting the use of zinc
- . developing, through research and communication, a fuller understanding of zinc's role in the environment.

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