CORROSION HANDBOOK

06/2021

FOREWORD

Corrosion is a ubiquitous natural process. Most of us, at some point in our everyday lives, become familiar with the effect that corrosion has on rusted steel parts. Corrosion has a huge economic impact. About a fifth of the world's annual steel production simply goes towards replacing parts damaged by corrosion. Even though it may involve higher up-front cost, correct and efficient corrosion protection at source helps save money and resources in the long run. For fastening systems, it's even more critical because safety is key. Failure due to corrosion may have dramatic consequences.

The goal of this handbook is to raise your general awareness of what corrosion is all about. It provides you with essential information on corrosion and the behavior of the materials used to protect our products from it.

Hilti conducts comprehensive laboratory and field-based tests to assess the corrosion resistance of its products. Some long-term tests started in the 1980s and are still running today. Thanks to in-house research and close collaboration with renowned universities and laboratories, Hilti is in a position to help offer the right solutions with the most suitable corrosion protection for a wide variety of environmental conditions.

Nevertheless, the choice of the material or the corrosion protection method for a specific application remains the responsibility of the user. Your local Hilti contact will be pleased to provide further assistance. He or she will also be able to obtain support at any time from the specialists in our Corporate Research & Technology department, allowing you to take advantage of the wealth of in-depth know-how we have available.

CONTENTS

1   BASICS OF CORROSION

1.1   What is corrosion?

Corrosion is the physicochemical interaction between a metal and its environment, which results in changes in the metal's properties and may lead to significant functional impairment of the metal, the environment, or the technical system of which they form a part (see ISO 8044:2010).

We only talk about corrosion when there is a change in the metal's or system's properties that may lead to an undesirable outcome. This can range from simple cosmetic damage to complete failure of technical systems potentially causing great economic damage and even present a hazard to people.

The commonly used metals in construction and engineering like steel, aluminum and zinc have a tendency to return to its original state as found in nature. For this reason, corrosion can be regarded as metal-winning in reverse. Fig. 1 shows how this looks like when iron is extracted from iron ore.
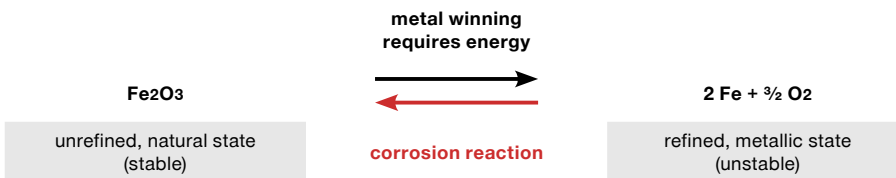

	metal winning requires energy	
Fe_2O_3		**$2\ Fe + \frac{3}{2}\ O_2$**
unrefined, natural state (stable)	**corrosion reaction**	refined, metallic state (unstable)

Fig 1: Chemical reactions of iron during corrosion and the metal-winning process.

Types of corrosion reactions
By far the most common type of the corrosion reaction is electrochemical in nature. Such reactions imply a transfer of electrons from the metal via an environment that can conduct ions, such as a water film on its surface.
In rarer cases corrosion reactions can also be purely chemical, as the reaction of a metal surface with hot gases or liquid salts.
The overall electrochemical corrosion reaction can be separated into two partial reactions:
- Metal dissolution, also known as oxidation or anodic reaction
  $Fe \rightarrow Fe^{2+} + 2\ e^-$
- Reduction or cathodic reaction
  In neutral environment and with a sufficient supply of oxygen the cathodic reaction is as follows:
  $O_2 + 2\ H_2O + 4\ e^- \rightarrow 4\ OH^-$

This is the most important cathodic reaction we must consider when corroding our parts in common environmental conditions (also called atmospheric corrosion).
In acidic environment and with the lack of oxygen following reaction may occur:
$2H^+ + 2e^- \rightarrow H_2$

Even if this reaction, as a partial reaction of corrosion, occurs much less frequently in atmospheric environments compared to the oxygen reduction, it must nevertheless be taken into account, since the formation of hydrogen here can lead to embrittlement of the metals concerned (see chapter on forms of corrosion).

These two partial reactions can take place on the metal surface in a fairly even distribution leading to uniform attack (see section 1.2.1). Alternatively, they can occur locally and separately, leading to localized forms of corrosion such as pitting corrosion.

The mechanism and the electrochemical nature of the corrosion reaction define the necessary requirements for atmospheric corrosion to take place:
- a conducting metal
- an electrolyte (a thin, even invisible moisture film on the surface is already sufficient)
- oxygen for the cathodic reaction
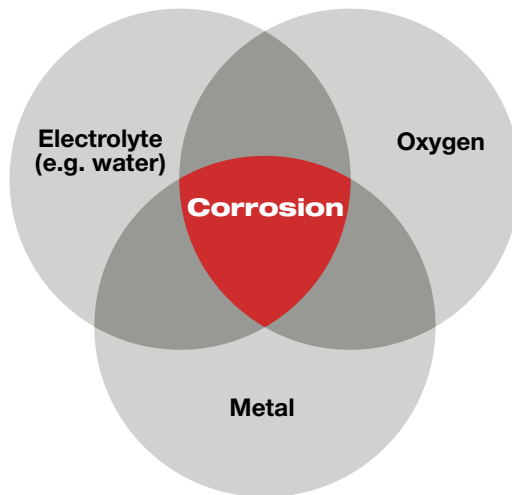
Fig. 2: Requirements for an atmospheric corrosion reaction.

The illustration in Fig. 2 shows the basic corrosion mechanism of iron under a drop of water. Both metal dissolution and oxygen reduction reactions take place with slight separation on the surface, while their products (Fe-ions and OH-ions) react in the water drop to form iron oxide (red rust).

In general, the same scheme applies to other metals such as zinc or aluminum, but with slightly different chemical reactions in the electrolyte.

With the simple model of the corrosion reaction, as seen in Fig. 3, we are able to explain many forms of corrosion and also to put measures in place to help mitigate it. By mitigating these partial reactions, the overall corrosion rate is also reduced.

Fig. 3: Corrosion of iron under a drop of water, showing metal dissolution, oxygen reduction and the formation of rust.

1.2   Forms of corrosion
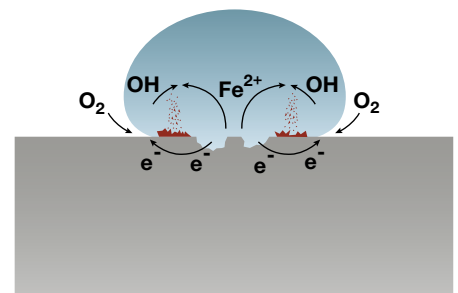
1.2.1 Uniform corrosion / shallow pitting corrosion

Uniform corrosion removes a metal's surface almost evenly.
The partial reactions (metal dissolution and oxygen reduction) are statistically distributed over the surface, leading to a largely homogenous dissolution of the metal and uniform formation of corrosion products (e.g. red rust on steel).
The extent of this form of corrosion can usually be well estimated on the basis of previous experience. The rate of corrosion is usually given in micrometers per year (μm/a). Using these average values, it is possible to estimate the life expectancy of a component, and thus to enhance its life expectancy by increasing its thickness. Unprotected carbon steel and zinc-coated steel are materials, which typically show uniform or shallow pitting corrosion in outdoor environments.

In reality, truly homogenous corrosion attack is unlikely to take place. There are always areas, especially on complex metal parts, which will corrode faster than others – leading to a more or less rough surface with an irregular covering of corrosion products (see Fig. 4).
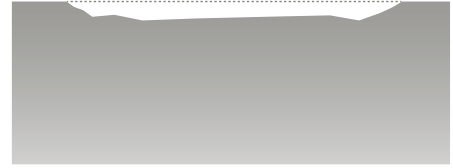
Fig. 4: Corrosion of steel components.

1.2.2 Pitting corrosion

Pitting corrosion is a localized form of corrosion that leads to the creation of small holes or "pits" in the metal (see Fig. 5). This form of corrosion is mainly found on passive metals. Passive metals and alloys, such as aluminum, titanium and stainless steel owe their corrosion resistance to a thin oxide layer of only a few nanometers on their surface. The corrosion process starts with a local break-down of the passive layer. Local corrosive attack can be initiated on stainless steels, for example, by chloride ions.

Fig. 6 shows the most significant phases of this corrosion phenomenon on stainless steel. Pitting corrosion can be quite problematic. Whereas uniform corrosion can be seen clearly on the surface, pitting corrosion often appears only as small pinholes. The amount of material removed below the pinholes is generally unknown as hidden cavities may form, making this type of corrosion more difficult to detect and predict. Technically, there is no reasonable way to control pitting corrosion so it must be excluded from the outset via design considerations and use of the right materials, engineering and quality control.

In addition, pitting corrosion can often be the starting point for more severe forms of corrosion such as stress corrosion cracking (see section "Stress corrosion cracking (SCC)" on page 10).

Fig. 5: Example of pitting corrosion on a stainless steel product.

a. Stainless steel with passivated surface.

b. Local breakdown of passivation due to attack of chloride ion.

c. Start of corrosion on the active (not passive) part of the surface.

$Fe \rightarrow Fe^{2+} + 2\ e^-$

d. Anodic dissolution of iron in the pit, oxygen reduction takes place outside.
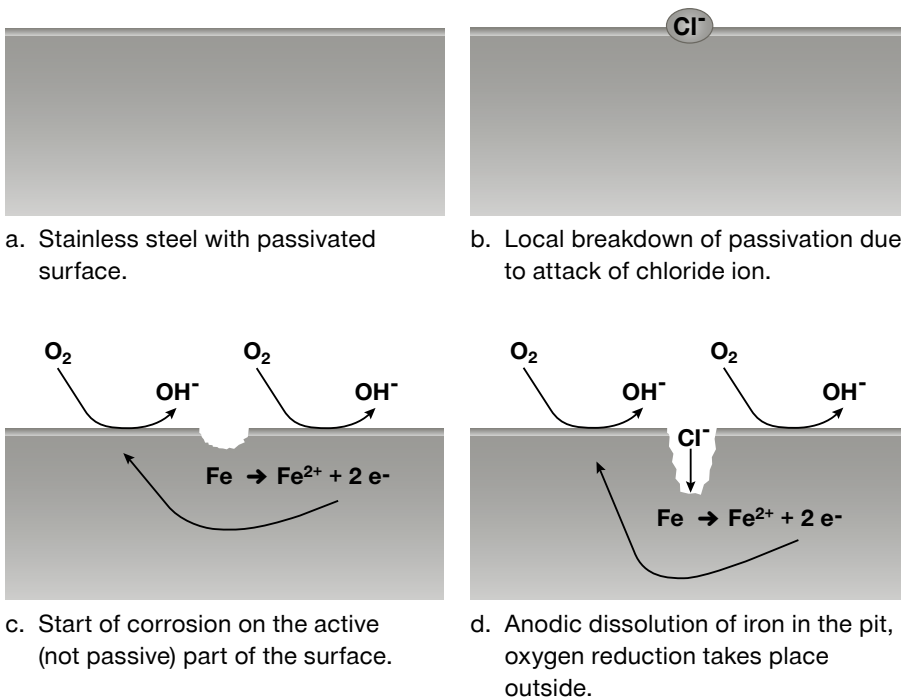
$Fe \rightarrow Fe^{2+} + 2\ e^-$

Fig. 6: Phases of pitting corrosion on stainless steel.

1.2.3 Crevice corrosion

Crevice corrosion refers to corrosion occurring in cracks or crevices formed between two surfaces (made from the same metal, different metals or even a metal and a non-metal). This type of corrosion is initiated by the restricted entrance of oxygen from the air. The access of oxygen into the crevice area is hindered, whereby the cathodic partial reaction (see 1.1) preferably takes place only outside the crevice. The crevice area itself becomes the anode, and thus the preferred region for metal dissolution. (see Fig. 7).

It may also occur under washers or gaskets, when the entry of water underneath is not prevented (see Fig. 7).

There are lower and upper limits to the size of a crevice in which corrosion may be induced. If the crevice is too tight, no electrolyte for corrosion will be introduced. If the crevice is too wide to reduce oxygen entrance, the aeration cell and consequently different concentrations of oxygen cannot develop. However, the critical crevice width depends on several factors such as the type of metals involved, the corroding environment and the wet/dry cycles.
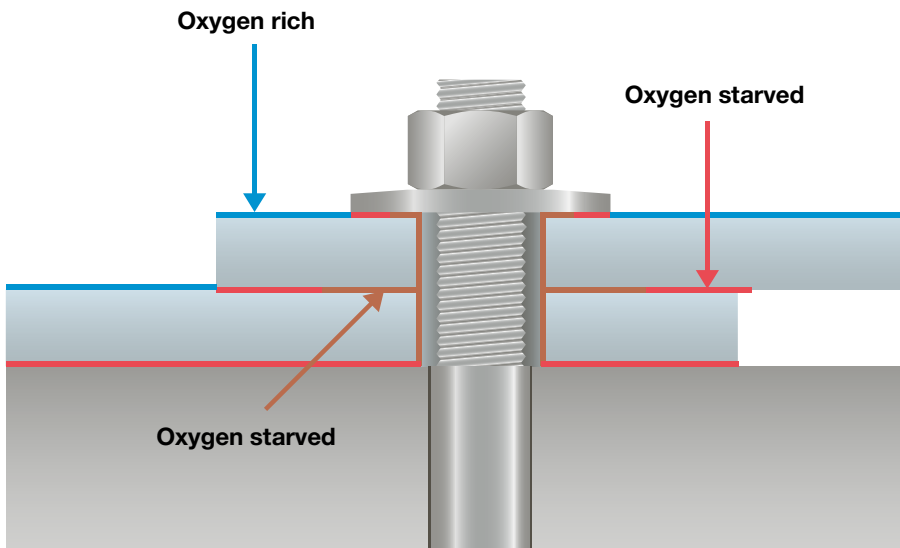
Fig. 7: Possible areas for crevice corrosion in a fastening structure.

1.2.4 Environmentally induced cracking

Stress corrosion cracking (SCC)

Stress corrosion cracking (SCC) is a combined mechanical and electrochemical corrosion process that results in cracking of certain materials. It can lead to unexpected sudden brittle failure of normally ductile metals subjected to stress levels well below their yield strength. The stress in a material can be either applied (external) or residual (internal) and sufficient to initiate an attack of stress corrosion cracking.

Stress corrosion cracking is not simply an overlapping of corrosion and mechanical stresses. Instead, it is an autocatalytic, self-accelerating process leading to high metal dissolution rates (anodic reaction). Initially, a small pit is formed and develops into a crack due to applied or residual stress in the material. The crack formation opens up a new active (non-passive) metal surface, which again will corrode very easily. This leads to further crack propagation and once more to the exposure of new highly active metal surfaces in the crack. Metal dissolution in the crack will advance rapidly until mechanical failure occurs.

SCC is a highly specific form of corrosion that occurs only when the following three different requirements are fulfilled at the same time (see Fig. 9)
• Material (e.g. generally alloyed metals)
• Stresses (applied or residual)
• Corrosive Environment

Fig. 8: SCC of a bracket made of the material 1.4301 (A2, 304) after approx. 4 years of use in an indoor swimming pool.
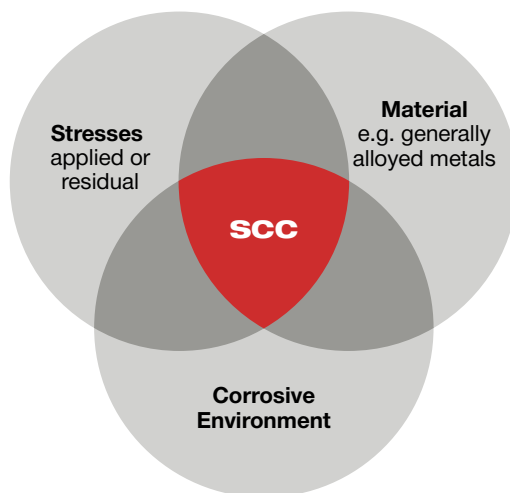
Fig. 9: Factors required for the occurrence of stress corrosion cracking.

It is well known that certain grades of austenitic stainless steel can suffer stress corrosion cracking in harsh environments such as indoor swimming pools. In most of these cases, corrosion is initiated by chlorides attacking the passive layer.
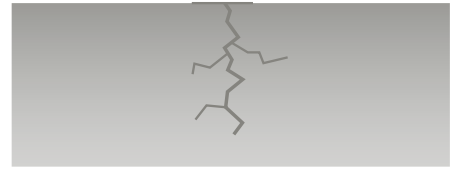
Hydrogen-assisted cracking

Hydrogen-assisted cracking is caused by the diffusion of hydrogen atoms into the metal. The presence of hydrogen in the lattice weakens the mechanical integrity of the metal and leads to crack growth and brittle fracture at stress levels below the yield strength. Like stress corrosion cracking, it can lead to sudden failure of metal parts without any detectable warning signs.
In common applications, hydrogen damage is usually only relevant for high-strength hardened steels.

As with SCC, three different conditions must be present at the same time (see Fig. 10)
• Material (e.g. high strength, hardened steels)
• Stresses (applied or residual)
• Hydrogen source
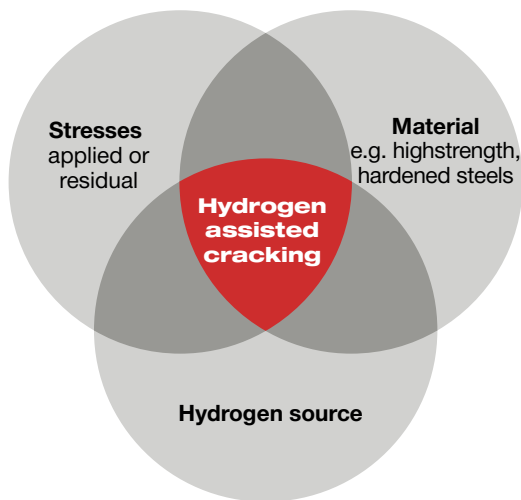
Fig. 10: Factors required for the occurrence of hydrogen-assisted cracking.

The source of hydrogen can be a production process such as steel making, pickling and electrogalvanizing (primary hydrogen-assisted cracking). A secondary source can be the hydrogen formed during a corrosion process occuring in-use, which then diffuses into the material (secondary hydrogen-assisted cracking). During the corrosion process, hydrogen is formed and diffuses into the material. This hydrogen intake leads to a decrease in the toughness or ductility of a metal.

1.2.5 Intercrystalline (intergranular) corrosion

Intercrystalline corrosion is a special form of localized corrosion, where the corrosive attack takes place in a relatively narrow path, preferentially along the grain boundaries in the metal structure. The most common effect of this form of corrosion is a rapid mechanical disintegration of the material (loss of ductility). Usually it can be prevented by using the right material and production process.

A well-known example relevant to the construction industry is the sensitization of stainless steel. When certain grades of this material are kept within a temperature range of 500 °C to 800 °C for a considerable time, such as during a welding process, chromium-rich carbides are formed, resulting in chromium depletion at the grain boundaries. Consequently, the grain boundaries possess a lower degree of corrosion resistance than the residual material, leading to localized corrosive attack (see Fig. 11).

Fig. 11: Scanning electron micrograph image of a selective attack Welded zone of a 1.4401, (A4, 316) material.

1.2.6 Galvanic (contact) corrosion

Galvanic corrosion refers to damage caused by two dissimilar metals having an electrically conducting connection while being in contact with a common corrosive electrolyte (e.g.: humidity in the air). In the electrochemical model of corrosion, one of the two partial reactions (anodic metal dissolution and cathodic oxygen reduction) takes place almost exclusively on one metal.

Generally, the less noble metal will be dissolved (anodic metal dissolution), whereas the more noble part is not attacked by corrosion (it serves only as the cathode for oxygen reduction). Where galvanic corrosion takes place, the rate of corrosion of the less noble metal is higher than it would be in a free corroding environment without contact to another metal.

Using thermodynamic data and taking into account common experience gained in typical applications, it is possible to predict which material combinations will be affected by galvanic corrosion (see 3.3). A positive application of the galvanic corrosion phenomenon is the way in which zinc or zinc alloys such as Zinc Magnesium (here on referred to as ZM) protect carbon steels and low-alloyed steels. Zinc or zinc alloys such as ZM are the less noble metals which actively protect steel by being corroded themselves (see Fig. 12).
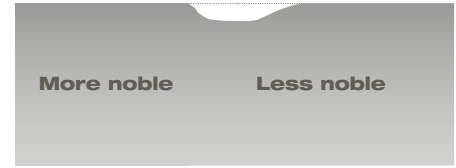
More noble   **Less noble**

Fig. 12: This is a typical case of contact corrosion. A zinc-plated carbon steel (washer) and stainless steel (screw and part) were used together. The surface area of the more noble metal – the stainless steel – is larger, causing strong corrosion of the washer.

2 HILTI CORROSION PERFORMANCE ASSESSMENT AND PRODUCT QUALIFICATION METHODS

Hilti conducts comprehensive laboratory and field corrosion tests to assess the corrosion protection of its products. Thanks to in-house research Hilti has a wide variety of tested corrosion protection solutions for different environmental conditions.

Many methods for testing corrosion resistance are specific to particular materials and are based on conditions prevailing in certain environments. A large number of factors affect corrosion behavior. Hence there is not a unique and universal corrosion test covering all aspects of materials in use. The most reliable indicator of corrosion behavior is service history, but this information is not always available exactly as needed. Corrosion protection of our fasteners is also tested by installing the items on steel or in concrete to simulate potential damage during the installation process.

Corrosion tests can be a suitable method for assessing new products and to compare them with known corrosion protection systems. However, such tests alone are not sufficient to qualify a product for a certain application as the corrosivity of the environment can differ greatly from one project to another. In the end, it is the responsibility of the user to choose the right corrosion protection based on detailed

information about the application, long-term experience and fundamental knowledge of the subject.

2.1 Purpose of corrosion testing

Accelerated corrosion lab tests are state-of-the-art when it comes to evaluating the performance of materials. This is because they represent standardized and reproducible conditions and allow an assessment to be made after a short period of testing (days to weeks). One major use of this type of test is in the quality control of corrosion protection coatings. In order to pass quality control, products must meet the required performance standards (e.g. two days without showing red rust). Moreover, these types of tests are very useful in product development activities, where screening and classifying new coatings and materials for new products is crucial.

2.2 Lab facilities/tests

At our in-house research facilities, Hilti performs the most relevant lab corrosion tests available for our products (see Fig. 13).

Neutral salt spray test: EN ISO 9227, ASTM B117
The salt spray test is one of the oldest and most widely used accelerated corrosion tests. The samples are exposed permanently to a saline fog made from a five percent sodium chloride solution. The salt spray test is not directly representative of corrosion protection in real atmospheres because of the high chloride concentration and lack of dry periods. However, it is a practical test primarily used for process qualification and quality acceptance. Hilti uses the salt spray test to check the homogeneity of zinc coatings on fasteners as quality control in production (see Fig. 15 and Fig. 14).
Zn alloy coatings like ZM and ZnNi coatings show a significantly better performance in the neutral salt spray test.

Fig. 13: Picture from our corrosion lab with various corrosion testing chambers.

Fig. 14: Electrogalvanized screws with around 5 µm zinc coating after 48 h (up) and 96 h (down) in the salt spray test.
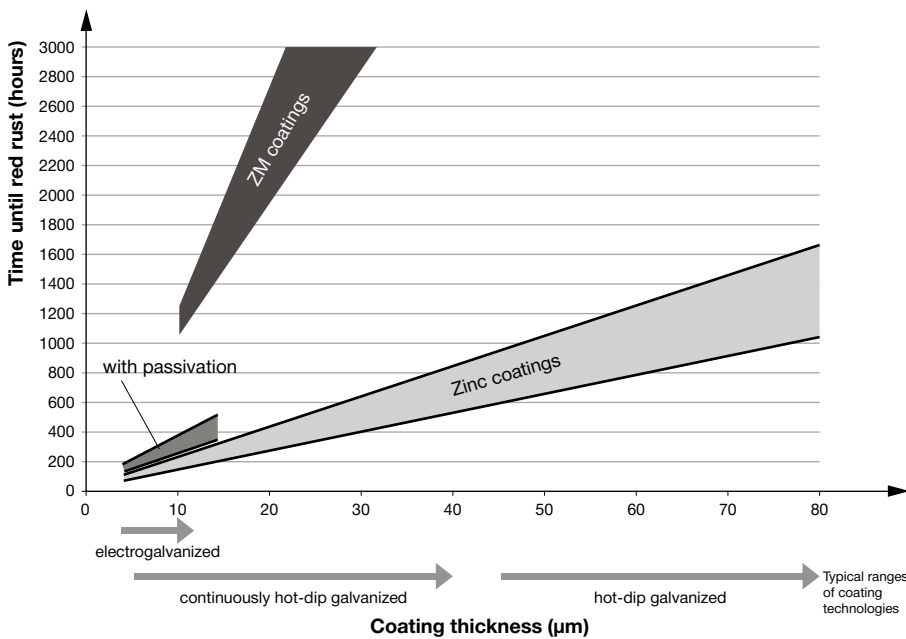

Fig. 15: Typical time until the first appearance of red rust (corrosion of the steel substrate) in the salt spray for zinc and Zinc magnesium (ZM) coated products with varying coating thickness.

Cyclic corrosion test: EN ISO 16701

In the cyclic corrosion test EN ISO 16701, temperature and relative humidity are varied to simulate typical wet/dry cycles like those taking place in natural outdoor environments. Additionally, the samples are sprinkled with a dilute sodium chloride solution (1%) twice a week to induce corrosion. While still not directly representative of most real atmospheres, due to the wet/dry cycles as well as the lower chloride concentration, this test is much better suited to triggering natural corrosion processes than the simple salt spray test. However, it requires longer test times (several weeks) (see Fig. 16 and Fig. 17).
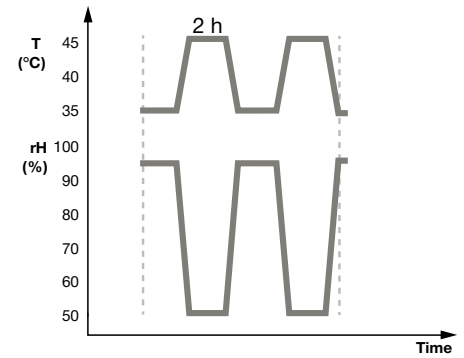

Fig. 16: Daily temperature and humidity cycle of the ISO 16701 cyclic corrosion test: twice a week, a 1 % NaCl solution is sprayed onto the samples for 3 × 15 minutes.
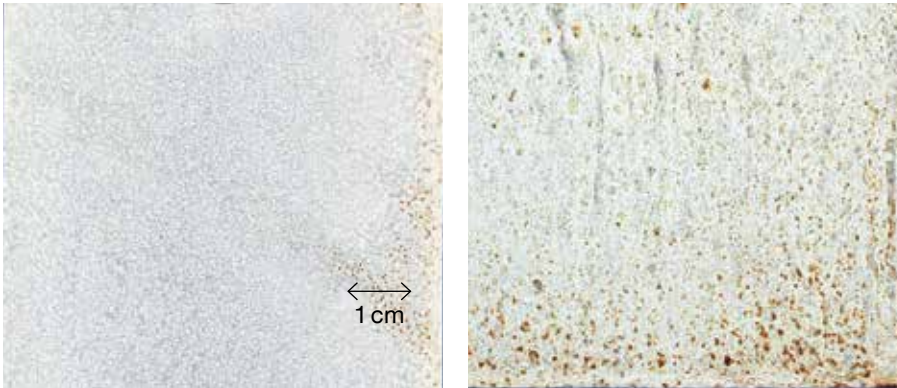
Fig. 17: Zinc-coated steel (hot-dip galvanized, HDG) after one year in a tropical coastal climate (left) and after 12 weeks in the ISO 16701 cyclic corrosion test (right). Similar corrosion behavior was observed in the field test and cyclic corrosion test.

Cyclic corrosion test with exposure to UV radiation: ISO 20340, similar to ASTM D5894

This test additionally exposes the samples to high-energy ultraviolet radiation. It is combined with water condensation, as well as chloride exposure and a freezing period (see Fig. 18). Organic polymers such as paints and varnishes can show degradation when exposed to sun light. This test is therefore mainly used for products with organic coatings (see Fig. 19). Apart from corrosion testing, it is also used to check the ageing effect on UV-sensitive products such as plastic parts.

Fig. 19: Connector part with multilayer coating (organic flake topcoat) after ten weeks in the ISO 20340 test with UV radiation.

Fig. 18: Cyclic corrosion test procedure in combination with exposure to UV radiation, salt spray and freezing cycle according to ISO 20340.

Humidity test: EN ISO 6270/ ASTM D2247, and with sulfur dioxide (EN ISO 6988, ASTM G87)

In the humidity test, samples are exposed to an atmosphere with 100 % relative humidity. This test can be combined with the addition of a certain amount of sulfur dioxide gas. This creates a highly corrosive and acidic environment that simulates the effect of heavy industrial pollution (see Fig. 20).
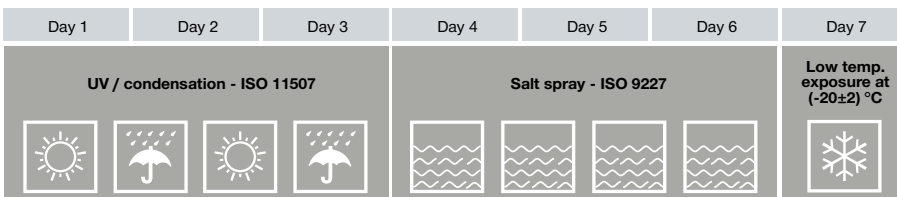
Electrochemistry

The electrochemical nature of the corrosion process make electrochemical techniques useful for the investigation of corrosion reactions of certain materials. Besides the accelerated corrosion tests, our lab is equipped with electrochemical testing equipment (potentiostat) which is mainly used for the examination of pitting corrosion and the repassivation behavior of stainless steel.

Metallographic laboratory

Accelerated corrosion tests, as well as field exposure tests always have to be supported by various analytical methods for proper interpretation of the results. In the metallography lab we use a state-of-the-art scanning electron microscope (SEM) plus elemental analysis for deeper investigation of our products (see Fig. 21, Fig. 22 and Fig. 23).

Fig. 20: Screws with highly corrosion-resistant multilayer coating after 15 cycles of the sulfur dioxide corrosion test (showing no corrosion).

Fig. 21: Scanning electron microscope (SEM).

Fig. 23: Metallographic laboratory equipment (grinding and polishing).
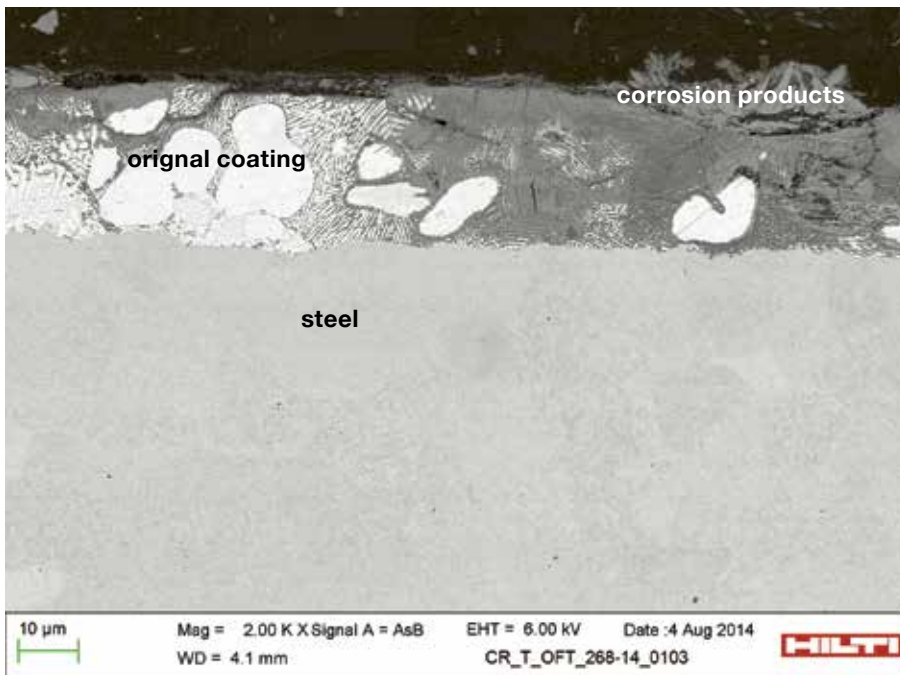
Fig. 22: Metallographic cross section in the scanning electron microscope of a ZM coating after three years exposure in a coastal climate. The stable corrosion products help protect the layer from further attack.

2.3   Outdoor field tests

Corrosion protection of products can be assessed most accurately by exposure tests of specimens and products in real atmospheric environmental conditions. For this purpose, Hilti conducts multiple ongoing outdoor field tests for its products at various sites all over the world, in conditions ranging from cold temperate to tropical, and from coastal to industrial and even offshore atmospheres (see Fig. 24).
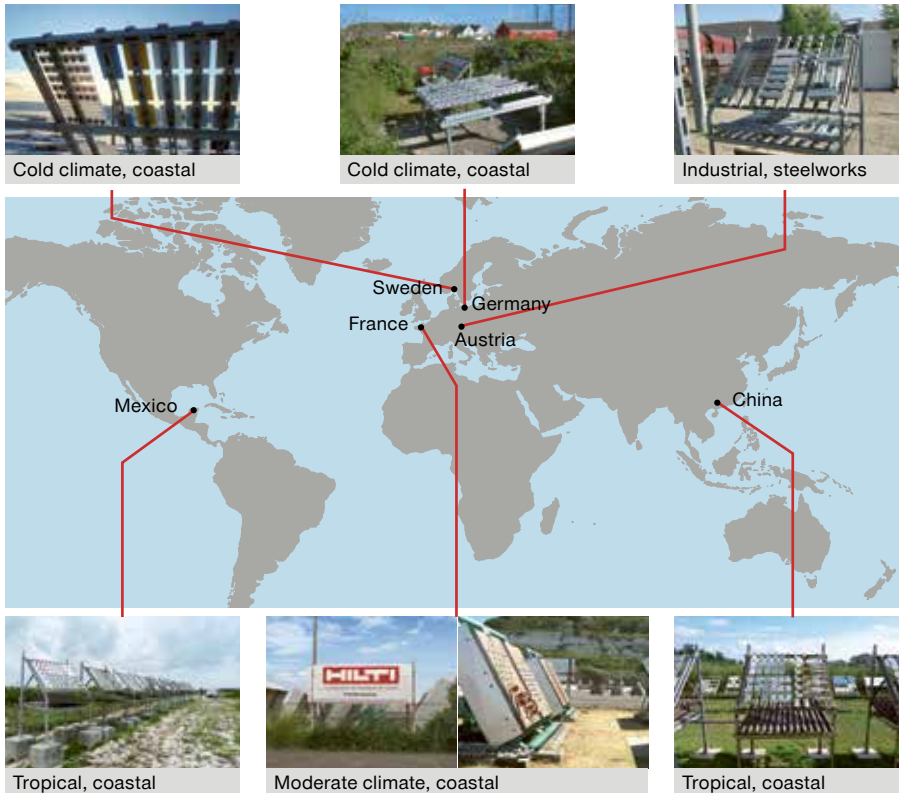
Fig. 24: Map showing the various field test locations for Hilti products

Hilti has operated the site near Le Havre on the Atlantic coast in France since the 1980s. Here we not only test the corrosion behavior of our fastening products, but also their long-term functionality. The fastening elements, especially anchors, are set in concrete. After certain periods of time, the remaining load values are measured in pull-out tests (see Fig. 25).
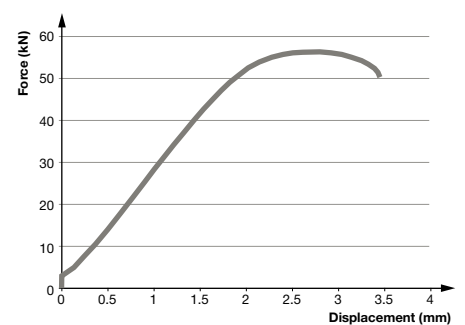
Fig. 25: Typical force-displacement measurement result for an installed anchor after 16 years of exposure in the coastal environment.

From the beginning of the 1980s until 2005 Hilti also carried out extensive studies on the corrosion behavior of various materials in road tunnels in the Alpine region. Our long-term observations have given us the ability to improve the performance of our products in these highly corrosive surroundings and thus supply our customers with more effective fastening systems for use in these environmental conditions. The high-alloyed stainless steel grade 1.4529 (HCR) has proven to be the one material that shows little to no signs of corrosion. The results of these studies have also influenced standards and codes of practice for products and fasteners made of stainless steel used for tunnel applications (see Fig. 26).

Our fasteners and installation products are not the only products that are thoroughly tested. Hilti's power tools also undergo many functionality tests, combined with typical corrosion conditions. This leads to high performance even in tough environments (see Fig. 27).

Fig. 26: Road tunnels present a very corrosive environment (de-icing salt and exhaust fumes from traffic).

Fig. 27: Fastening tools in a humidity chamber.

3 HILTI CORROSION PROTECTION SOLUTIONS

The corrosion protection solutions applied to Hilti products, their typical corrosion behavior and their suitability for certain applications are described in this section.

Classification of corrosion protection measures

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                    ┌─────────────────────────┐
                    │  Corrosion protection   │
                    │       measures          │
                    └─────────────────────────┘
                      │                    │
          ┌───────────────────┐   ┌───────────────────────┐
          │ Preventing corrosion│   │ Protecting the material│
          └───────────────────┘   └───────────────────────┘
                    │                       │
          ┌───────────────────┐   ┌───────────────────────┐
          │   Use of corrosion │   │   Coatings on steel   │
          │ resistant materials│   │                       │
          └───────────────────┘   └───────────────────────┘
                    │              │         │         │
          ┌───────────────┐  ┌──────────┐┌─────────┐┌───────────┐
          │ Stainless steel│  │ Metallic ││ Organic ││ Inorganic │
          └───────────────┘  └──────────┘└─────────┘└───────────┘
                                   │          │           │
                              ┌─────────┐┌─────────┐┌────────────┐
                              │  Zinc   ││ Painting ││ Phosphating │
                              │ coating ││         ││            │
                              └─────────┘└─────────┘└────────────┘
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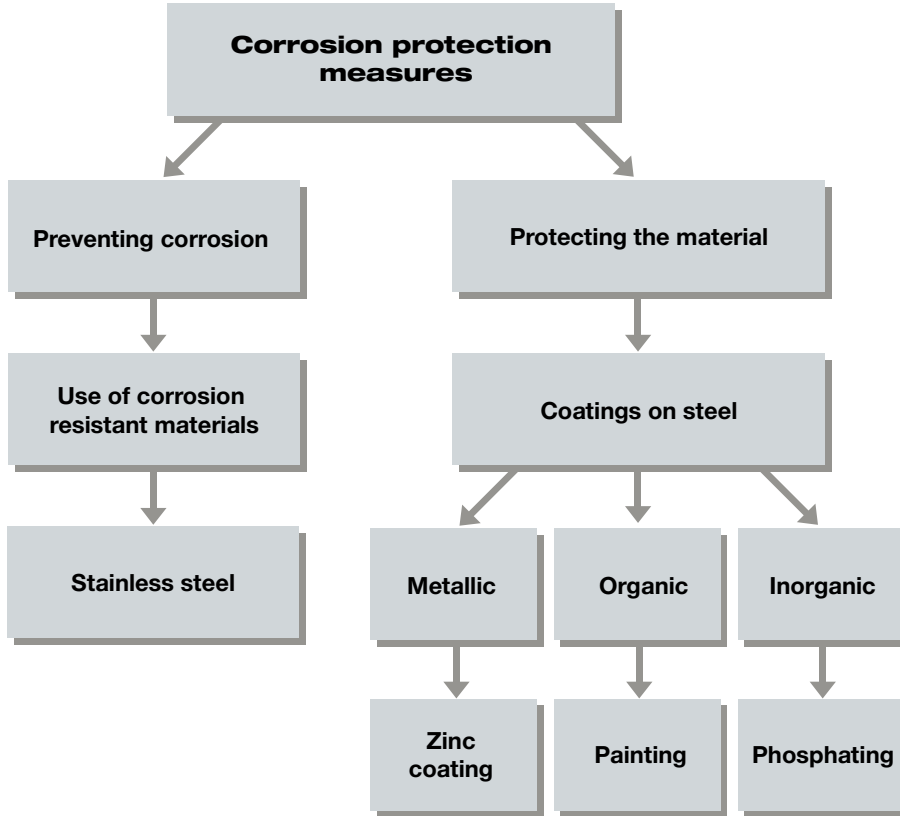
The table below provides an overview of the corrosion protection coatings applied to Hilti products.

Hilti corrosion protection solution for carbon steel	Coating thickness	Product examples
Phosphating		Screws
Electro-galvanizing Zn and ZnNi	From 5 to 20 µm	Nails, anchors, screws
Hot-dip galvanizing	From 35 to 100 µm	Installation channels
Hot dip galvanizing with Zn and ZM	From 20 to 40 µm	Stud anchors, installation channels
Sherardizing/Thermal diffusion	Up to 45 µm	Anchors
Multilayer (Zn plus additional organic coating – painting)		Anchors and installation parts

Table 1: Corrosion protection coatings applied to Hilti products

3.1 Corrosion and corrosion protection of carbon steel

The unalloyed steel (i.e. mild steel or carbon steel) from which the majority of our fastening and installation products are manufactured requires corrosion protection. In most environments, the corrosion rate of carbon steel (typically around 20 µm/a in a rural outdoor atmosphere and rising to more than 100 µm/a in coastal environments) is usually too high for a satisfactory outdoor application. The product design does not generally account for a material loss. Hilti therefore offers a wide range of suitable, cost-efficient corrosion protection solutions for carbon steel products.

In alkaline surroundings like when covered by concrete, however, iron and steel usually remain stable. This explains why, for example, reinforcing bars made of carbon steel are already very well protected against corrosion in the alkaline environment of the surrounding concrete.

Fig. 28: Phosphate crystals on a steel surface at 3000X magnification in the scanning electron microscope.

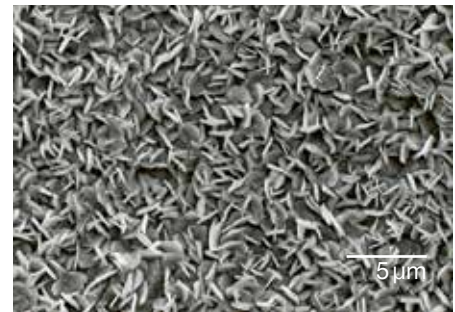| Phosphating	
Process description	Steel is dipped into an acidic solution containing metal (Zn, Fe) phosphate salts. The solution reacts with the steel surface forming a micro-crystalline layer of phosphates on the surface (see Fig. 28). This results in a rough surface with excellent oil-retaining properties.
Corrosion behavior and further information	Oil applied for corrosion protection is intended to stay long enough on the surface in order to provide protection during normal transport and deliver slightly increased general corrosion protection. Such products can be used only in dry indoor environments. Hilti uses phosphatizing on drywall screws.

Zinc and Zn alloy coatings

Zinc is an excellent choice for the corrosion protection of carbon steel. Several suitable processes are available for the application of zinc coatings on steel parts ranging from small screws to channels of several meters in length.

The corrosion rate of zinc is more than ten times lower than that of steel, ranging at around 0.5 to 1 µm/a in rural/urban atmospheres and rising to up to around 5 µm/a in coastal environments. Zinc alloy coatings such as electroplated ZnNi or continuously hot dip galvanized ZM have a significantly reduced corrosion rate, which in most applications is only about half that of zinc. Fig. 29 provides an overview of the typical service life of zinc-coated steel and ZM coated steel under various conditions. The low corrosion rates are the result of the formation of stable layers of corrosion products containing carbonates (from CO_2 in the air) and chlorides (if they are present in the atmosphere). Conditions where the formation of such insoluble corrosion products is not possible will lead to much higher corrosion rates and hence will limit the suitability of zinc as a protective coating. These include permanently wet conditions or exposure to high concentrations of industrial pollutants such as sulfur dioxide. In these environments, soluble corrosion products are formed preferentially and they can be washed off by rainfall.

In addition to decreased corrosion rates, zinc also provides cathodic or sacrificial protection to the underlying steel. Where scratching, chipping or any other damage to the zinc coating exposes the steel, a special form of galvanic corrosion takes place (see section 1.2.6). Zinc, being a less noble metal than steel, corrodes preferentially, thereby helping to keep the exposed steel surface protected.

Zinc coatings are consumed quite homogenously during atmospheric corrosion. Accordingly, in a given application, doubling of the coating thickness usually also doubles the time until the zinc is consumed and red rust on the steel substrate occurs. Zinc is not stable in alkaline environments and is readily attacked in solutions with a pH-value of 10 or higher. Likewise, on the jobsite, the spilling of aggressive construction materials on zinc products, e.g. cement or fresh concrete, should be avoided.
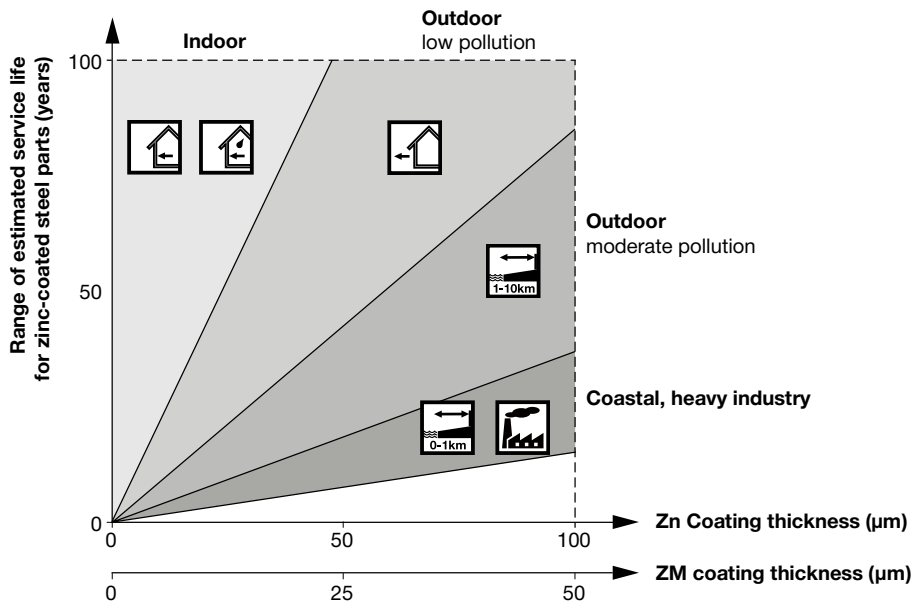
Fig. 29: Typical service life of Zn and ZM coated steel in various environments.

Electrogalvanizing

Process description	Electrical current is passed through an aqueous solution containing zinc ions leading to the deposition of zinc metal on the steel substrate. Prior to this step, the parts usually undergo a cleaning and pickling process and subsequent passivation after the deposition of zinc. It is an excellent way to protect small threaded parts due to the formation of homogeneous and dense coatings.
Coating thickness	It can vary from 5 to 15 µm.
Corrosion behavior and further information	Due to the limitations of the achievable coating thickness, Zn electroplated parts without further corrosion protection should only be used in dry indoor conditions. Using electroplating, it is also possible to deposit Zn alloys such as ZnNi coatings. Electrogalvanizing can lead to hydrogen uptake. Hilti's high-strength fasteners such as nails for direct fastening are therefore baked after electroplating (kept at temperatures of around 180 °C for 24 h) to remove hydrogen.

Hot-dip galvanizing

Process description	During this process, steel parts are dipped into a bath of molten zinc. Large parts with a size of several meters can be coated using this technique. Small parts like bolts and anchors are centrifuged after hot-dip galvanizing in order to remove excess zinc from the threads.
Coating thickness	The typical thickness is between 35 and 100 µm, depending on the material thickness and the steel composition. The duration of dipping is usually several minutes.
Corrosion behavior and further information	The molten zinc reacts with the steel substrate forming a ZnFe alloy layer with a thinner pure Zn layer on top (see Fig. 30). Corrosion products of hot-dip galvanizing may look brownish due to Fe in the zinc coating. This, however, is not necessarily a sign of corrosion of the steel substrate (see Fig. 31). HDG is applicable for some outdoor environments, depending on the thickness of the zinc coating and the exposure conditions

Continuous hot-dip galvanizing / Sendzimir galvanizing

|	
Process description	During this process, sheet metal from coils is drawn continuously through a bath of molten zinc after the surface has been cleaned and it has been subjected to a special annealing (heat treatment) process. The zinc bath contains small amounts of Al. The Al reacts with the steel surface to create an inhibition layer with a thickness of a few nanometers, which inhibits the formation of ZnFe phases. The coating consists mainly of pure zinc.
Coating thickness	It can vary from 10 to 70 µm on both sides and it is controlled by removing excess zinc with a jet of air.
Corrosion behavior and further information	Apart from pure Zn, also coatings consisting of Zn alloys such as ZM can be produced by continuous dip galvanizing. Typical coatings have around 2–4 % of Al and Mg and show increased corrosion protection, which is around two times higher than that of a Zn coating with the same coating weight.
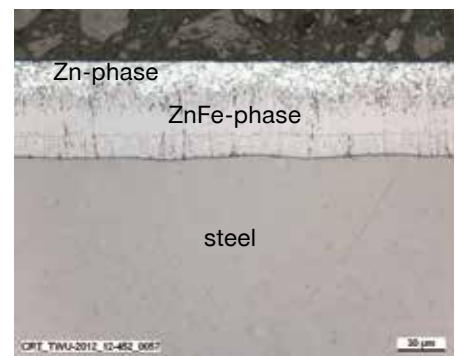
Fig. 30: Micrograph of hot-dip galvanized steel.
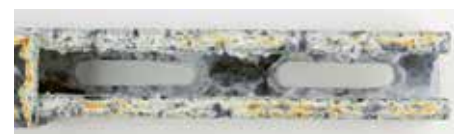
Fig. 31: Brown staining on a hot-dip galvanized channel after 200 h in the salt spray test. No corrosion of the steel yet.

Sherardizing / thermal diffusion

Process description	Sherardizing is a method of zinc coating utilizing a thermal diffusion process. The steel parts are placed in a drum containing Zn powder and then heated to temperatures above 320°C. The Zinc is not liquid, and the coating forms by thermal diffusion of the Zn powder into the steel parts.
Coating thickness	The achievable coating thickness ranges up to 45 μm.
Other features	These coatings consist mainly of a ZnFe alloy which offers very good protection against corrosion that can be compared with hot-dip galvanizing at the same thickness. Even on complex threaded parts, this process produces tough and uniform coatings.

Multilayer coatings / duplex-coated carbon steel

When the corrosion protection provided by the metallic coating is not sufficient, the parts can be further protected by additional coatings, mainly organic paint with or without metallic flakes.

An example of this is the multilayer coating on fasteners consisting of an electroplated Zn alloy coating with an additional organic top coat (see Fig. 32).
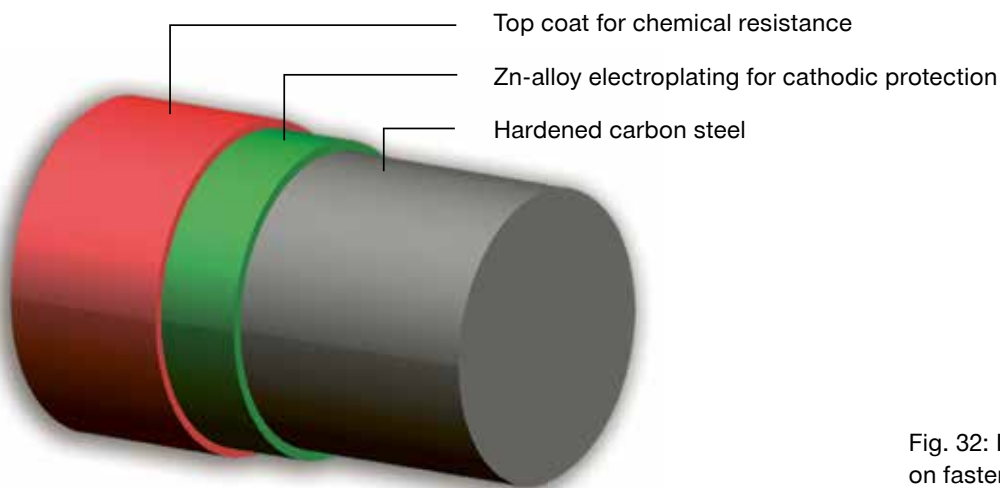
Top coat for chemical resistance

Zn-alloy electroplating for cathodic protection

Hardened carbon steel

Fig. 32: Illustration of multilayer coating on fasteners and connectors.

3.2   Corrosion behavior of stainless steel

Steel alloyed with at least 10 % chromium is called stainless steel. The addition of chromium causes the formation of a stable, very thin (few nanometers) oxide layer (passivation layer) on the surface. Stainless steel therefore does not readily corrode or stain when in contact with water like carbon steel does.

However, under some circumstances, the passivation layer can break down causing local attack such as pitting corrosion (see 1.2.2). Pitting corrosion, as the predominant form of corrosion of stainless steel, does not allow lifetime prediction as is possible with zinc coatings. In general, for a given application, a grade of stainless steel which is stable and does not show any corrosion in the given environment has to be selected.

The resistance of stainless steels against pitting corrosion can be roughly estimated by the PREN (pitting resistance equivalent number). The PREN is based on the chemical composition of steel, taking into account the amount of chromium, molybdenum and nitrogen. In literature, various equations for this calculation are given. The most common equations are:

PREN = %Cr + 3.3 x %Mo
(for stainless steels Mo < 3%)

PREN = %Cr + 3.3 x %Mo + 30 x %N
(for stainless steels Mo ≥ 3%)

Another severe form of corrosion relevant for stainless steel is stress corrosion cracking. Austenitic stainless steel can be prone to this form of corrosion under specific highly aggressive environments such as in indoor swimming pools. In such cases, highly corrosion-resistant grades of stainless steel must be used for some applications, e.g. grades with a molybdenum content of more than 6 %.

You will find more information about selecting stainless steel grades in section 4.

Stainless steel grades
There are various grades of stainless steel with different levels of stability. The most common grade is alloyed with around 18 % Cr and 10 % Ni (see Fig. 33). Increasing or reducing the amount of specific elements in the steel changes its corrosion properties, its mechanical properties or some processing properties such as weldability. If the nickel content is significantly reduced the alloy phase will no longer be purely austenitic, but will then combine austenitic and ferritic phases (duplex stainless steel). Additionally to these grades, there are the martensitc stainless steel grades.

Stainless steel designations
The illustration in Fig. 33 shows the three most common forms of stainless steel grade designations:
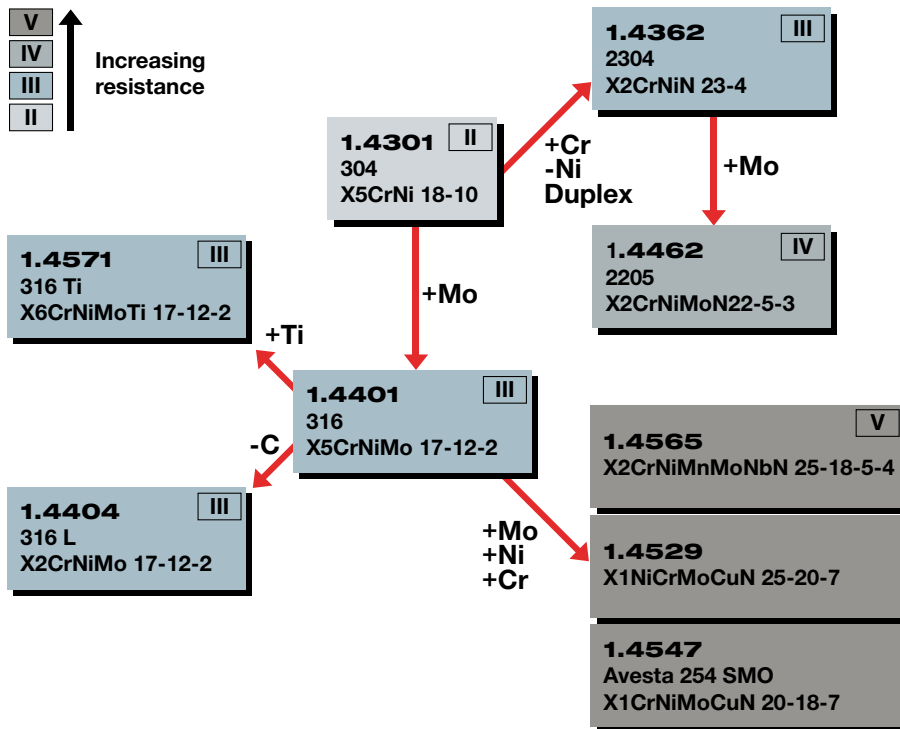

Fig. 33: Classification tree for the most common austenitic and austenitic-ferritic stainless steel grades. The Roman numbers indicate the corrosion resistance class (see also 4.3)

MATERIAL NUMBER

Description

The system of numbering materials in accordance with EN 10088-1:2014 is used in several countries. Each number has five digits, such as 1. 4404

The first digit 1 means steel, the second and third digits 44 mean chemically resistant steels with Mo, and without Nb or Ti. In addition to designation 44, the following designations for stainless steel exist:

“41”   = with Mo, without Nb and Ti, Ni < 2,5 %
“43”   = without Mo, Nb and Ti, Ni ≥ 2,5 %
“44”   = with Mo, without Nb and Ti, Ni ≥ 2,5 %
“45”   = with additional elements

The last two digits 04 designate the exact alloy.

AISI DESIGNATION (E.G. 316)

Description

The designation system of the American Iron and Steel Institute (AISI) is used worldwide. It consists of a number to which one of several letters may be added depending on the composition.

200 – designates an austenitic steel containing chromium, nickel and manganese
300 – designates an austenitic steel containing chromium, nickel
400 – designates ferritic and martensitic chromium steels

The additional letters (some shown below) indicate the following:

L   = low carbon   Ti   = titanium

The newly-developed duplex stainless steel grades have a four-digit designation (e.g. 2205 for the 1.4462)

SHORT NAME DESIGNATION

Description

X 2 Cr Ni Mo 17 12 2

X =   High-alloy steel
2 =   Carbon content in 1 / 100 %, in this case: C= 0.02 %
Cr =   Chromium, in this case: 17 %
Ni =   Nickel, in this case: 12 %
Mo =   Molybdenum, 2 %

This steel grade in the given examples corresponds to the AISI type 316 L and the DIN material no. 1.4404.

TERMS V2A AND V4A – DESIGNATION ACCORDING TO EN ISO 3506-1:2009

Description

The terms V2A and V4A date back more than 100 years and have their origin in the designation of the first trial productions of stainless steel. The V stands for "Versuch", which is German for "test or trial", and the A for "austenite". V2A denotes a Cr/Ni alloy and V4A a CrNiMo alloy. The terms are still used as synonyms for stainless steel in some countries.

The EN ISO 3506-1:2009 standard (mechanical properties of corrosion-resistant stainless steel fasteners, bolts, screws and studs) uses designations ranging from A1 to A5 for austenitic stainless steel. This range is based on the alloy composition and does not fully reflect corrosion behavior. For example, the grade 1.4401 is in the A4 group and 1.4571 is in the A5 group. However, both stainless steel alloys exhibit practically the same corrosion resistance.

Often the terms A2 and A4 are used to talk about a group of stainless steel grades with certain corrosion resistance. However, this is not completely accurate, since specific information about the alloy composition and thus also some properties such as weldability cannot be deduced from these terms.

3.3 Prevention of galvanic corrosion

Galvanic corrosion (described in section 1.2.6) can be avoided by the right choice of material combinations. This, however, is not always possible and sometimes other measures have to be considered. One example is galvanic separation of the different materials, as shown in Fig. 34.

No conducting connection

Electrolyte

Metal 1 | Metal 2

Insulation

No significant potential difference between electrodes (metals)

Electrolyte

Metal 1 | Metal 2

No connective electrolyte

Electrolyte

Metal 1 | Metal 2
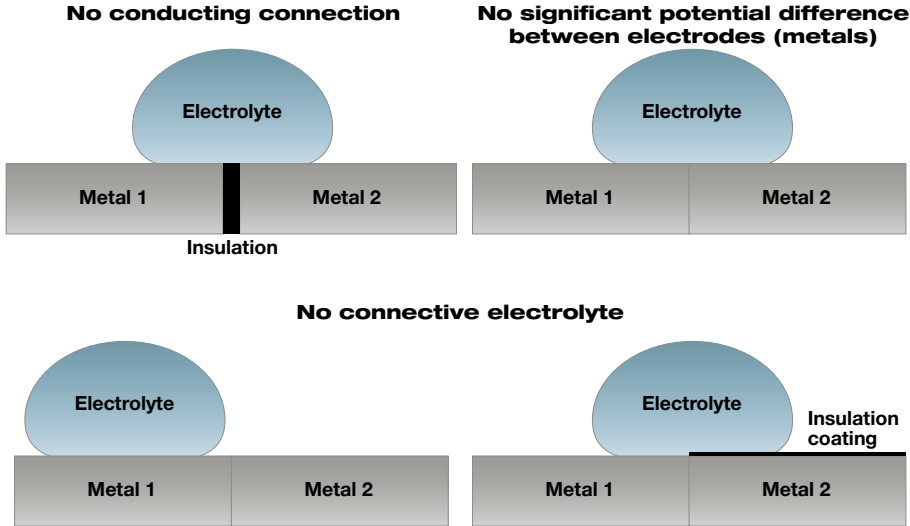
Electrolyte

Insulation coating

Metal 1 | Metal 2

Fig. 34: Conditions for metal combinations without risk of galvanic corrosion.

To minimize galvanic corrosion, the difference in free corrosion potential between the materials should be as low as possible, and/or the surface ratio of less noble metal to nobler metal should be very high. The free corrosion potential depends on the standard potential, a given thermodynamic value for each metal and the corrosive environment.

Fig. 35 shows the free corrosion potential of various materials when immersed in seawater. The higher the potential, the nobler is the metal. Contact with a metal of a lower potential leads to galvanic corrosion of that less noble metal. The differences in corrosion potentials between Zn and ZM are small enough not to cause any contact corrosion issues.

Active ← **Potential (V) vs. AG/AgCl** → **Noble**

	Platinum
	Gold
Silver	
Nickel	
Molybdenum	
Stainless steel	
	Copper
Carbon steel	
Aluminum Alloys	
Zinc	
Magnesium	

-1.8 -1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6
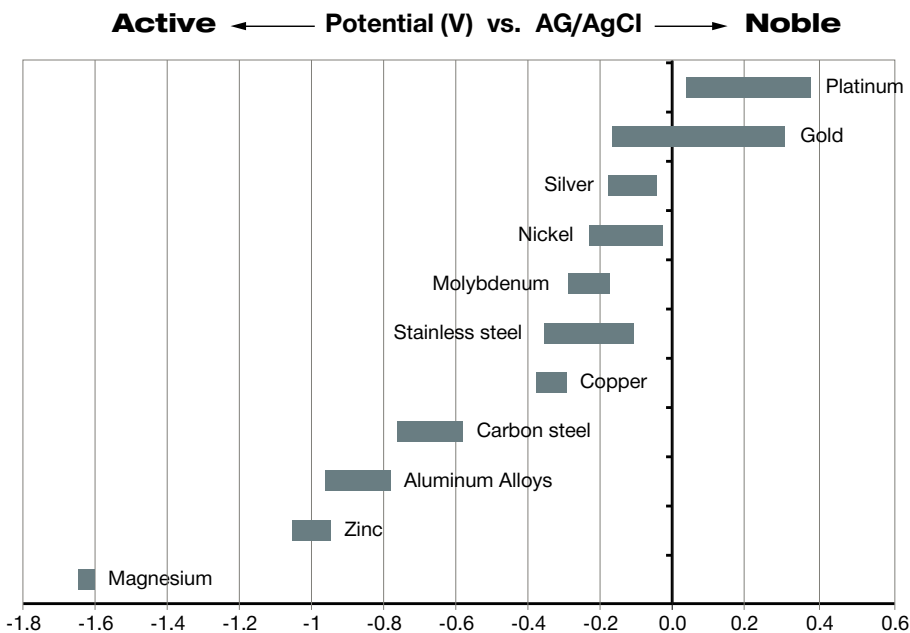
Fig. 35: Corrosion potential of various metals in sea water.

As a general rule of thumb, a fastener should always be made of the same or a more noble metal than the part to be fastened, since it typically has the smaller surface area, and failure of the fastener is usually critical.

Table 2 shows the impact of galvanic corrosion under atmospheric **outdoor conditions** for various material combinations.

Fastened part (large area)	Fastener (small area)			
	Electro-galvanized	Duplex-coated carbon steel	Hot-dip galvanized	Stainless steel
Electrogalvanized	☐	☐	☐	☐
Hot dip galvanizing Zn and ZM	☐	☐	☐	☐
Aluminum	▨	▨	▨	☐
Structural or cast steel	■	■	■	☐
Stainless steel (CrNi or CrNiMo)	■	■	■	☐
Tin	■	■	■	☐
Copper	■	■	■	☐
Brass	■	■	■	☐

Table 2: Impact on lifetime of the fastener by galvanic (contact) corrosion

☐ No impact on lifetime
▨ Moderate impact on lifetime, technically acceptable in many cases
■ Strong impact on lifetime

In environments, that are considered non- or very low corrosive (i.e. dry indoor applications), contact corrosion can generally be neglected and usually there are little to no susceptible material combinations. In most outdoor applications with combinations of materials one has always to consider the general guidelines and limitations for certain materials. For example, even if the accelerating galvanic effect can be neglected, as in the combination of Zn electroplated parts with aluminum, in general the service life of such parts is quite short due to their low coating thickness.

In the selection tables shown in section 5, galvanic corrosion is taken into account by providing two different rows for the fastened part (divided into "steel", "aluminium" and "stainless steel").

4 HOW TO ASSESS CORROSION IN A SPECIFIC ENVIRONMENT AND APPLICATION

The following section describes ways to help determine the corrosivity of certain environments. The parameters influencing the corrosion can only be checked by specialists working locally on a specific project. Accordingly, the final decision regarding the chosen material and products is the responsibility of the user and/ or specifier. While Hilti personnel can provide you with the necessary basic information about our products, it is not possible for them to carry out a fully comprehensive check of the expected corrosivity of the intended application.

4.1 Factors influencing atmospheric corrosion

Under specific circumstances, the corrosivity and, respectively, the corrosion rates of zinc and steel products can be estimated when typical atmospheric parameters are known for a certain application (see Fig. 36).
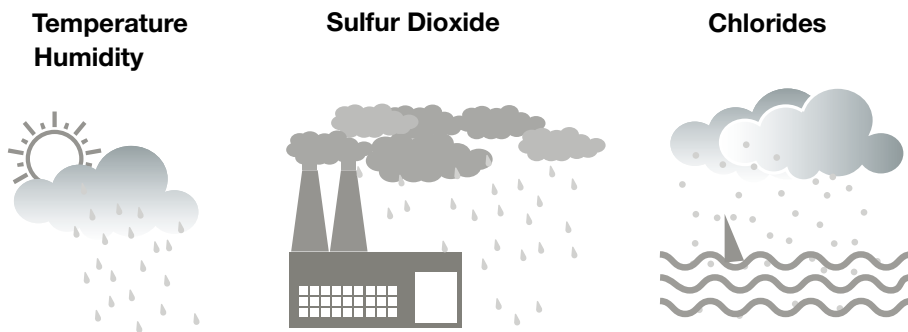
Temperature Humidity   **Sulfur Dioxide**   **Chlorides**

Fig. 36: Factors influencing atmospheric corrosion.

The important variables for atmospheric corrosion are:

Temperature

General influence	An increase in temperature leads to an increase in the rate of chemical reaction and therefore also an increase in the corrosion rate. This is especially true at constant relative humidity levels.
Additional information	On the other hand, increasing temperature facilitates the drying of wet surfaces and can slow down corrosion rates. At temperatures below freezing point corrosion is negligible. The influence of the temperature on corrosion can therefore go in both directions.
Examples	For similar environments such as maritime regions, which usually show high humidity levels, an increase in the average temperature also accelerates the corrosion rate. As a result, coastal and offshore areas in tropical climates result in much higher corrosivity than similar zones in colder regions.

Humidity

General influence	Atmospheric corrosion only takes place when a moisture film is present on the metal surface. In the absence of humidity, most contaminants would have little or no corrosive effect. The period in which a moisture film is present is also called time of wetness. As a commonly used rule of thumb according to the ISO 9223:1998 standard, the time of wetness is defined as the periods in which the relative humidity exceeds 80 %. This is only a rough estimation since the formation of a moisture film on the surface also depends on the presence of hygroscopic salts (e.g. corrosion products or salt deposits). Condensation in maritime environments with chlorides will therefore take place at lower levels of relative humidity. Calculation of corrosion rates according to the latest ISO 9223:2012 standard takes into account only the mean relative humidity measured in one year (see 5.1).
Additional information	Water in the form of rain does not always increase corrosivity. It may even have a beneficial effect by washing away chlorides and pollutants. However, in usually dry and mildly corrosive environments, rainwater can provide the moisture necessary to trigger a corrosion reaction.
Examples	In rural/urban atmospheres, sheltered parts usually show less corrosion than the ones exposed to rain. On the other hand, the lack of the washing effect of the rain in coastal areas often leads to stronger corrosion.

Chlorides

General influence	Atmospheric salinity distinctly increases corrosion rates. Chlorides have multiple detrimental effects on the corrosion of metals. In particular these are: • Decrease in the saturation humidity: the presence of salts facilitates condensation at lower relative humidity values. This leads to longer periods with wet metal surfaces • Formation of soluble corrosion products: the dissolved metal ions form metal chlorides, which usually do not provide enough protection from further corrosion. • Destruction of passive films: chlorides attack the oxide films formed on passive metals such as stainless steel and aluminum
Additional information	The corrosion behavior of a particular metal in atmospheres containing chloride strongly depends on its ability to form stable and insoluble corrosion products together with the chlorides present. For example, this is the case with zinc, which explains the much lower corrosion rate of zinc compared to steel.
Examples	In maritime atmospheres the main source of chlorides is the seawater. It contains mainly sodium chloride (more than 90 % of the salt), accompanied by calcium and magnesium chlorides. The main source of anthropogenic chlorides is the use of de-icing salts on roads during winter time.

Sulfur dioxide

General influence	Of all the atmospheric contaminants originating from industrial processes such as fuel combustion and metal smelting, sulfur dioxide is the most important one in terms of concentration and its effect on corrosion rates. Sulfur dioxide gas in the atmosphere acidifies the electrolyte on the surface and leads to the formation of soluble corrosion products. Corrosion rates are thus increased on many metals, e.g. zinc, steel, aluminum and stainless steel.
Additional information	Sulfur dioxide emissions are on the decline in large parts of the industrialized world and have reached insignificant levels in many urban and even industrial areas (below $10\,\mu g/m^3$ or even lower). However, heavily polluted hot spots around the world still exist, where an increase in corrosion due to SO_2 has to be considered when it comes to material selection.
Examples	The ISO 9223:2012 standard classes atmospheres with SO_2 concentrations of over $50\,\mu g/m^3$ (yearly average) as strongly contaminated environments.

4.2 Assessment of corrosivity for zinc and ZM coated products

The following section describes a way of helping to assess and estimating the expected corrosion in a given environment for zinc-coated and ZM coated products. It has to be noted that this only applies to pure atmospheric corrosion where the item is fully exposed to the weather. Applications where, for example, the item is in contact with soil, immersed in sea water or positioned in the splash zone are excluded, as are additional effects resulting from galvanic corrosion, erosion or exposure to chemical substances.

Estimation of the corrosivity of the application can be carried out in two different ways according to the ISO 9223:2012 standard (see Fig. 37).

1. Corrosivity estimation using the classification of ISO 9223:1998 or the dose-response function given in the new version of this standard (ISO 9224:2012).
2. By conducting one-year exposure tests of the material/product to be used and measuring the corrosion rate.

For most projects it is not feasible to conduct one-year exposure tests and therefore estimation becomes the most frequently used approach. For the estimation approach, the main climatic and environmental parameters previously described are required as input. These are, in particular, the mean temperature, mean relative humidity, chloride deposition and SO_2 concentration.
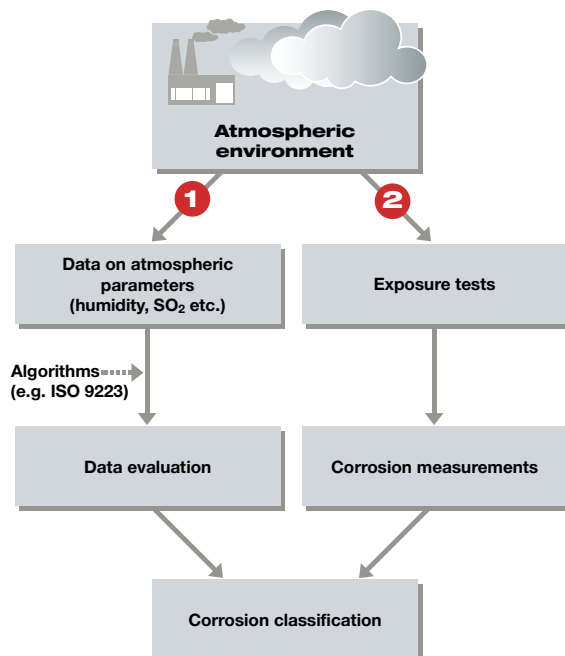
Fig. 37: Methods for assessment of atmospheric corrosivity.

The outcome of this approach is an estimated rate of corrosion of zinc or steel in a given environment. The resulting corrosion rates define the prevalent corrosivity category (C-class, see table 3).

As stated in the standard, the possible deviation using environmental data and the dose-response function may be up to 50 %. It must be noted that the results are only valid for macroclimatic and fully exposed (unsheltered) conditions. Moreover, factors such as accumulation of corrosive substances or galvanic corrosion, which can have a significant effect on the corrosion rate, are not taken into account in this approach. Nevertheless, as long as these other potential sources of corrosion are not present, the results of this calculation are usually accurate enough to allow selection of the right material.

Corrosion is a natural process influenced by varying environmental factors which cannot be foreseen for the entire designed lifetime. A conservative approach is therefore always advised when it comes to the use of fastening and installation products.

Corrosivity category C	Corrosion level	Typical environments	
		Indoor	Outdoor
C1	Very low	Heated spaces with low relative humidity and insignificant pollution, e.g. offices, schools, museums.	Dry or cold zone, atmospheric environment with very low pollution and time of wetness, e.g. certain deserts, Central Arctic / Antarctica.
C2	Low	Unheated spaces with varying temperature and humidity. Low frequency of condensation and low pollution, e.g. storage, sports halls.	Temperate zone, atmospheric environment with low pollution ($SO_2 < 5\,\mu g/m^3$), e.g. rural areas, small towns. Dry or cold zone, atmospheric environment with short time of wetness, e.g. deserts, subarctic area.
C3	Medium	Spaces with moderate frequency of condensation and moderate pollution from production processes, e.g. food-processing plants, laundries, breweries, dairies.	Temperate zone, atmospheric environment with medium pollution (SO_2: $5\,\mu g/m^3$ to $30\,\mu g/m^3$) or some effect of chlorides, e.g. urban areas, coastal areas with low deposition of chlorides. Subtropical and tropical zone, atmosphere with low pollution.
C4	High	Spaces with high frequency of condensation and high pollution from production processes, e.g. industrial processing plants, swimming pools.	Temperate zone, atmospheric environment with high pollution (SO_2: $30\,\mu g/m^3$ to $90\,\mu g/m^3$) or substantial effect of chlorides, e.g. polluted urban areas, industrial areas, coastal areas without salt water spray, or exposure to strong effect of de-icing salts. Subtropical and tropical zone, atmosphere with medium pollution.
C5	Very high	Spaces with very high frequency of condensation and/or with high pollution from production processes, e.g. mines, caverns for industrial purposes, unventilated sheds in subtropical and tropical zones.	Temperate and subtropical zone, atmospheric environment with very high pollution (SO_2: $90\,\mu g/m^3$ to $250\,\mu g/m^3$) and/or significant effect of chlorides, e.g. industrial areas, coastal areas, sheltered positions on coastline.
CX	Extreme	Spaces with almost permanent condensation or extensive periods of exposure to extreme humidity effects and/or with high pollution from production processes, e.g. unventilated sheds in humid tropical zones with penetration of outdoor pollution including airborne chlorides and corrosion-stimulating particulate matter.	Subtropical and tropical zone (very high time of wetness), atmospheric environment with very high SO_2 pollution (higher than $250\,\mu g/m^3$) including accompanying and production factors and/or strong effect of chlorides, e.g. extreme industrial areas, coastal and offshore areas, occasional contact with salt spray.

Table 3: Corrosivity categories and description of typical environments as stated in the ISO 9223 standard

This table gives a description of possible environments with respect to the corrosion class. Although it can be used to estimate the corrosion class of the application, one has to keep in mind that strictly following the standard means that the corrosion class has to be determined by measurement of the corrosion rate or the most important environmental parameters. Furthermore, the table only takes typical atmospheric conditions into account.

The corrosion rates for steel, zinc, aluminum and copper with respect to the corrosivity classes can be found in the ISO 9223 standard.

Zn-alloy coatings like ZM have significantly reduced corrosion rates in atmospheric applications. For lifetime estimation of such coatings the DIN 55634 provides a useful selection table for general guidance. It is based on the technically sound assumption that ZM coatings have half the corrosion rate compared to pure Zn coatings.

	Coating Thickness		Timespan until start of red rust (per exposure class)*														
			C2			C3			C4			C5-I			C5-M		
		(µm)	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Zinc	Z140	10	x	x													
	Z275	20	x	x		x											
	Z600	42	x	x	x	x	x	x	x	x		x			x		
ZM	ZM140	11	x	x	x	x											
	ZM275	21	x	x	x	x	x	x	x								
	ZM310	24	x	x	x	x	x	x	x	x							

* L = 2–5 years   M = 5–15 years   H = > 15 years

Table 4: Expected service life of Zn and ZM coatings

4.3 Assessment of corrosivity for stainless steel products

Strictly speaking, the corrosivity categories (C-classes) according to the ISO 9223 standard are applicable only to zinc, carbon steel, aluminum and copper. The different corrosion mechanism of stainless steel makes it necessary to work with a system of classification different to that used for zinc. Stainless steel is generally stable against humidity and water when no corrosive contaminants are present. The breakdown of the passive layer by substances like chlorides, however, has to be taken into account specifically and limits the use of certain grades of stainless steel.

In contrast to zinc, the influence of pure humidity without other contaminants is negligible for the corrosion of stainless steel. For stainless steel it is more important to consider the effect of chlorides and of rain or other moving water in washing off the corrosion products and corrosive substances. In many applications the effect of this washing makes the use of weaker grades of stainless steel possible. For applications like roofs and the facades of buildings this can be an option. However, in typical applications where fasteners and installation products are used there can be areas sheltered from the rain.

International (Eurocode 3, EN 1993-1-4 draft version) and national standards and guidelines (such as the German technical approval DIBt Z.30.3-6) usually work with a special scoring system when evaluating the suitability of certain stainless steel grades.

This system takes the risks presented by the main influencing factors into account, from which a corrosion resistance factor (CRF) is calculated. Each risk factor (chlorides, sulfur dioxide, washing effect) is linked to a certain number of points.

The CRF depends on the severity of the environment and is calculated as follows:
CRF = F1 + F2 + F3, where
- F1 = Risk of exposure to chlorides from salt water or de-icing salts
  (categories ranging from +1 to -15, mainly determined by the distance from the coast or roads, where de-icing salts are used)
- F2 = Risk of exposure to sulfur dioxide
  (categories ranging from 0 to -15, determined by the average sulfur dioxide concentration)
- F3 = Cleaning regime or exposure to washing by rain
  (categories ranging from +1 to -7)

Summing up all of the factors results in a number of points (the CRF) which then relate to five corrosion resistance classes (see Table 4). This is only an excerpt of the procedure. For details please refer to the standards.

Corrosion resistance class CRC (link to the corrosion resistance factor CRF)

I CRF = 1	II 0 ≥ CRF > -7	III -7 ≥ CRF > -15	IV -15 ≥ CRF ≥ -20	V CRF < -20
1.4003	1.4301	1.4401	1.4439	1.4565
1.4016	1.4307	1.4404	1.4462	1.4529
1.4512	1.4311	1.4435	1.4539	1.4547
	1.4541	1.4571		1.4410
	1.4318	1.4429		1.4501
	1.4306	1.4432		1.4507
	1.4567	1.4162		
	1.4482	1.4662		
		1.4362		
		1.4062		
		1.4578		

Table 4: List of stainless steel grades in the corrosion resistance classes based on the tables in EN 1993-1-4:2006 (final draft version 2014)

In the Hilti range of fasteners and installation systems you will find grades such as 1.4301, 1.4404 and the most stable 1.4529 (see Table 6), covering all important corrosion resistance classes.

Steel grades	Corrosion resistance class	Products
1.4301 (A2, 304)	II	Screws, anchors, installation products
1.4401 (A4, 316)	III	Screws, anchors, installation products, fasteners driven by powder-actuated tools
1.4404 (A4, 316L)	III	Screws, anchors, installation channels, fasteners driven by powder-actuated tools
1.4571 (A5, 316Ti)	III	Installation products
1.4362 (duplex, 2304)	III	Anchors, fasteners driven by powder-actuated tools
1.4462 (duplex, 2205)	IV	Fasteners driven by powder-actuated tools
1.4529 (HCR)	V	Anchors

Table 5: Examples of stainless steels used in Hilti products

For more detailed information on the stainless steel grades used in our products please refer to our product catalogs or visit www.hilti.com.

5   HOW TO SELECT A SUITABLE FASTENER AND INSTALLATION SYSTEM

Information about the selection tables

Hilti offers fasteners and installation systems in a wide range of suitable, cost-efficient materials. However, the differences in corrosion behavior, the complexity of the factors influencing corrosion and the number of national and international standards and guidelines applicable to the field of corrosion can present a challenge when it comes to making the right choice of material for a certain application.

In order to provide an initial overview of the performance of the various products, our tables show general suitability and, where applicable, also a rough estimate of lifetime of products in some typical environments.

"Important notes" provides information that must always be taken into account when using the tables:

Important notes

The ultimate decision on the required corrosion protection must be made by the customer. Hilti accepts no responsibility regarding the suitability of a product for a specific application, even if informed of the application conditions. The tables are based on an average service life for typical applications.

For metallic coatings, e.g. zinc layer systems, the end of lifetime is the point at which red rust is visible over a large fraction of the product and widespread structural deterioration can occur – the initial onset of rust may occur sooner.

National or international codes, standards or regulations, customer and/or industry-specific guidelines must be independently considered and evaluated.

The tables published in this handbook describe only a general guideline for commonly accepted applications in typical atmospheric environments.

Suitability for a specific application can be significantly affected by localized conditions, including but not limited to:
- Elevated temperatures and humidity
- High levels of airborne pollutants
- Direct contact with corrosive products, such as found in some types of chemically-treated and/or acidic wood, waste water, concrete additives, cleaning agents, etc.
- Direct contact with soil, stagnant water
- Direct contact with fresh/young concrete (less than 28 days old)
- Electrical current
- Contact with dissimilar metals
- Confined areas, e.g. crevices
- Physical damage or wear
- Extreme corrosivity due to combined effects of different influencing factors

In Table 6 the environmental conditions given in the tables are described in more detail. The underlying predominant corrosion categories and corrosion resistance classes are also listed.

	Corrosion categories according to ISO 9223:2012	Corrosion resistance class Stainless steel
Indoor applications		
Dry indoor environments (heated or air-conditioned areas) without condensation, e.g. office buildings, schools	C1, C2	1
Indoor environments with temporary condensation (unheated areas without pollutants), e.g. storage sheds	C1, C2	1
Outdoor applications		
Outdoor, rural or urban environment with low pollution Large distance (> 10 km) from the sea	C2, C3	2
Outdoor, rural or urban environment with moderate concentration of pollutants and/or salt from sea water Distance from the sea 1-10 km	C2, C3, C4	2, 3
Coastal areas Distance from the sea < 1 km	C3, C4, C5, CX	3, 4
Outdoor, areas with heavy industrial pollution Atmospheric SO_2 concentration > 10 µg/m$_3$ as yearly average (e.g. petrochemical, coal industry)	C4, C5, CX	3, 4
Close proximity to roadways treated with de-icing salts Distance from roadways < 10 m	C3, C4, C5	3, 4
Special applications		
Special applications Areas with special corrosive conditions, e.g. road tunnels with de-icing salt, indoor swimming pools, special applications in the chemical industry (exceptions possible).	Special climates not covered by C-classes	4, 5

Table 6: Environmental conditions and their link to corrosivity categories and corrosion resistance classes, per ISO 9223:2012.

Selection tables for fasteners and installation systems
Fasteners such as anchors, nails and screws are often used for single-point and safety-relevant fixtures. Poor or limited visibility of the fasteners after installation, the inability to repair or replace them, the part to be fastened, and (in the case of expansion anchors) the friction conditions in the drilled hole all mean it is necessary to take a conservative approach to minimize the risk of corrosion to the fastener material. With zinc-coated fasteners, the end of the fastener's lifetime coincides with the start of the loss of the underlying steel. The selection table for fasteners therefore does not state a lifetime range, but gives a general yes/no recommendation based on the building service defined in the approval guidelines, e.g. 25 or 50 years – see selection tables footnotes for details.

Fasteners often form part of a building's structure, which means that the lifetime of the fastener is required to be equal to the design lifetime of the building. Secondary structures such as **installation supports** are often not required to last the entire lifetime of the primary structure as building services are subject to more frequent exchanges and modifications.

Furthermore, many applications with installation channels allow repair or lifetime extension measures, for example, through application of zinc spray. With proper assessment of the corrosivity of the environment including the planned lifetime and also the implementation of periodic inspection and repair intervals, coated carbon steel products can be used suitably and economically for a wide range of applications in a wide range of surroundings.

In the case of zinc-coated installation systems the onset of corrosion of the steel substrate does not cause immediate problems in terms of mechanical integrity. The occurrence of around 5 % of red rust on the surface is considered to indicate the end of the period of protection provided by the zinc coating. It is therefore possible to state a guideline range of expected lifetime for a specific environment.

European Technical Approval – metal anchors for use in concrete
For anchors, the current European Technical Approval (ETA) requires use of stainless steel in the corrosion resistance class III ("A4 class") for outdoor applications in general. Special applications such as road tunnels and indoor swimming pools require an even higher grade (class IV or V). The reason for this is, of course, to provide the user with a conservative and practical guideline for selection of a proper material for outdoor applications. The intent of the ETA approach is to eliminate the need for a detailed assessment of the environment and the application when strictly following the ETA (assuming non-atmospheric corrosion issues are not present). The user, for instance, does not have to evaluate the influence of chlorides on the jobsite resulting from proximity to sea water or the use of de-icing salts.

However, in cases where chlorides can be neglected it is possible to go beyond the ETA specifications. From a technical point of view, hot-dip galvanized or stainless steel anchors in the CRC II ("A2 class") may be suitable for outdoor environments with certain lifetime and application restrictions. This is based on long-term experience with these materials. Please note that this requires a specific assessment and deeper understanding of the application and the environment (see following tables).

5.1 Selecting the right corrosion protection for anchors, power-driven fasteners and screws

For fasteners to be perfectly satisfactory and reliable for their entire service life from a corrosion perspective, all the influencing factors must be identified before a suitable fastener can be selected.

The following table provides a general guideline for the most common applications for fastening elements. The appropriate corrosion protection for each fastening material is shown based on the typical atmospheric environments (see notes).

Hilti anchor channels (HAC) are available in hot-dip galvanized steel according to E ISO 1460:2009-10. HBC special bolts are available in electro-galvanized, hot-dip galvanized and A4 versions. HAC may be used together with HBC in any material combination in dry indoor environments according to ETA-11/0006 (28th February 2012). When HBC are hot-dip galvanized, they may also be used in indoor environments with temporary condensation.

Anchors, power-driven fasteners and screws	product examples **Anchors**	HSA, HUS3, HST, HIT-V, HRD	HUS3-HF	HSA-F, HIT-V-F	HSA-R2, HRD-R2	HUS-HR, HSA-R HST-R, HIT-V-R HIT-Z-R, HRD-R	HST-HCR
	Screws	S-DS01, S-DD01	S-MD Z, S-MP Z	S-CD C, S-IT C		S-MD S, S-CD S	S-MD SS, S-CD SS
	Power-driven fasteners	X-ENP [1], X-U X-GHP, X-GN	X-FCM-M, X-GR			X-BT, X-BT-ER X-CR, X-FCM-R	On request
	Coating/ material	Carbon steel with or without phosphating	Electro-galvanized	Duplex-coated carbon steel	HDG/sherardized 45-50 µm	A2 AISI 304	A4 AISI 316	HCR, e.g. 1.4529

Environmental conditions	Fastened part	Carbon steel	Electro-galv	Duplex	HDG	A2 AISI 304	A4 AISI 316	HCR
Dry indoor	Steel (zinc-coated, painted), aluminum, stainless steel	■	■	■	■	■	■	■
Indoor with temporary condensation	Steel (zinc-coated, painted), aluminum	–	–	■	■	■	■	■
	Stainless steel			–	–	■	■	■
Outdoor with low pollution	Steel (zinc-coated, painted), aluminum	–	–	□[2]	□[2]	■[2]	■	■
	Stainless steel			–	–		■	■
Outdoor with moderate concentration of pollutants	Steel (zinc-coated, painted), aluminum	–	–	□[2]	□[2]	■[2]	■	■
	Stainless steel			–	–		■	■
Coastal areas 0-1km	Steel (zinc-coated, painted), aluminum, stainless steel	–	–	–	–	–	■	■
Outdoor, areas with heavy industrial pollution	Steel (zinc-coated, painted), aluminum, stainless steel	–	–	–	–	–	■	■
Close proximity to roads	Steel (zinc-coated, painted), aluminum, stainless steel	–	–	–	–	–	■	■
Special applications		**Consult experts**						■

■ = expected lifetime of anchors made from this material is typically satisfactory in the specified environment based on the typically expected lifetime of a building. The assumed service life in European Technical Assessments is 50 years for concrete anchors, 25 years for power-driven fasteners, steel and sandwich panel screws, and 10 years for flat roof insulation screws.

□ = a decrease in the expected lifetime of non-stainless fasteners in these atmospheres must be taken into account (≤ 25 years). Higher expected lifetime needs a specific assessment.

– = fasteners made from this material are not suitable in the specified environment. Exceptions need a specific assessment.

[1] Outdoor exposure for up to 6 months during construction is permissible for Hilti high-strength electro-galvanized siding and decking fasteners such as the X-ENP (see instructions for use for details).

[2] From a technical point of view, HDG/duplex coatings and A2/304 material are suitable for outdoor environments with certain application restrictions. This is based on long-term experience with these materials as reflected e.g. in the corrosion rates for Zn given in the ISO 9224:2012 (corrosivity categories, C-classes), the selection guidelines for stainless steel grades provided in Eurocode 3 EN 1993 (final draft 2014) or in the national technical approval issued by the DIBt Z.30.3-6 (April 2014) and the ICC-ES evaluation reports for our products for North America (e.g. ESR-1917, May 2013). The use of those materials in outdoor environments however is currently not covered by the European Technical Assessments (ETA) of anchors, where it is stated that anchors made of galvanized carbon steel or stainless steel grade A2 may only be used in structures subject to dry indoor conditions, based on an assumed working life of the anchor of 50 years.

5.2 Selecting the right installation system

Hilti's installation systems are supplied in various coating technologies to meet the requirements in all conditions:

Hilti system	Indoor Coated	Outdoor Coated		Outdoor Plus	
	Zn	HDG Zn	HDG ZM	S A2	S A4
MM-Channels	X				
MM-Components	X				
MQ-Channels	X	X	X	X	X
MQ-Components	X	X			X
MT-Channels	X		X		
MT-Components	X	X			
MI & MIQ-Channels		X			
MI & MIQ-Components		X			
MC-Channels	X	X			
MC-Components		X			

The typical lifetime expectancy of Hilti's installation systems is shown in the table below:

Installation systems		Indoor coated (C1–C2)	Outdoor coated (C3)		Outdoor Plus	
	Channel system	MT, MQ, MM, MC	MT-OC. MQ-F,MQ ASTM, MC-OC, MI, MIQ		MQ system stainless A2/ AISI 304	MQ system stainless A4/ AISI 316
	Pipe fastening	Indoor pipe rings[1]	HDG pipe rings[2]	MI-UB, MI-PS	Stainless pipe rings[3]	
Environmental conditions		**Lifetime (in years)**				
Dry indoor		50–100	100		■	■
Indoor with temporary condensation		25–70	50–100		■	■
Outdoor with low pollution		5–10	25–70		■	■
Outdoor with moderate concentration of pollutants		–	15–40		■	■
Coastal areas		–	5–20		–	■
Outdoor, areas with heavy industrial pollution		–	5–20		–	■
Close proximity to roads		–	–		–	■
Special applications		**Consult experts**				

■ = expected lifetime of an installation system made from this material is typically satisfactory in the specified environment.
[1]   Indoor pipe rings: MP-H, MP-HI, MP-LH, MP-LHI, MPN, MP-MI, MP-MIS, MP-M, MP-MXI, MP-MX, MP-PI, SDC, MP-SP
[2]   HDG pipe rings: MP-MI-F, MP-M-F, MP-MXI-F, MP-MX-F
[3]   Stainless pipe rings: MP-SRN, MP-SRNI, MP-MR, MP-MRI, MP-MRXI

Note
1. Lifetime refers to the potential numbers of years until there is 5% red rust formation on any given product's surface within the system (generally threaded parts, not profiles, connectors or baseplates)
2. Lifetime is influenced by the exact environmental conditions of the project location

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Stainless steel
http://www.edelstahl-rostfrei.de/
http://www.bssa.org.uk/
http://www.worldstainless.org/
http://www.euro-inox.org/ (information available in many languages)

Standards
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7 DISCLAIMER

All information given in this handbook is based on the tests, principles, formulas, standards and approvals described in this handbook, current as of the date of publishing (June 2021). It applies only to applications comparable to the conditions described. Extrapolation of the results to other environments is not permissible. The selection guidelines and life expectancy information is based on atmospheric corrosion only, and is intended only as an approximate guide to assist in initial assessment. Site-specific conditions, including general corrosion parameters (e.g. temperature, air and water movement, local pollutants, mechanical abrasion), other forms of corrosion, lifetime requirements, application criticality, inspection programs and local legal, code or project requirements can significantly affect the selection process and must always be evaluated. Significant scatter of values may also occur within the bandwidth of coating / material performance and environmental parameters applicable to a specific structure. Full assessment and final selection is the responsibility of the project specialist or, respectively, the purchaser. This report must be regarded as a unit and may be passed on to others or copied for further use only in its entirety. As this information is intended only as a general guideline, Hilti accepts no liability whatsoever for damage or injury resulting from use of this handbook.

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