

The Basics of Corrosion



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Introduction



Prepainted steel and aluminium sheets are used for a wide variety of applications in the construction, domestic appliance, general engineering and transportation industries. The durability, high-quality surface finish, formability, and relatively low cost are the major reasons for the widespread use of these prepainted metals. However, one of the disadvantages of all metals is that they are prone to corrosion which can cause aesthetic defects and the gradual deterioration of mechanical properties. Coating the metal with an appropriate paint system will prevent corrosion and so preserve the appearance and physical properties of the product.

Corrosion resistance is essential for the long-term performance of building cladding and for other applications of prepainted metals. The selection of the correct corrosion protection technology for prepainted metal products is crucial to avoid premature in-service failure. The successful development of corrosion resistant products is demonstrated by the extended performance guarantees (up to 40 years) that are available for prepainted metals construction applications. This long-term durability performance is achieved by using chrome-free pretreatment and primer technologies; the use of hazardous chromium-containing chemicals has been largely eliminated from the industry. Ongoing R&D within the industry ensures that the prepainted products will meet future market and regulatory requirements.

The main aims of this publication are:

- to describe the mechanisms of the corrosion reactions that occur at metallic surfaces.
- to explain the most common forms of corrosion for prepainted metals.
- to present the technologies that are used to prevent the corrosion of prepainted metals.

Corrosion

Nature of corrosion

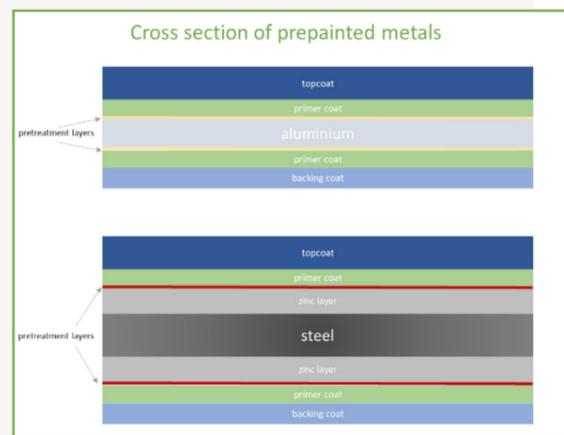


What is corrosion?

The corrosion of a material leads to a gradual deterioration of its properties until it fails to fulfil its original purpose and needs to be replaced. Corrosion also causes aesthetic problems and can lead to significant costs of reparation and replacement. In order to successfully prevent corrosion, it is important to understand the fundamental mechanisms of corrosion and how they can be prevented.

Metals usually exist as oxides in their natural form e.g. bauxite (aluminium), magnetite (iron); extensive processing is, therefore, required to convert the metal oxides to pure metals. The corrosion of a material can, therefore, be simply defined as a driving force that returns the metal to its natural, lowest energy state.

If not protected properly, any metal will oxidise resulting in rust formation. One of the most effective ways to protect metals from corrosion is to apply an organic coating onto its surface. Pre-painted metals contain a multi-layer system of pretreatment, primer and topcoat to prevent corrosion and to meet the market requirements for long-term durability and appearance. For indoor applications, one coat systems may be used; for more demanding construction applications, 3 and 4 coat systems are available.



Electrochemical nature of corrosion

Corrosion of any metal is an electrochemical reaction between the metal and its surroundings. A corrosion reaction involves the flow of electrons and ions between two metallic electrodes – the anode and cathode. There are four necessary elements needed to form a corrosion cell: an anode, a cathode, an electrolyte, and a return path. The electrolyte is normally an aqueous solution, such as rain water, and the return path is a metallic pathway connecting the anode and cathode to each other which facilitates the electron transfer between the two electrodes.

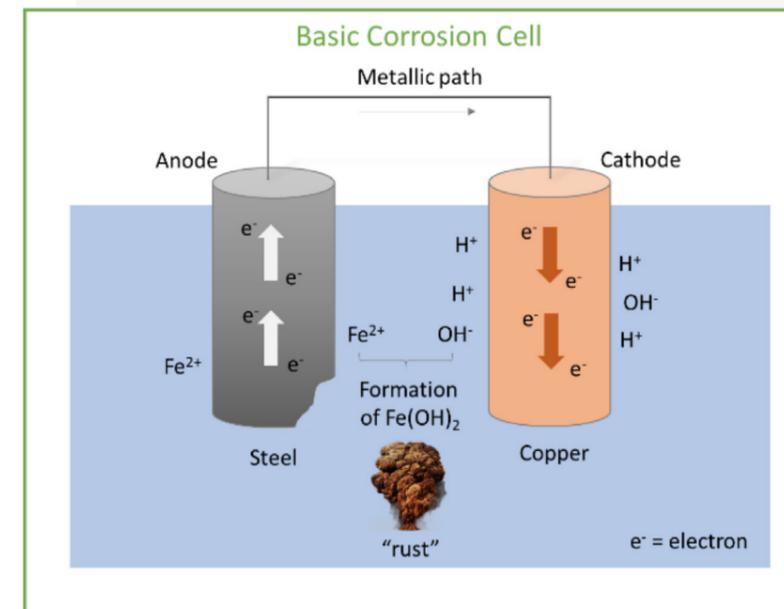
The anode is the part of the metal where the oxidation reaction and corrosion take place. In an oxidation reaction, electrons are freed from the anode into the metallic pathway and are consumed at the cathode in a reduction reaction. In the case of iron, the result of this reaction is commonly called rust.

The electrochemical potential difference between the anode and cathode drives the electrons towards the cathode creating the corrosion current. The electrolyte is needed for the transfer of the metallic ions that are released in the corrosion reaction.

The oxidation reaction at the anode and reduction reaction at the cathode always occur together.

The corrosion reaction is a closed loop and for the corrosion cell to work, all the four elements need to be present. If one of them is eliminated, the corrosion reaction is inhibited. For example, pre-painted steel is not likely to corrode in a completely dry environment because there is no water to function as an electrolyte. The metal will also remain intact if either the anodic or the cathodic reaction is prohibited as the overall corrosion reaction is prevented.

Pre-painted aluminium will not corrode in most environments nor under exposure to a wide variety of chemical agents. This is because the metal, although very reactive with a high affinity for oxygen, is protected by a natural and/or converted oxide layer which is inert. Atmospheric moisture and rain water are not able to migrate through the protective coating film, as long as it remains intact.



Galvanic corrosion

As explained earlier, when two dissimilar metals are in contact and immersed in an electrolyte, a potential difference usually exists between them and an electrolytic (or corrosion) cell is formed. The metal that is less corrosion resistant becomes anodic and starts to corrode for the benefit of the more corrosion resistant metal. This type of corrosion is called galvanic corrosion. The corrosion resistance of metals can be explained by the Galvanic series of metals and alloys. The more electronegative a material, the more prone it is to corrosion. The order of some metals in the Galvanic series is shown in the table below. Metals are listed from the most active (most electronegative) metals down to the most inert ones.

Galvanised steel

Galvanised steel is the classic example of a metallic system where galvanic corrosion is utilised for the benefit and protection of the product. Galvanised steel consists of a steel substrate coated with a layer of metallic zinc or zinc alloy. Zinc is less resistant to corrosion (more electronegative) than steel and will sacrificially corrode for the benefit of the steel substrate. The steel will remain intact as long as the zinc coating is present; once it is consumed, the steel itself will start to corrode. It should be noted, that when zinc is coupled to steel it will corrode faster than it would without the connection to steel.

The rate and speed of the galvanic corrosion of steel is dependent on the atmospheric conditions surrounding the paint-metal system. In coastal and highly industrialised areas, atmospheric moisture contains dissolved salts which makes it more conductive and, therefore, more corrosive. The rate of galvanic corrosion is also dependent on the surface area of the two metals in contact. A small anode next to a large cathode will increase the corrosion rate whereas a large anode in contact with a small cathode will have the reverse effect.

Galvanic corrosion is usually observed at the cut edges of prepainted steel where the bare steel is exposed to the environment. The corrosion protection of the cut edge can be increased by increasing the thickness of the zinc coating as this extends the period of sacrificial protection by the zinc.

Tin-plated steel is an example of the unfavourable effects of galvanic corrosion. Tin is electropositive compared to steel, meaning that any defect in the tin coating will eventually lead to the sacrificial corrosion of the steel substrate under the tin coating.

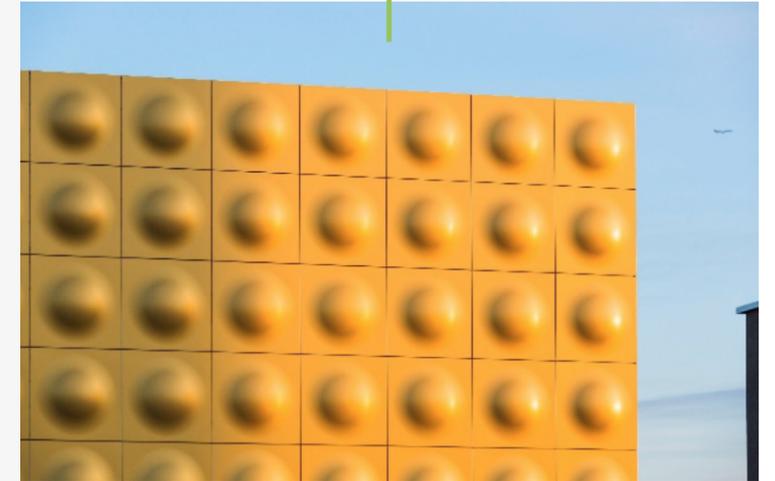
Arrangement of metals in the Galvanic series



Any one of these metals and their alloys will theoretically corrode whilst offering protection to any other metal below it in the series (provided they are electrically protected).

Zinc is the most effective metal in terms of galvanic protection. It is widely used for the protection steel substrates; it is usually deposited onto the surface via dipping or electroplating.

Galvanic corrosion



Aluminum

Aluminium is widely used in the construction market because it has a very long service life if used correctly. This is despite the fact that in most combinations with other metals, aluminium is the least noble metal. Therefore, aluminium presents in theory a higher risk of galvanic corrosion.

Galvanic corrosion of aluminium occurs only outdoors, or in environments with high chloride levels such as areas bordering the sea. In a salty, wet atmosphere the humidity is acting as the electrolyte. Galvanic corrosion of aluminium does not occur in dry indoor atmospheres.

Galvanic corrosion between aluminium and more noble metals (e.g. stainless steel, copper) should also be avoided by using proper insulation to avoid direct metal-metal contact.

For better understanding of material compatibility, the 'Anodic Index' is a good guide to follow:

- Harsh environments, such as outdoors, high humidity, and salt environments: typically recommended anodic index difference should not be more than 0.15 V
- Normal environments, such as warehouses, humidity-controlled environments, requires a typical difference of max. 0.25 V in the anodic index.
- Controlled (temperature and humidity) environments can tolerate a difference of 0.50 V in the anodic index.

Galvanic corrosion

Environmental classification for prepainted metals

The rate of corrosion reaction of any metal is highly dependent on the environment in which it is placed. The environments where prepainted metals are used are classified according to the reduction of mass (or thickness) of certain metals and metal alloys when present in that atmosphere. The classification according to the standards EN ISO 12944-2:2017 is shown in the table below. Note that another corrosion class of higher corrosiveness exists, as mentioned in ISO 9223: 2012. It is called CX (Extreme) but is not relevant for European locations.

Corrosion class according to the EN ISO 12944-2:2017.	ALUMINIUM Mass reduction (g/m ² /yr)	STEEL Mass reduction (g/m ² /yr)	STEEL Thickness reduction (µm/yr)	ZINC Mass reduction (g/m ² /yr)	ZINC Thickness reduction (µm/yr)
C1	negligible	≤10	≤1.3	≤0.7	≤0.1
C2	≤0.6	>10 to 200	>1.3 to 25	>0.7 to 5	>0.1 to 0.7
C3	>0.6 to 2	>200 to 400	>25 to 50	>5 to 15	>0.7 to 2.1
C4	>2 to 5	>400 to 650	>50 to 80	>15 to 30	>2.1 to 4.2
C5-I and C5-M	>5	>650 to 1500	>80 to 200	>30 to 60	>4.2 to 8.4

Environment classification

Industrial atmosphere C3-C5

- High pollution
- Long wet time
- High humidity
- Corrosion rate of zinc often > 1.5 µm/year



Marine atmosphere C3-C5

- High content of salt in the atmosphere
- Corrosion speed varies with temperature, wet time, and relative humidity
- Corrosion rate of zinc often > 4.0 µm/year

Country atmosphere C3-C5

- Hardly any pollution
- Low contents of salts in the atmosphere
- Low wet time
- Corrosion rate of zinc often < 0.4 µm/year



Corrosion of prepainted metal

Edge corrosion

Edge corrosion is one example of galvanic corrosion. It occurs at the cut edge of galvanised steel where the cross section of the paint coated metal is exposed to the environment. In the cross section, the surface area of zinc is significantly smaller than that of the steel substrate. The zinc layer provides sacrificial protection for the bare steel but once this protection is exhausted, the corrosion reaction starts. The corrosion protection can be increased by increasing the thickness of the zinc coating or by using a zinc alloy coating (see later). Selection of the appropriate pretreatment/primer technology is essential in protecting the product from cut edge corrosion. An effective, but expensive, way to prevent edge corrosion is to cover the cut edge e.g. by applying a paint layer after cutting.



Edge corrosion

Edge corrosion

Corrosion products on the cut-edge of a prepainted hot-dip zinc-coated steel product following accelerated corrosion testing in the laboratory.

Cut edge corrosion is generally not a significant issue for prepainted aluminium, due to the inert oxide layer which is generated immediately after the cutting process.



Cross section of cut-edge on prepainted steel

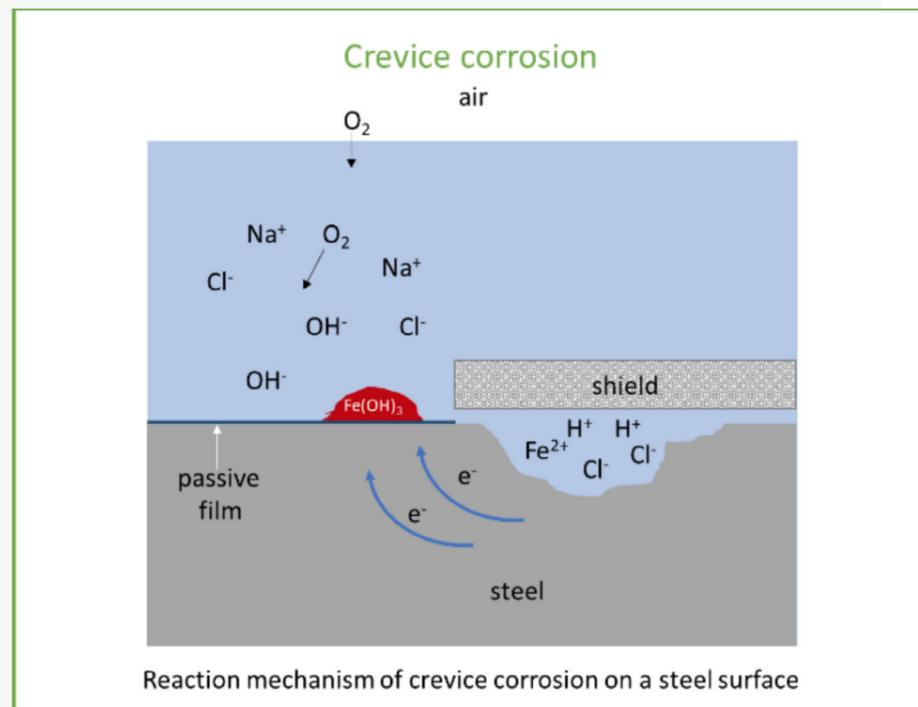


Zinc (more anodic than the steel) sacrificially corrodes to protect the steel substrate. Electrons (e^-) flow from the zinc to the steel. Once the zinc in the vicinity of the cut-edge is depleted, the steel starts to corrode and produces red rust.

Crevice corrosion

Crevice corrosion

Intensive, localized corrosion that often occurs within the shielded areas on a painted surface is called crevice corrosion. Crevice corrosion can be caused by surface defects, holes, or deposits of dirt allowing a stagnant solution to be formed on the surface. The hole of the defect on the surface must, therefore, be wide enough to allow the liquid to enter, but small enough to assure a stagnant solution.



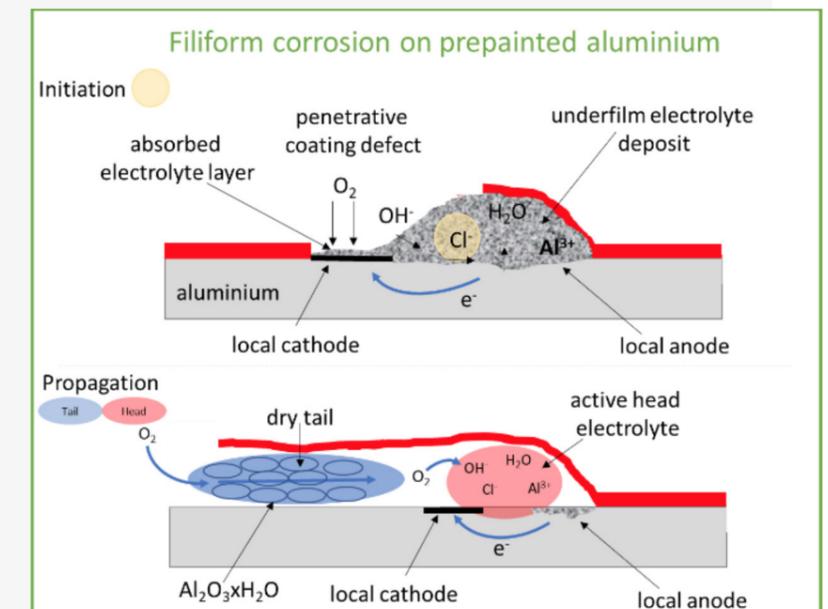
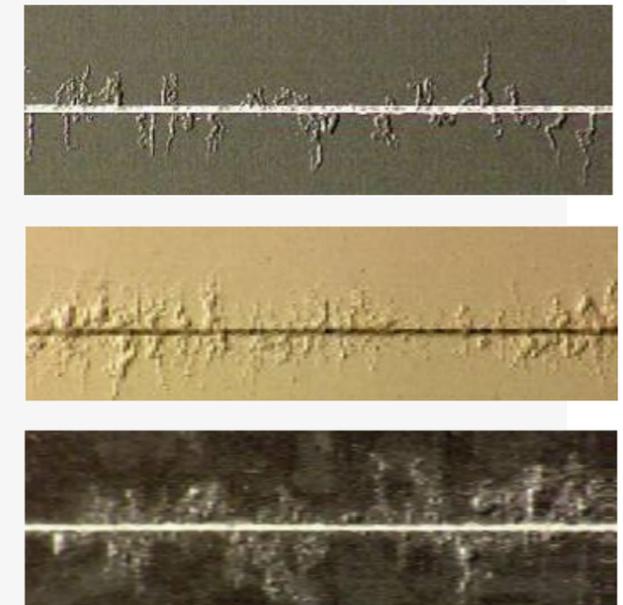
Filiform corrosion

Filiform corrosion

Filiform corrosion occurs under the protective paint film and can be seen as thin filaments randomly distributed on the surface. Filiform corrosion is mainly an aesthetic effect and does not usually weaken the material or significantly reduce its functionality. The filaments start from an edge or a defect in the surface coating. They have an active head and a corrosion product tail; the corrosion occurs only in the active head of the filaments, never in the inactive tails. The filaments tend to move in straight lines and do not cross each other.

The relative humidity of the atmosphere is the single most important factor for initiating filiform corrosion. The most favourable humidity for filiform corrosion is 65-90%. The type of the coating on the surface is less important and thus filiform corrosion can be seen even under metallic coatings. Coatings with very low moisture permeability inhibit filiform corrosion.

Filiform corrosion is most often seen on aluminium substrates, zinc-coated steel is less prone to this type of corrosion defect.



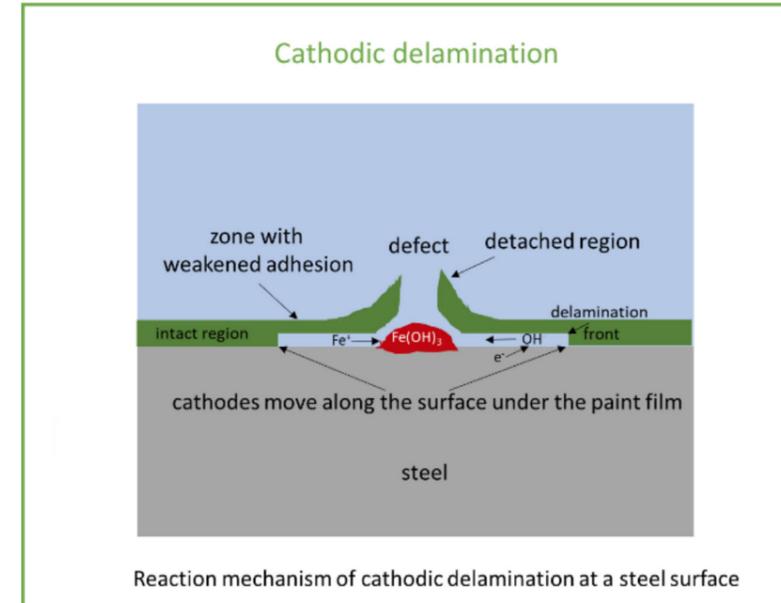
Paint blistering

Paint blistering

One of the main purposes of a paint film is to function as a barrier between the metallic substrate and the environment. However, no paint film is perfect; paints are semipermeable materials which allow some water and air to pass through. There may also be small holes and imperfections that allow water and impurities to reach the surface of the metal substrate. This can lead to the formation of corrosion cells on the metallic surface and to blisters on the painted surface.

Paint blistering starts with a defect, such as salt residues, metal oxides, scratches or solvents on the metallic surface at the interface of the metal and coating. Due to the permeability of the paint film an osmotic pressure drives water through the paint film to the paint-substrate interface. Eventually the amount of moisture in the interface reaches the point where it breaks the adhesive bonds between the metal and the paint. The paint starts to lift from the surface to form the blisters. Quite often the centre of the blister becomes an anode and starts to corrode. The resulting corrosion products can eventually break through the paint film and become even more visible on the paint surface.

Blistering will also occur at cut edges and scribes (cuts) through the surface. In both cases, the bare metal is exposed to the atmosphere and galvanic corrosion will start under the paint film once the sacrificial protection of the zinc is exhausted.



Cathodic delamination

Cathodic delamination can be observed in both uncoated and galvanised steel. This form of paint failure also starts by surface defects and is driven by the cathodic reactions of an electrolytic cell. The defect area on the metal surface becomes the anode and the cathodic reactions take place at the edge of the delaminated area, where the corrosion reaction is advancing. Due to the semi-permeability of the paint film, water and oxygen are transmitted to the metallic surface to function as the electrolyte. Electrons are freed in the anodic reaction in the centre of the defect and transfer through the metal to the advancing interface.

Anodic delamination

Anodic delamination is a common paint failure when aluminium is used as the substrate. The main mechanism is similar to cathodic delamination and usually starts on a defect on the metallic surface. The advancing interface in this reaction is, however, the anode, and the protecting oxide layer on the aluminium surface is consumed in this reaction.

Delamination

Corrosion protection for prepainted metal

Aluminium

It is commonly believed that aluminium doesn't corrode like other metals. In fact, it does, but in the case of aluminium, an oxide layer forms a uniform and dense barrier between the metal and the environment resulting in very good corrosion protection. This oxide layer is usually 2-20nm thick and repairs itself rapidly if the bare metal is damaged. In most environments the aluminium oxide layer is stable and protects the metal from further corrosion. However, even aluminium can corrode if the conditions are unfavourable, or if it is not maintained properly. The oxide layer cannot protect the metal in very acid (pH < 4) or very alkaline (pH > 9) environments. Impurities, such as other metal particles or halide ions, on the surface can also lead to corrosion.

Steel

Steel oxidises rapidly in most environments forming an oxide layer ("rust") on the surface of the metal. However, the oxide layer on steel is not as stable as the aluminium oxide layer and does not protect the metal from corrosion. Protection of the steel surface is essential in coil coating and is usually achieved by applying a coating of zinc or zinc alloy onto the surface. These metallic coatings protect the steel substrate in two ways: by acting as a physical barrier which prevents impurities and water from reaching the steel surface and by providing galvanic protection (see above: Galvanic corrosion).

Metallic coatings

Zinc

Hot-dip galvanised (HDG) steel is the predominant substrate type for prepainted steel. The zinc coating is applied on a galvanising line by dipping the steel strip into a hot bath of molten zinc after which the thickness of the zinc layer is adjusted by air knives which wipe the excess zinc off the surface. The zinc layer is usually applied at 275 g/m² (both sides) which gives a zinc coating thickness of approximately 20µm on each side. The zinc layer may vary from 100 g/m² up to 350 g/m² depending the application and the in-service environment; the more zinc, the longer the corrosion protection.

Pure zinc will corrode in preference to the steel substrate and reacts with oxygen to form zinc oxide and then with carbon dioxide to form zinc carbonate. The zinc carbonate forms a dense, fairly strong layer on the surface thus protecting the steel substrate from corrosion.

Zinc/Aluminium/Magnesium (ZM)

Zinc magnesium coated steel sheets (ZM) were first introduced in Europe in 2007 and, with a growing market share, have become an important substrate especially for the architectural market. ZM coatings consist of a zinc alloy with 1.5 to 8% by mass of magnesium and aluminium with a minimum content of magnesium of 0.2% by mass. Compared to conventional zinc coatings, the corrosion resistance of ZM coatings in high chloride environments is enhanced which permits a reduction of coating thickness in the product. This helps to conserve resources and protect the environment. The typical weight of ZM coatings is 120 -140 g/m².

Galfan

Galfan is a patented zinc-aluminium alloy coating. It contains nearly 5% aluminium and specific quantities of some rare metals which give an improved corrosion protection of the steel substrate compared to a pure zinc layer, especially at the cut edges.

Precleaning and Pretreatment

In order to ensure good adhesion of the primer coat and enhanced corrosion protection in the prepainted metal product, the metallic substrate is cleaned and pretreated with a carefully formulated chemical system prior to application of the paint coating layers. The metallic surface is thoroughly cleaned of rolling oil, impurities and metal oxides to provide the optimum surface for application of the pretreatment layer (or conversion coating). The role of the pretreatment layer is to ensure satisfactory adhesion of the applied coatings and to provide corrosion protection even if the paint layer gets damaged.

Cleaning the surface (degreasing) and pretreatment are distinct processes and both are required to ensure the proper corrosion protection and paint adhesion to the substrate.

There are many different types of conversion coatings that are used in the coil coating industry. They are typically zirconium or titanium-based systems; these have been developed to replace the traditional chromate systems which are now regulated under REACH legislation. These chromate-free systems are more environmentally friendly and offer equivalent or better performance than the chromate systems.

Primers

The primer coat in a prepainted metal product is to provide adhesion for the topcoat to the metallic substrate. The primer is formulated to be compatible with the pretreatment coating applied on the metallic surface. It must also be compatible with the topcoat technology.

The primer also plays a key role in optimising the corrosion resistance of the product. The primer formulation will contain suitable anti-corrosion pigments that provide a barrier to moisture ingress and some form of chemical protection at the cut edge or areas of surface damage. The pigments can migrate through the coating to the exposed edge where they can inhibit the main corrosion reaction.

Primer formulations in the coil coating industry are now chromate-free; a wide range of inorganic pigments and compounds are used in the different coatings.

Corrosion testing

Before any product can be supplied to the market its properties must be thoroughly evaluated. The most reliable way to test the corrosion protection of a product is to expose it in a similar environment to its intended purpose for the duration of its expected lifetime. For this purpose, there are outdoor exposure sites in Europe where prepainted products can be tested in environments classified according to EN ISO 12944-2:2017 (C1- C5). However, most external testing usually requires at least one year's exposure before any results can be seen. For longer-lasting products, four year's weathering data is now required before any final decision can be made on performance guarantees. Therefore, a range of accelerated corrosion tests are under development to help predict the prepainted product's durability in its in-service environment.

The primary requirement for any accelerated corrosion test is that the results correlate with the performance of the product in outdoor conditions. The salt spray test is widely used in the coil coating industry as an initial screening test for prepainted products. The test panels are exposed to a continuous salt spray solution for a defined length of time, usually 1000h. The amount of corrosion on the surface of the panel is evaluated after the test and this gives an indication of the corrosion resistance of the product. The widespread use of this test, despite its poor correlation to field test results, is because it has been used for a very long time and many product specifications demand a certain level of performance in the salt spray test.

The main criticism of the salt spray test is that the test panels are exposed to a continuous salt spray solution without any dry time in between. This is hardly ever the case in real outdoor conditions, and it has been shown that the dry periods are vital for the corrosion preventive actions to take place in the substrate/paint system. For example, the protective oxide/carbonate layer of a galvanised coating cannot form if the surface is constantly wet; it needs a dry cycle to become effective.

In order to improve the correlation of the accelerated corrosion tests to real outdoor conditions, different

cyclic tests are being developed. The aim of these new tests is to better replicate the corrosion mechanisms that occur during the external weathering of a building. ECCA is currently developing, in conjunction with the French Corrosion Institute, new cyclic tests for both prepainted steel and aluminium. These new tests will help the industry to further develop its product offering and to maintain compliance with the product standards defined in EN 1396: 2015 for prepainted aluminium, and EN10169: 2012 for prepainted steel.

ECCA methods

ECCA has developed a comprehensive a series of Test Methods, a very helpful tool for those wanting to test and use prepainted metal. These methods are defined within EN 13523, a European standard with over 25 parts. The test methods that are of particular relevance to corrosion testing are as follows:

ECCA methods

EN 13523-8 (2017)	Coil Coated metals - Test Methods - Part 8: RESISTANCE TO SALT SPRAY (fog)
EN 13523-9 (2014)	Coil Coated metals – Test Methods – Part 9: RESISTANCE TO WATER IMMERSION <i>This part of EN 13523 describes the procedure for determining the resistance to water immersion of an organic coating on a metallic substrate</i>
EN 13523-10 (2017)	Coil Coated metals – Test Methods – Part 10: RESISTANCE TO FLUORESCENT UV LIGHT AND WATER CONDENSATION. <i>This part of EN 13523 describes the basic principles and procedure for determining the resistance of an organic coating on a metallic substrate (coil coating) to a combination of fluorescent UV light, and water condensation and temperature under controlled conditions.</i>
EN13523-19 (2011)	Coil Coated metals – Test Methods – Part 19: ECCA RECOMMENDATION FOR PANEL DESIGN AND METHOD FOR ATMOSPHERIC EXPOSURE TESTING. <i>This part of EN 13523 covers all aspects of panel design, panel preparation, exposure orientation and a possible rack design which would be suitable for outdoor exposure and testing of coil coated material and simulate building application.</i>
EN 13523-21 (2017)	Coil Coated metals – Test Methods – Part 21: EVALUATION OF OUTDOOR EXPOSED PANELS <i>This part of EN 13523 specifies the procedure for evaluating the behaviour of an organic coating on a metallic substrate during and after outdoor exposure.</i>
EN 13523-23 (2015)	Coil Coated metals – Test Methods – Part 23: COLOUR STABILITY IN HUMID ATMOSPHERES CONTAINING SULPHUR DIOXIDE <i>This part of EN 13523 defines terms of the procedure for determining the colour stability of an organic coating (coil coated) on a metallic substrate when exposed to humid atmospheres containing sulphur dioxide.</i>
EN13523-25 (2014)	Coil Coated metals – Test Methods – Part 25: RESISTANCE TO HUMIDITY <i>This part of EN 13523 specifies a procedure for evaluating the humidity resistance of an organic coating (coil coated) on a metallic substrate, by means of exposure in a humidity cabinet under controlled conditions.</i>
EN13523-26 (2014)	Coil Coated metals – Test Methods – Part 26: RESISTANCE TO CONDENSATION OF WATER <i>This part of EN 13523 describes a procedure for evaluating the condensation resistance of coil coated materials. Changes of the coating film such as blistering, colour and gloss differences can be evaluated.</i>

The full list of test methods can be found on www.prepaintedmetal.eu



Ecca objectives

- Increasing the awareness of prepainted metal through targeted marketing programmes
- Promoting the benefits of prepainted metal through the provision of innovative solutions and with particular emphasis on environmental, cost, quality and design benefits
- Stimulating market, application, product and process development
- Setting quality performance standards and developing test methods
- Granting of Quality and Sustainability Labels for prepainted metal on the basis of the technical and sustainability requirements defined in the ECCA Premium® Label manual and based on independent third party control
- Creating an industry network and forum for the development and exchange of ideas
- Representation of the Industry in its contacts with Public Officials, Public Authorities, other Trade Associations and Professional Bodies.

**Source : Akzo Nobel Hilden GmbH*