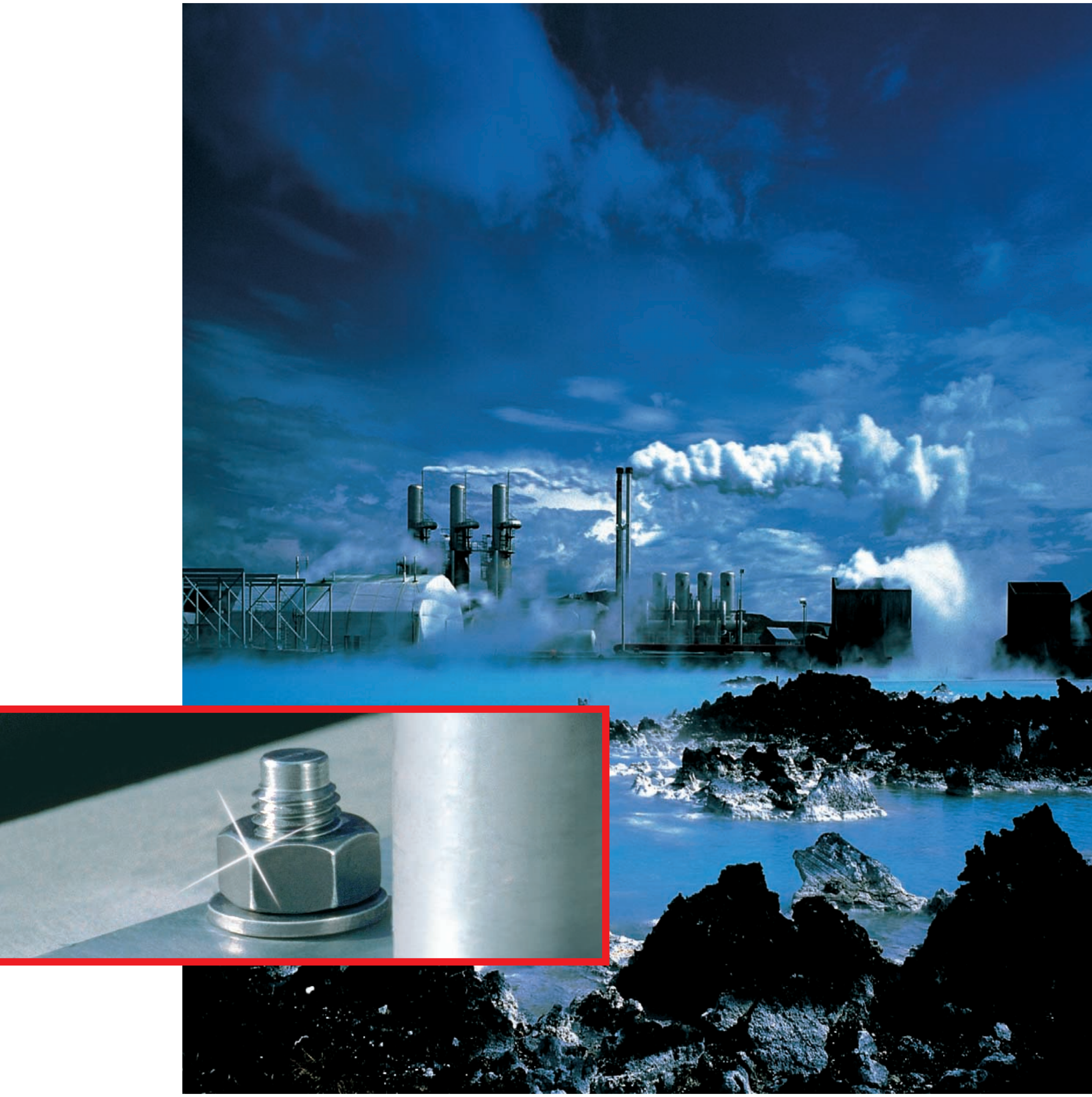
Corrosion-resistant Fastenings



HILTI

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Foreword

This corrosion brochure contains the most important fundamentals of corrosion and protection against corrosion, while providing an introduction to the corrosion behaviour of materials and protective coatings used in fastening systems. This brochure is intended to give users basic information for the right use of systems for protection against corrosion in the field of fastening technology.

The various fields of application of fasteners are given on the basis of examples and recommendations for correct material selection. These recommendations do not apply generally to all applications in their respective surroundings. In view of this, it is each user's task to check each application and, if necessary, to consult a corrosion specialist.

In view of this, we must draw the following to your attention.

When you have read this brochure, you will still not be an expert on corrosion. It is important though, for you to be informed about possible suitable solutions, but it is even more important for you to be aware of the potential risk of using an unsuitable material.

Your local Hilti engineer will be pleased to advise you and can furnish you with the necessary information. He / she also has the possibility of obtaining support from the specialised knowledge available in our corporate research department at any time.

Schaan, May 2000

Gerald Felder
Research Engineer
Materials and Mechanics
Corporate Research

Introduction

Roughly a fifth of annual steel production in the world is needed to replace steel parts damaged by corrosion or lost forever through rusting. This is a considerable economic loss. The greater part of this loss could be avoided in view of the current level of knowledge. In the long term, even if initial costs are higher, selecting a suitable means of protection against corrosion, using suitable materials and designing to resist corrosion are the more economical approach.

Where fastening systems are concerned, great importance must be attached to safety aspects in addition to the economics. To make allowances for today's much greater awareness of safety, it is extremely important that products are brought into line with the "the state of the art". Hilti is aware of its responsibility as a fastener manufacturer and regards this as a major challenge. By conducting practical research into corrosion and working with selected university as well as college laboratories, Hilti strives to meet these stiff requirements. As a result, we are in a position to decisively improve the "state of the art" with applications in many highly corrosive surroundings and thus to increase the safety level of fasteners, e.g. those subjected to a road tunnel atmosphere.

To safeguard the quality of our fasteners, numerous tests are carried out and the long-term behaviour, i.e. up to 18 years, observed in a wide variety of environmental conditions like rural, industrial and coastal atmospheres. These studies help researchers to understand the corrosion processes taking place on fastenings. This is a prerequisite when developing suitable protection against corrosion. Furthermore, in-place fastenings are regularly examined. For users, this gives the assurance of the highest level of safety if they decide to use a Hilti product.

Introduction

Although laboratory tests can give valuable input about general corrosion behaviour, they are not always able to provide adequate long-term data on the corrosion behaviour of materials and systems for protection against corrosion. In view of this, systems protecting against corrosion and the corrosion behaviour of materials for special uses are kept under observation during special field tests.

Conditions prevailing in a road tunnel, for example, were investigated jointly by Hilti and the Swiss Federal Institute of Technology Zurich in the Mont Blanc Tunnel and several Swiss road tunnels. While doing so, many materials and protective coatings were, and still are, exposed to tunnel atmospheres. Results from these tests have been made available to the public. As a consequence, the grade of steel recommended by Hilti, i.e. HCR as per DIN 1.4529, is specified for use in road tunnel atmospheres and indoor swimming pools in most industrial countries of the world for safety reasons. (HCR = highly corrosion resistant).

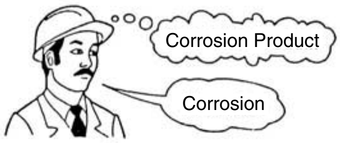
Further to the mentioned tests in road tunnel atmospheres, Hilti corporate research carries out corrosion tests in several other highly corrosive surroundings. The goal of testing in this way is to learn more about the specific conditions in individual areas so that suitable and safe materials for fastenings can be made available.

1. What is corrosion?

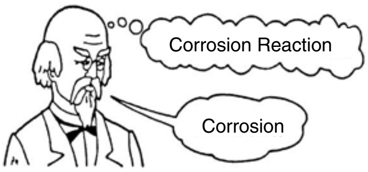
Corrosion is understood to be the tendency of a metal to revert from its synthetically produced state to its natural state, i.e. from a high-energy pure form to the low-energy but thermodynamically stable form of a metal oxide (ore). As a rule, an ore is the chemical compound of a metal with oxygen, hydrogen and, possibly, other elements. *Corrosion is thus a natural process.*

In everyday usage, the word corrosion has many meanings.

A practical person understands the word corrosion **to mean rust and its** outward forms.



A technically minded person thinks of the **chemical and electrochemical processes and reactions** taking place when mention is made of **corrosion.**



When a legal authority or judicial officer speaks of corrosion **it is generally a matter of** damage by corrosion **and its consequences.**

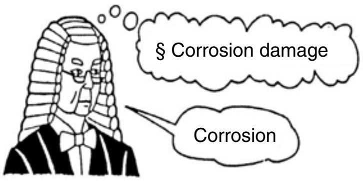


Fig. 1: Corrosion is rust?

What is corrosion?

With a view to achieving standardisation when referring to and writing about this subject, the main terms have been defined, i.e. in DIN 50900 and ISO 8044. Accordingly, corrosion is a property of a system that is defined as follows.

Corrosion is the chemical or electrochemical reaction of a material with its surroundings through which a measurable change in the material and impairment of the function of a building component can take place. DIN 50900

Material

The definition of material corrosion does not, actually, exclude the destruction of wood, ceramics, textiles, etc., but in practice the term applies primarily to metals and plastics, i.e. corrosion is directly associated with metals. The subject of materials, as such, however, includes all conceivable kinds of influence that can change the state of a material, i.e. alloying, heat treatment, cold forming, etc., as well as the loads occurring under working conditions which can considerably influence the corrosion behaviour.

Environment (surroundings)

The environment, in principle, is understood to be the aggregation of all physical states where, however, first and foremost corrosion in liquid mediums – the electrolytic solutions – is of significance for field practice. Apart from the possibly wide variation in concentration and composition of these electrolytes, other predominating factors, such as temperature and pressure, exert an exceptionally strong influence.

Reaction

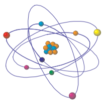
Unlike mechanical wear, corrosion is a fundamental chemical process during which metal atoms change from the metallic to the non-metallic, ionic state of solid or dissolved chemical compounds. Consequently, the theory of corrosion comes within the discipline of physical chemistry. Boundary reactions, reaction formulae, thermodynamics and kinetics permit the processes taking place to be described.
Generally, a distinction is made between types and forms of corrosion, which are explained in detail in the following.

2. Types of corrosion

Chemical reaction

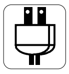
A “negative” example of oxidation, for instance, is the scale that forms during a heat treatment process, e.g. welding. A “positive” result of oxidation processes, on the other hand, is the oxide layers on stainless steels that form from oxygen in the air and are the reason why a stainless steel actually resists corrosion.

Metallophysical reaction



An example here is the embrittlement caused by hydrogen which diffuses into a material, then recombines and, as a consequence, can lead to failure of a building component. Embrittlement can be the result of a careless manufacturing process, e.g. surface coating like electrochemical zinc plating, and it can be initiated by corrosion processes too (metal dissolution). In the latter case, reference is made to corrosion-induced hydrogen embrittlement.
In general: the higher the strength of a component, the greater will be its tendency to suffer hydrogen embrittlement.

Electrochemical reaction (most frequent type of corrosion)

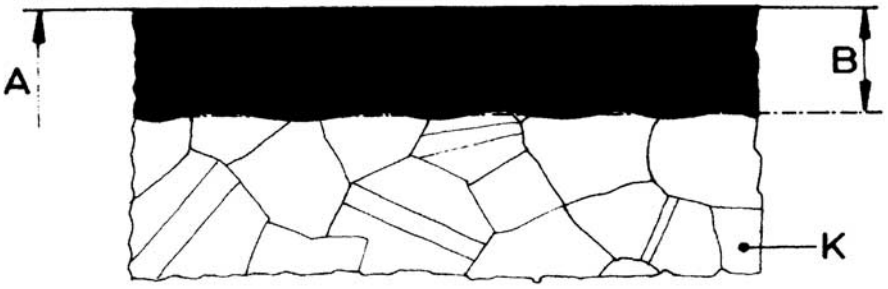


When moisture is present, mass transport through ions and a charge exchange through electrons take place at the metal-electrolyte phase boundary. An electrically conductive medium, e.g. water, is always required. In ion-conducting mediums, corrosion always takes place on an electrochemical basis. This type of corrosion is also often described as a “galvanic reaction”.

3. Forms of corrosion

General (surface or superficial) corrosion

“Active” metals can suffer general corrosion. According to the German standard DIN 50900, general corrosion is a form during which the entire surface is eaten away virtually uniformly. This also includes wide / shallow pit corrosion during which attacks at points various points differ widely. Most damage to materials is caused by general corrosion. The extent of this form of corrosion can usually be well estimated by carrying out laboratory tests. The rate of corrosion is mostly given as mm/year or g/m^{2}h. Using these average figures, it is possible to calculate the life expectancy of a component, and thus to alter a life expectancy by, for example, increasing a component thickness. Examples of general (surface) corrosion are corrosion phenomena taking place on plain-carbon and low-alloy steels when a covering layer forms in neutral mediums.



Uniform material removal

A... starting level
B... Reduction of component thickness due to uniform removal by corrosion
K... Grain: many grains together form a grain structure, i.e. base material

Fig. 2: Schematic depiction of uniform surface removal

Virtually flat and monotonic removal of a material takes place over large areas of a metal surface during uniform general corrosion (zone B in fig. 2). This chronological monotonic removal of material takes place in virtually constant corrosive conditions. In actual field conditions, the surface is eaten away non-uniformly, while becoming rough and rugged (see fig. 3).

The formation of wide / shallow pits is a kind of corrosion with locally different rates of material removal. This shallow pitting is caused by the presence of corrosion cells. A corrosion cell is a galvanic cell with locally differing partial current densities that cause metal dissolution. The different rates of dissolution may often be due to material inhomogeneity, local variances in concentration and varying surrounding conditions, such as temperature fluctuations in the attacking medium, which affect both material and medium.

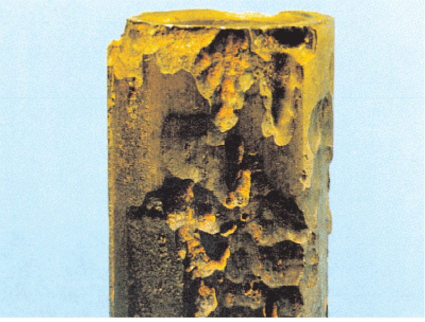


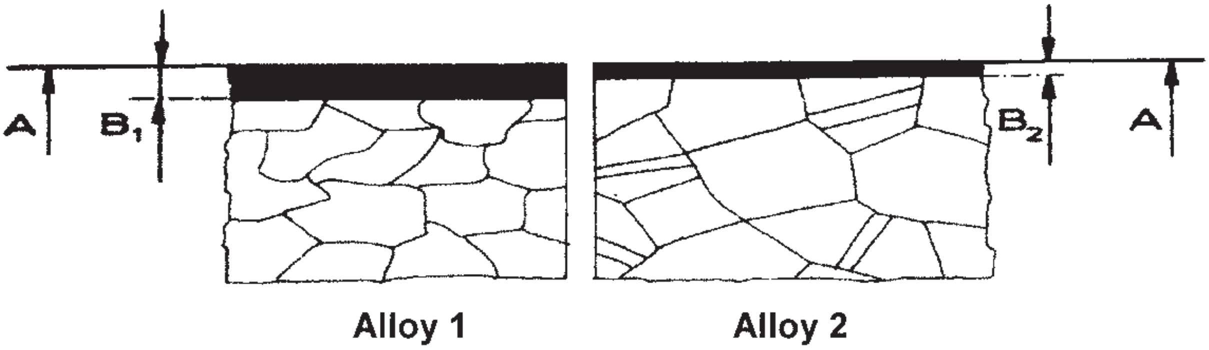
Fig .3: Non-uniform general corrosion – wide / shallow pits on a structural steel exposed to sea water

Many so-called base (ignoble) metals are not resistant in acidic or even neutral mediums. In the case of pure iron, plain-carbon steel and low-alloy steel, for example, rates of corrosion highly dependent on the pH value can be observed in the range below 5. In the pH range between 5 and approx. 10, their rate of corrosion is not dependent on the pH value, while the iron has a passive behaviour at pH values above about 10. This is why conventional reinforcing steels, and also fasteners, are protected against corrosion in alkaline concrete. In the same vein, the constituents of a material and how it has been treated are crucial. In 1% sulphuric acid, a steel containing approx. 1 % carbon that was heat-treated at about 350°C (martensitic structure) has a rate of corrosion about four times higher than if it had been tempered at 260°C.

The rate of corrosion of “active” materials that can suffer general (surface) corrosion is dependent on the following, important factors, apart from those mentioned above: temperature of medium, salt content, oxygen content, exposure time, air pollution and medium flow conditions.

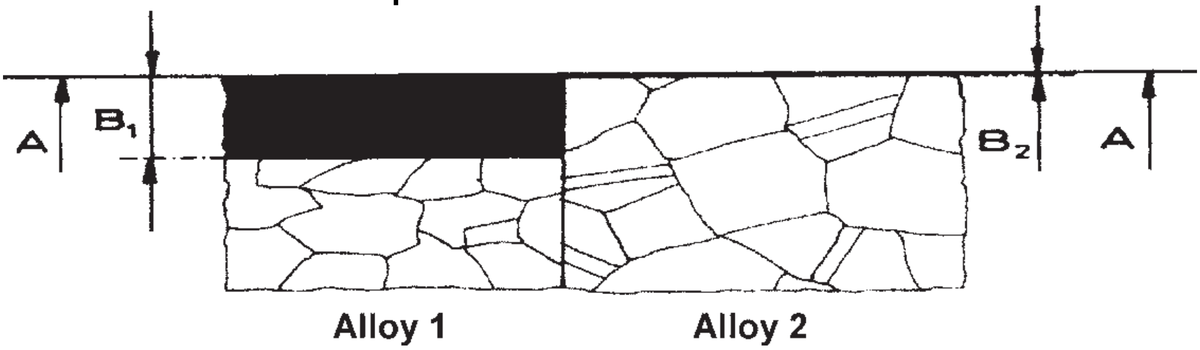
Contact corrosion An electrically conductive link between two dissimilar metals in an aggressive medium (electrolyte) leads to contact corrosion.

Example 1:



Non-touching materials of different resistance/ polarity exposed to same media
A... Starting level
B_1 B_2 ... Reduction of thickness depending on the material's resistance

Example 2:



Connected materials of different resistance in the same aggressive medium

A ... Outset level
B_1 B_2 ... Greater dissolution of less resistant alloy 1, while the more resistant alloy 2 is protected electrochemically and the corrosive attack reduced or stopped.

Fig. 4 : Schematic depiction of contact corrosion

The driving force behind contact corrosion is the potential difference of a metal couple. The less noble material (alloy 1 in fig. 4) suffers stronger corrosion and acts electrochemically like an anode, while the more noble material (alloy 2) acts like a cathode and suffers less corrosion. Whereas, in example 1, the two metals are linked only by the medium, they are in direct contact in example 2 which clearly increases the rate of corrosion of the less noble metal. The nobler metal is even protected electrochemically in this way.

Three factors govern the rate of attack during contact corrosion:

1. The difference in resting potentials of the linked metals
2. The surface condition of the linked metals (noble / not noble)
3. The conductivity of the electrolyte

A positive example of active utilisation of the described contact corrosion phenomenon is the way zinc protects plain-carbon and low-alloy steels. Zinc is the less noble metal which actively protects steel by being corroded itself. To avoid contact corrosion, and this is of the greatest importance for fasteners too, the ratio of the surface areas of linked components must be taken into account. As a fastener is always the smaller part of such a system, it must at least be made of an equivalent or, even better, a more noble material. To avoid contact corrosion around a fastener, such measures as galvanic separation, sealing the point of contact, etc., are conceivable. (See active protection against corrosion.)

Fig. 5 This is a typical case of contact corrosion. Here, zinc, carbon steel and Cr/Ni steel were used together. The noblest metal, the Cr/Ni steel, has the largest surface area which first causes strong corrosion of the fastener zinc. Afterwards, the carbon steel of the fastener, also less noble, suffers a higher rate of corrosion.
Electrochemically zinc-plated fastener in sheet metal of material 1.4301 (304) (wrong solution), Hilti weathering test, coastal climate

Pitting corrosion

Passive metals and alloys, such as aluminium alloys, titanium, chromium steels and chromium-nickel steels owe their resistance to corrosion to a sub-microscopic passivation (oxide) layer that forms on their surface. A local attack of corrosion can be initiated on stainless steels, for example, by only very slight amounts of halogenides (anions: chloride, bromide and iodide). Mostly, these anions are chlorides from sea water, road salt, etc. The initiating process takes the form of a local break-down of the passivation layer. A range of what, in some cases, are extremely hazardous corrosion phenomena propagate from local points of surface break-down of this kind. In the following, the most significant of these corrosion phenomena, most importantly due to their extreme relevance to fasteners, are discussed in connection with stainless steel.

Pitting corrosion takes place when a critical threshold of the electrode potential is exceeded (critical pitting potential). Each material has a different such potential which, furthermore, is influenced by the respective medium. Whether or not pitting corrosion will appear on a stainless steel depends on a great many influencing factors. These include, for example, the type and amount of oxidising agent, i.e. oxygen and others, the chemical constituents, most importantly the chromium, molybdenum and nitrogen content, the state of the grain structure and the surface condition (finish) of the material as well as the chemical composition and pH value of the medium. Generally, the susceptibility to pitting increases as the temperature rises. The susceptibility of a material to pitting can be roughly estimated using the so-called “activator total” based on the chemical constituents of a CrNi or Cr steel. In pertaining literature, a whole range of so-called “activator totals” exists. Only the generally known, “classical” activator total, AT = % Cr + 3.3% Mo is given as information here.

With pitting, the attack of corrosion has the appearance of pinholes, and it can eat through even thick-walled components in a short time. In view of this, pitting is much more hazardous than general corrosion. Attacks by this type of corrosion are facilitated by zones on a metal surface that have been mechanically scored, roughened or subjected to extensive local cold forming. Pitting corrosion, or simply pitting, is referred to when the depth at the point of attack is equal to or greater than the diameter. A clear demarcation between this and shallow / wide pit corrosion is not always possible.

Fig. 6 shows the pitting phenomenon on a competitor’s powder-actuated fastener made of a simple Cr/Ni steel.

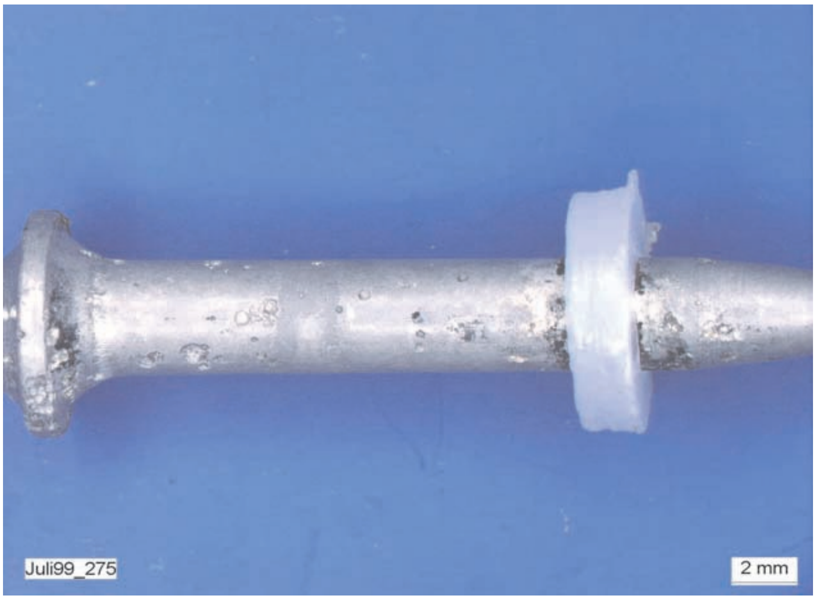


Fig. 6: Pitting of a fastener made of the 1.4301 (AISI 304) material (Competitor Product)

During pitting corrosion, the process takes place in several chronological steps.

The first step, described in fig. 7 as pit formation, is when the passivation layer breaks down. The second step decides whether or not actual pitting will take place. In case 1, below, a passive film forms again over the pit produced by the break-through, i.e. repassivation or healing, provided that sufficient oxygen is available and conditions permit this. Then, <u>no</u> pitting corrosion takes place.
Case 2, below, on the other hand, shows the situation in which the surrounding conditions do not permit repassivation. The material is overtaxed. Stable growth of the pit takes place. This is now referred to as pitting corrosion which, depending on the circumstances, can propagate into a component. Rates of corrosion of more than 10 mm per year are not seldom.

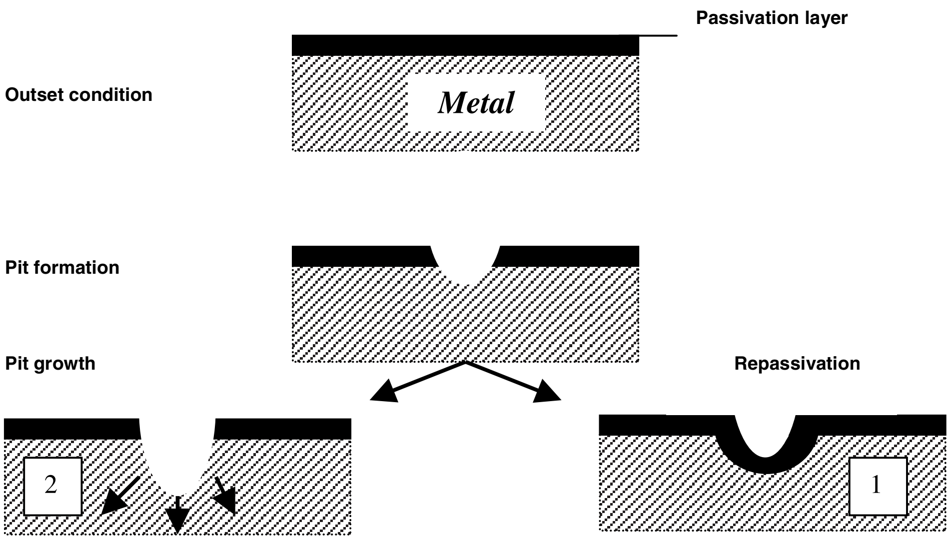
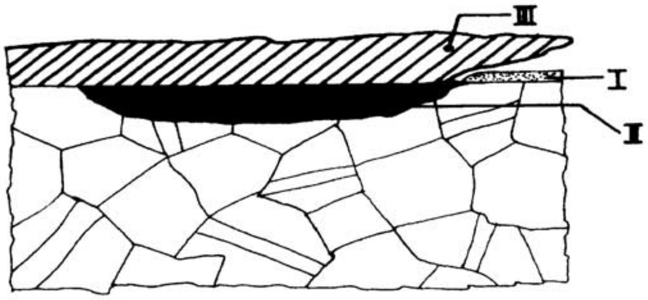


Fig. 7: Schematic depiction of pitting corrosion development

Crevice corrosion

During an attack of crevice corrosion, the same processes take place as during pitting corrosion. Substances causing pitting corrosion can accumulate in crevices. As a result, there is a locally accelerated attack of corrosion, and repassivation is difficult.

Crevices (fig. 8: between zones 1 and 3) generally suffer pitting corrosion sooner than the rest of a surface. In view of this, reference could also be made to intensified pitting corrosion. The narrower the crevice, the more critical the situation becomes (entry of insufficient oxygen into crevices, e.g. beneath washers, layers of dust, etc.).



I ... Passivation layer which can no longer form in the narrowing crevice.
II ... Active dissolution, propagating from the zone in the crevice where no or only incomplete formation of the passivation layer is possible.
III ... Design crevice, e.g. seal, surface contamination, poor weld, etc.

Fig. 8: Schematic depiction of crevice corrosion

Stress corrosion cracking (SCC)

This corrosion phenomenon occurs only in the presence of certain mediums and when a component is subjected to a purely static tensile load. Internal stresses in a material can be sufficient to initiate a sudden attack of stress corrosion cracking. Where fasteners are concerned, this means that the surrounding conditions must be taken into account, without fail, when selecting their material. For some years now, it has been known, for example, that materials of the A2 (304) and A4 (316) grades can suffer stress corrosion cracking in an environment containing chlorides.

In general, stress corrosion cracking in electrolytes can be characterised by the fact that critical limiting conditions exist for the corrosion system (medium and material), the potential and the magnitude as well as type of mechanical stressing. Stress corrosion cracking can occur with austenitic steels, i.e. those of the A2 (304) and A4 (316) grades in acidic mediums containing chlorides, e.g. chlorinated atmospheres in indoor swimming pools, road tunnels, etc.

Similarly, materials that would otherwise not suffer corrosion in a surrounding medium, i.e. would be stable, could lose their resistance if stressed mechanically.

The following fig. 9 is intended to explain the interaction of material, environment and tensile stressing which leads to stress corrosion cracking.

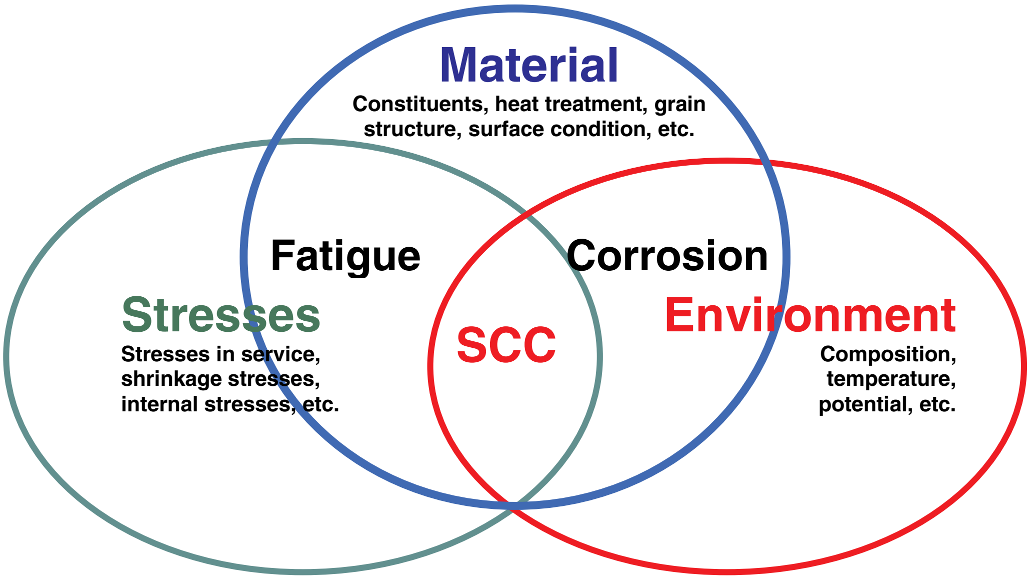
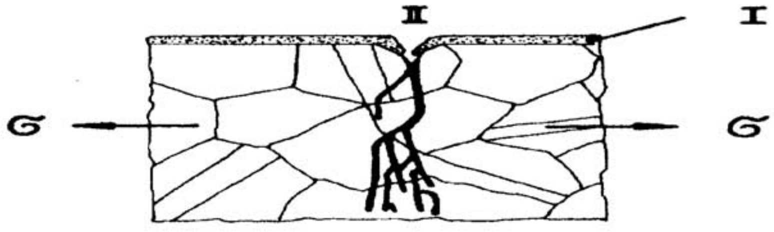
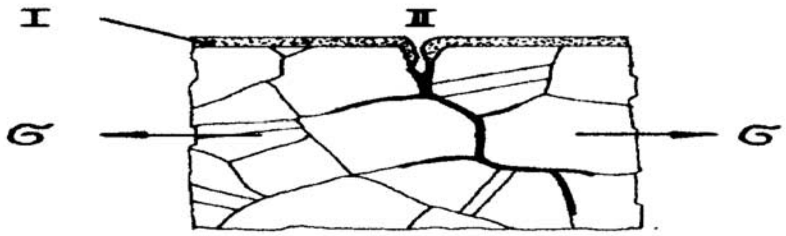


Fig. 9: Interaction resulting in stress corrosion cracking as per Prof. Hans Boehni



Transcrystalline (transgranular) stress corrosion



Intercrystalline (intergranular) stress corrosion

I ...	Passivation layer
II ...	Local breakdown of passivation layer and stress corrosion cracking, propagating more or less at right angles to tensile stress. The crack sides repassivate. The material at crack surface peaks are attacked.
σ ...	Tensile stress

Fig. 10: This depicts the possible cracking phenomena schematically. Crack propagation can be transcrystalline, i.e. through the middle of a grain, or intercrystalline, i.e. along grain boundaries.

In addition, a distinction is made with stress corrosion cracking between electrolytic (anodic metal dissolution as described above), and metallophysical cracking (cathodic absorption-induced brittle failure) - hydrogen embrittlement (hydrogen dissolved in the metallic lattice).
With high-alloy stainless steels, stress corrosion cracking is synonymous with anodic SCC, whereas embrittlement due to hydrogen is the case with high-strength steels.

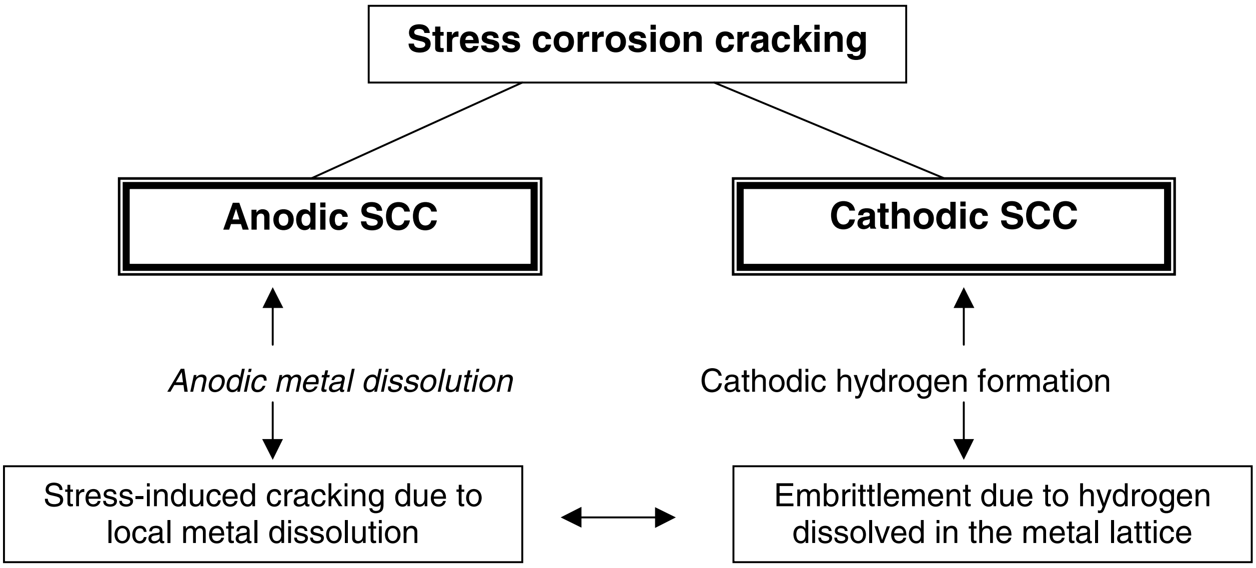


Fig. 11: “Anodic” and “cathodic” stress corrosion cracking as per Elsener

Fig. 12: This shows SCC of a retaining strap made of the material 1.4301 (A2, 304) after approx. 4 years of use in an indoor swimming pool (CH)

Hydrogen embrittlement

First and foremost, the high-strength steels with a tensile strength from approx. 800 to 1000 MPa suffer hydrogen embrittlement. A distinction is made between primary hydrogen embrittlement which, for example, can result during a galvanic zinc-plating process, such as pickling, and so-called secondary embrittlement, which is also referred to as corrosion-induced hydrogen embrittlement.

As a rule, primary hydrogen embrittlement can be counteracted by a suitable heat treatment, so-called baking (or disembrittlement). After a galvanic plating process, parts are tempered by keeping them, for example, at a temperature of about 200°C for several hours. During this time, a part of the hydrogen dissolved in the material is liberated, reducing the content of dissolved hydrogen to below the critical threshold for the component.

Generally, secondary (corrosion-induced) hydrogen embrittlement occurs with high-strength components that have already suffered an attack of corrosion. A typical example of this is damage by corrosion to, for example, electrochemically zinc-plated, high-strength bolts and nails used for fastenings directly exposed to the weather. As this type of SCC occurs only after a certain “incubation period”, it has also become known as “delayed fracture of screws and nails”. In general, the following applies: the higher the strength of a material, the greater will be the risk of hydrogen-induced stress corrosion cracking.

Fig. 13: These galvanised nails were used in a corrosive industrial environment. The cause of failure was secondary (corrosion-induced) hydrogen embrittlement.

Intercrystalline (intergranular) corrosion

A special kind of material damage due to chemical attack is intercrystalline corrosion. The attack takes place at grain boundaries. In certain steels, the corrosive attack can be so extreme that the microstructure is destroyed and the metal literally disintegrates (fig. 14).

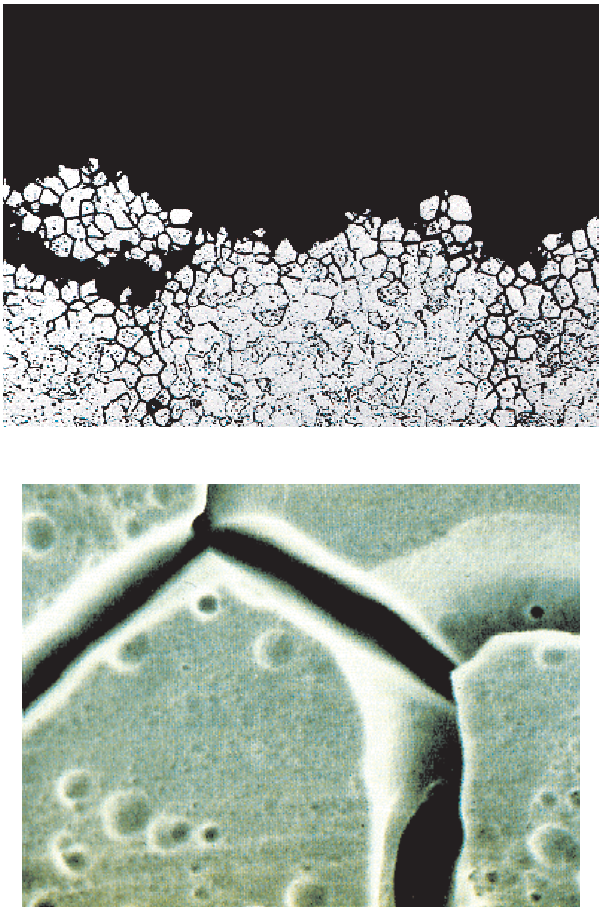


Fig. 14: Micrograph of a metal, and scanning electron microscope image of a selective attack
(Welded zone of a 1.4401, (A4, 316) material

A possible example:
If an austenitic, chromium-nickel steel is kept in the temperature range from 500 to 800 °C for a considerable time, e.g. when welding, etc., chromium-rich carbides can separate at grain boundaries, resulting in chromium depletion at these boundaries.
Remedy: The carbon content must be reduced to below 0.03 percentage by weight and / or the metal "stabilised" by adding titanium or niobium. An example of a "stabilised" and thus readily welded material of the A4 (316) grade is the titanium-stabilised material 1.4571 (316Ti) and the deep-carburised material 1.4404 (316 L < 0.003 % C).
(Comment: Fasteners may never be welded.)

Corrosion fatigue cracking

Transcrystalline cracks can result from alternating mechanical stress with simultaneous corrosive action. This cracking is not dependent on critical limiting conditions, i.e. any material-medium combination can be affected and there is no minimum loading limit as is the case in dry air. Hardly deformed, mostly transcrystalline cracks appear which can lead to sudden failure of a component. Corrosion fatigue cracking is often also called corrosion fatigue.

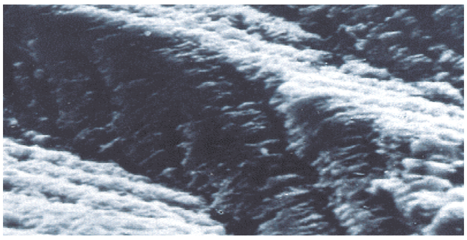


Fig. 15:
Image of a break surface after corrosion fatigue cracking of an anchor made of A2 (304) steel as per DIN 1.4301

Strain-induced corrosion

This takes the form of local corrosion with cracking of the metal. It is a consequence of damage to protective cover layers and repeated, critical extension or contraction of a component.

Microbiological corrosion

Microbiological corrosion is a type of attack in which microorganisms play a role. As an example, very aggressive products of metabolism or microbes can account for alloying components being chemically converted.

General comments

During many of the described forms of corrosion, the same corrosion reactions take place each time, but the circumstances change. Only in extremely seldom cases do the various corrosion phenomena and forms of corrosion of different metals and alloys occur alone. Mostly, during the interaction of different metals and various electrolytes, e.g. water and substances dissolved in it, extremely complicated processes take place that are influenced by the surroundings (environmental pollution, etc.). Despite continually increasing knowledge in the field of corrosion and extensive reference literature, it is often extremely difficult, even for specialists, to understand or explain certain corrosion processes. Consequently, widely differing experts’ opinions and models exist for certain corrosion processes.

In the field of fastening technology, it is absolutely essential, for understandable reasons, that corrosion research is continued and that findings are verified in field practice.

4. Protection against corrosion

Protecting a component from corrosion is a measure taken to avoid damage by corrosion with the aim of increasing the component’s service life expectancy. A distinction is made between active and passive protection. Active protection against corrosion is understood to be measures, like advance planning and design, that take corrosion into account, e.g. galvanic separation, resistant materials, protective measures in the medium and protection by impressed current. Passive protection is regarded as all measures which affect the component directly and by which medium access is stopped or hindered. This can be, for example, metallic or non-metallic protective coverings.

What protection against corrosion is used by Hilti and how are Hilti fasteners and fastening systems protected from corrosion?

Protection against corrosion / Materials	**Fastener protection**
Plastics	Polyamide, polypropylene, polyethylene, POM, HIT, HEA, HVU, RE 500, etc.
Organic coatings	Epoxy, acrylate and similar
Organic coatings with metallic contents and multiple-layer coatings	Dacromet, Delta- xx- coatings, Duplex coatings
Zinc-plated steel	Electrochemically zinc plated, sherardised, hot-dipped galvanised, Sendzimir zinc plated, etc.
Corrosion-resistant materials	Stainless steels, special alloys
Additional measures	Galvanic separation, etc.

Plastics

Polyamide is characterised by good chemical resistance, and it is used by Hilti for light-duty plastic anchors.
Plastic fasteners suitable for the respective application are used to install insulating materials and as other connecting parts. Attention is paid to good chemical resistance and, where necessary, to long-term resistance to UV light.
RE 500, HEA, HVU, etc. are used for chemical fastenings, i.e. adhesive anchors and injection systems. Synthetic resin, hardener and fillers are formulated for each other so accurately that there is only very slight shrinkage, tendency to creep and water absorption. The resistance to alkalis, saline solutions and acids is very good.
Organic coatings are used to only a very limited extent on fasteners as protection against corrosion. Mostly, coating systems of this kind are used on stainless steels to avoid cold welding processes.

Organic coatings

Virtually without exception, organic coatings provide passive protection against corrosion, i.e. they stop or delay the access of corrosive mediums to a component surface. If the protection offered is to be good, coating systems of this kind must be free from pores and adhere optimally. In practice, both are difficult to achieve with fasteners for the following reasons. Surfaces of fasteners are very often functional and their tribological properties are crucial for functioning under relatively high mechanical loading and exposure to corrosion, e.g. threaded parts. With this in mind, only organic coatings of restricted thickness can be used. If thin coatings are used, freedom from pores can hardly be achieved. These coatings thus provide only temporary protection against corrosion as in a humid atmosphere underfilm corrosion (underrusting) commences in a short time at imperfections, e.g. pores.

Organic coatings with metallic constituents

Coating systems with inclusions of metal spangle / glitter or metal powder, e.g. aluminium or zinc have a special status among “organic coatings”. If active pigments of this kind are used in organic coatings, such as zinc and aluminium, adequate protection against corrosion can also be achieved with coatings less than 20 microns thick. Coatings of this kind are known, for example, under the trade names DACROMET or DELTA. The protection against corrosion they offer can be similar to that of hot-dipped galvanising, depending on how well they are applied and the protection requirements to be met (environment). These coatings, however, if damaged, and this is mostly unavoidable with fasteners, i.e. threads, etc., have a corrosion behaviour far inferior to that of hot-dipped galvanising or Sherardising. Organic coatings can not only be applied straight to a steel surface as one or several layers, but also to zinc-plated sheet-metal items, electrochemically zinc-plated parts or hot-dipped galvanised components. Systems produced by follow-up treatment of a zinc-plated surface, such as applying a subsequent coat of paint or a coating, are called Duplex coatings. The protection against corrosion offered by Duplex coatings is extremely effective in many fields because the more or less electrically insulating properties of paint systems and the sacrificial (cathodic) protection of zinc are combined. Among pregalvanised Duplex systems, the greatest protection is provided by hot-dipped galvanising with a suitable organic coating, e.g. epoxy.

Protection against corrosion

Zinc-plated steel

From an electrochemical point of view, zinc is far less noble than steel. Zinc plating on steel thus provides so-called sacrificial or cathodic protection against corrosion for the underlying steel surface. In other words, zinc dissolves more or less quickly, continually and uniformly depending on the surrounding conditions, and, so to speak, sacrifices itself in favour of the substrate. Generally, the rate of corrosion is more or less linear with respect to time, depending on the atmosphere. Consequently, the duration of protection against corrosion is directly proportional to the plating thickness.

Atmosphere	Mean surface removal / year Zinc plating
Rural	1- 2 microns
Town	3- 5 microns
Industrial	6- 10 microns
Coastal / marine	5- 9 microns

Table 1: Rates of zinc removal in various surroundings as per Dechema Manual, volume 7

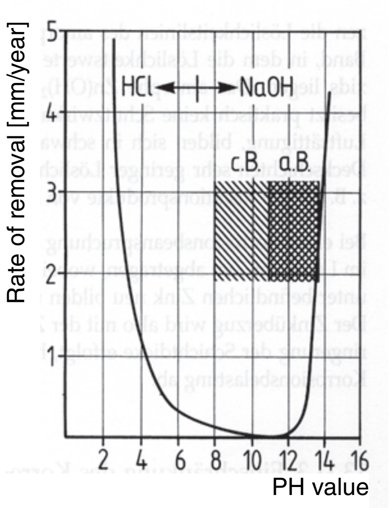
Consequently, the following applies: double the zinc thickness gives double the duration of protection. Thus, the desired duration of protection governs selection of the zinc-plating process.

Corrosion behaviour of zinc-plated steel

Zinc and zinc-plated components corrode uniformly over the surface in most cases. The products of corrosion are white to grey in the case of a pure zinc coating and this is referred to as white rust. On zinc-iron alloy coatings, e.g. hot-dipped galvanising or sherardised coating, the products of corrosion are red-brown. Red rust is the name given to the products of corrosion of the underlying carbon steel. It appears at defects and / or after the zinc plating has weathered away. The products of zinc corrosion, which are primarily basic zinc carbonate, form a protective layer that slows down the progress of corrosion. If exposed to the atmosphere, this protective layer is slowly removed by wind and rain. During atmospheric corrosion, zinc is eaten away approximately ten times slower than carbon steel.

In an atmosphere loaded with sulphur dioxide (industrial climate), the protective layer (zinc carbonate) cannot form. As a result of the reaction with sulphur dioxide and oxygen in the air, readily soluble zinc sulphate is produced and can be washed away by rain. The rate of zinc corrosion in an industrial atmosphere is thus far higher than in a rural or town atmosphere. Owing to the restricted coating thickness on threaded parts (dimensional accuracy), the limits to possible uses of zinc plating are reached, especially those of hot-dipped galvanising. Hot-dipped galvanising has also not proven satisfactory as protection against corrosion in poorly ventilated places with high humidity, e.g. in damp insulating materials.

To a certain extent, zinc can also protect patches without a zinc coating due to its sacrificial action, i.e. effect over a distance. Zinc and its alloys are only slightly or not resistant to acids and strong alkalis. Consequently, zinc plating has no significance in the fabrication of chemical apparatus. The rate of corrosion of a zinc coating is heavily dependent on the surroundings. Zinc-alloy coatings, e.g. galvanic Zn/Fe, Zn/Co, Zn/Sn, Zn/Ni, hot-dipped galvanising and sherardising, have a better corrosion behaviour and thus, under circumstances, provide a longer period of protection for the same coating thickness than conventional pure-zinc galvanic coatings.



c.B.: carbonated concrete
a.B.: alkaline concrete

Diagram 1:**Ranges of resistance of zinc coatings in relation to pH value**

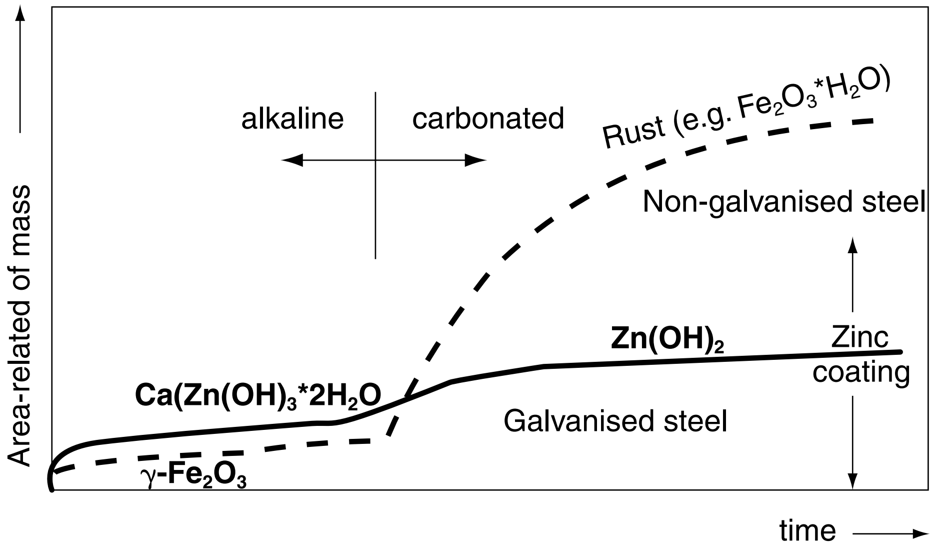


Diagram 2: Ranges of resistance and corrosion behaviour of galvanised and non-galvanised steel in alkaline and carbonated concrete

The behaviour of, for example, zinc-plated fasteners in concrete is shown by the foregoing diagrams 1 and 2. In general, it can be said that the alkalinity of concrete protects a fastener as long as the concrete is not carbonated (pH approx. >11). Although the rate of corrosion or rate of removal of zinc in new concrete is higher than that of the underlying steel, zinc-plated fasteners can still be used without second thoughts. As a rule, the part of a zinc-plated fastener seated in the concrete is protected against corrosion for a very long time. If possible, zinc-plated fasteners should not be placed in very new concrete (less than 28 days old) because this can dissolve the zinc and thus reduce the life expectancy, especially in the transition zone of hole to atmosphere. Even if the zinc coating is dissolved in this zone, protection against corrosion of the base material (bare carbon steel) is still very effective in alkaline concrete. This is why, for example, reinforcing bars are very well protected against corrosion as long as the surrounding concrete is sufficiently alkaline. If, however, the concrete loses alkalinity due to carbonation processes, etc., or is already carbonated, the rate of corrosion or rate of removal of both the zinc coating and the carbon steel will be far higher than in the alkaline zone (see diagrams 1 and 2: carbonated zones).

Zinc plating processes used by Hilti

The majority of Hilti fasteners (studs, nails, anchors, etc.) are also electrochemically zinc plated in addition to other zinc plating processes, such as hot-dipped galvanising, sherardising, etc.

Process	Products
Electrochemical zinc plating	DX nails and threaded studs, anchors, M installation system
Sendzimir zinc plating	Anchor parts, M installation system
Sherardising	Anchors
Hot-dipped galvanising	Anchors, M installation system
Others	Miscellaneous

Table 2: Zinc-plating processes used by Hilti

Electrochemical zinc plating

During electrochemical zinc plating, pure zinc or zinc alloy is deposited on steel from a zinc salt solution on applying a direct current. The adhesion is good. The achievable layer thicknesses are limited to approximately 25 microns in most cases. Typically, electrochemically zinc-plated fasteners have a zinc thickness of at least 5 microns and, with few exceptions, they are blue chromated. This gives them adequate protection against corrosion for use in dry inside rooms. If they are exposed to moisture though, for instance due to condensation from the surrounding air, their protection against corrosion (life expectancy) is limited. If, furthermore, this condensation is in the acid pH range (industrial climate), the rate of corrosion clearly increases.

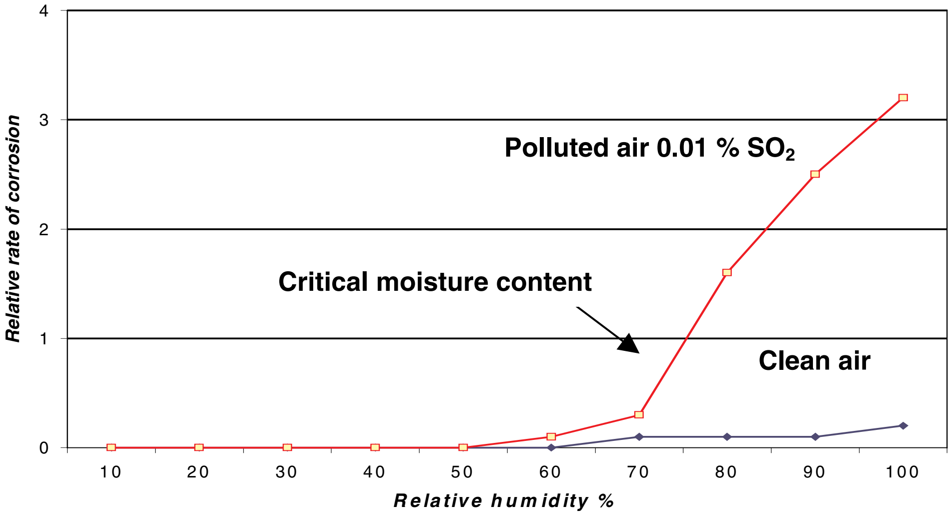


Diagram 3 shows that the rate of corrosion increases considerably when the relative humidity is about 60 to 70 %. If, in addition, the surroundings are polluted with, for instance, sulphur dioxide and the air humidity rises even more, the zinc actually dissolves.

Sendzimir zinc plating

During the Sendzimir process, a strip of steel, after its surface has been cleaned and it has been subjected to a special annealing process, is drawn continuously through a bath of molten zinc. The thickness of the coating, which is generally about 20 microns on both sides, is determined by removing zinc with a jet of air or steam. Sheet metal zinc plated in this way is used for connectors parts like hangers or, occasionally, anchor sleeves.

Sherardising

Sherardising is a dry diffusion process. As it takes place, zinc powder in an enclosed drum diffuses into / onto the surface of (small) metal parts at temperatures between 320° and 420 °C. Even on relatively complicated threaded parts, this produces relatively tough, wear and temperature-resistant, uniform zinc coatings. These zinc coatings consist of layers of Zn/Fe alloy which offer very good protection against corrosion that can be readily compared to that of hot-dipped galvanising. The achievable coating thicknesses range from 15 to 60 microns. The coating thickness on threaded parts and thus anchors is between 45 and 60 microns.

Hot-dipped galvanising

In general, when speaking of hot-dipped galvanising, a distinction is made between so-called conventional hot-dipped galvanising, that takes place at a temperature of about 460°C, and so-called high-temperature hot-dipped galvanising (HAT), that is carried out at approximately 560°C. The coating after HAT galvanising consists only of a Zn/Fe alloy unlike the coating composition after conventional hot-dipped galvanising. The layer of pure zinc at the surface, with its bright and shiny appearance, is missing.

Coating composition after conventional, hot-dipped galvanising:

1. Zn/Fe alloy layer
2. Formation of a thin, overlying layer of pure zinc which gives the coated part a bright appearance (zinc spangle). The formation of a pure zinc layer, however, is dependent on the reactivity of the steel being plated. Steels with a silicon content of approx. 0.03 to 0.12 or more than 0.30% form only a Zn/Fe alloy layer during conventional hot-dipped galvanising, i.e. the so-called Sandelin effect with a mouse-grey appearance.

On threaded parts and anchors, a coating can be obtained between 45 and 60 microns thick. Fig. 16 shows the composition of hot-dipped galvanising that was exposed to a corrosive atmosphere.

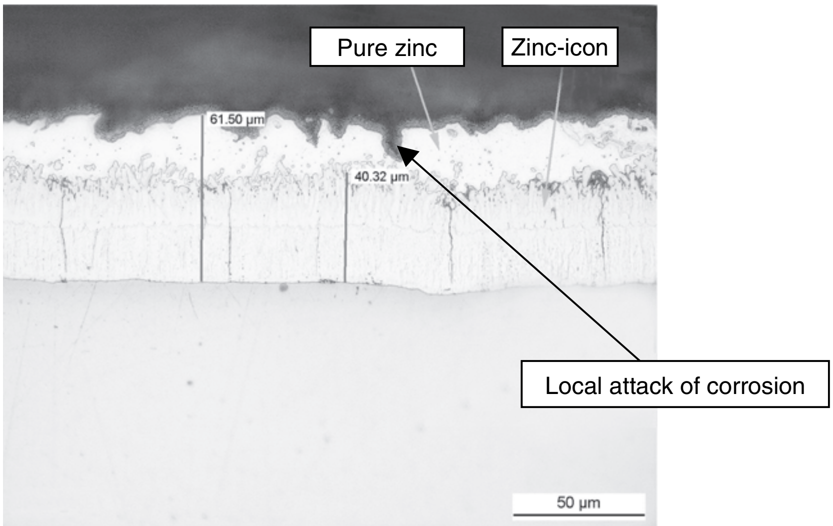


Fig.16: Micrograph of a hot-dipped galvanised channel with local points of corrosion in the zinc layer (white rust)

Hot-dipped galvanising with a well developed layer of pure zinc first suffers white rusting, i.e. the product of corrosion of the pure zinc layer. Afterwards, when the pure zinc layer has dissolved or broken down, red rust appears, i.e. the product of corrosion of the Fe/Zn alloy layer. Red rusting shows immediately with HT hot-dipped galvanising as also with a zinc sherardising layer because, of course, the layer of pure zinc is not present. Normally, the life expectancy (period of protection) of identical components is virtually the same when plated by either hot-dipped galvanising process, provided that both components have the same coating (g/m^2).

Corrosion-resistant materials

Stainless steels are being used increasingly for corrosion-resistant fasteners and connectors, also in highly corrosive atmospheres. These are mainly the austenitic CrNiMo steels (A4, 316) and, more and more seldom, the austenitic CrNi steels (A2, 304). Decisive for their use is not only the ideal combination of corrosion-resisting features, mechanical properties and economics, but also legislation and similar, such as construction supervisory authority approvals. Where very specific applications are involved and more stringent corrosion resistance requirements have to be met, special materials, such as titanium and titanium alloys or nickel-based alloys, etc., are offered as “special Hilti solutions”.

Stainless steels

Ordinary steel consists of iron and other elements, such as carbon, manganese, silicon, sulphur and phosphorous, some of which are necessary for steel production, but, in some cases, are undesirable contaminants. Reference is made to stainless steel suitable for use in slightly corrosive environments if the steel contains at least 13% chromium. Not only are the stainless steels currently available more or less free from contaminants (slight S and P contents), but they contain very high proportions of such elements as nickel, molybdenum, nitrogen, etc., that are intended to impart very specific properties.

The German general construction supervisory authority approval from the Deutsches Institut fuer Bautechnik (DIBT), number Z-30.3-6, dated August 3, 1999 “Components and fasteners of stainless steels” specifies the compulsory use of certain stainless steels for a whole range of applications, apart from other ranges of properties. (See the extract from Z-30.3-6 table 1, appendix 1 in the appendix.)

Corrosion behaviour of stainless steels

As a result of their capability to form a so-called passivation layer, stainless steels have a corrosion behaviour different from that of plain-carbon or low-alloy steels. Whereas the plain-carbon and low-alloy steels corrode uniformly and clearly visibly while forming rust, the stainless steels generally suffer a local attack of corrosion that is mostly not visible with the naked eye. In the past, this has led to a certain amount of uneasiness, above all since an accident occurred in an indoor swimming pool at Uster in Switzerland, as well as to the trend of completely avoiding the use of stainless steels, while reverting to “traditional” materials, like hot-dipped galvanised steel. If, though, allowance is made for the material’s properties, the mechanisms of corrosion and the limits to use, stainless steels are the only technically and economically meaningful solution for many applications. In the meantime, stainless steels have been fully accepted in many areas of everyday life, not least due to the development of prices. The main fields of application for fasteners and connectors are in road construction, bridge building, façade installation, the fabrication of industrial equipment and waste-water technology. A general answer cannot be given to the question of where the limits to use of various materials lie. Apart from the surrounding conditions, the strength and state of processing as well as design features have an influence on the corrosion behaviour of stainless steels. Many different aspects have to be considered when critical applications are involved and these sometimes make long-term field tests, etc., necessary. For many years, Hilti has conducted long-term field tests in a variety of highly corrosive surroundings.

In a clean atmosphere, stainless steels do not suffer an attack of corrosion due to their protective passivation layer. This is why they are called stainless or non-rusting steel in everyday language. On the other hand, corrosion must be expected and can take place on exposing the steel, for example, to the following mediums depending on the steel grade and its state:

- Very acidic mediums (mineral acids, etc.)
- Oxidising or reducing mediums (chlorine gas, hypochlorite, NOx, HCl, etc.)
- Substances containing chlorine (halogens) or chlorides, e.g. road salt, sea water, etc.
- Combinations of mediums containing chlorides and acids
- Poor ventilation, inadequate access of oxygen into crevices, beneath deposits, etc.

Among the cases of damage caused by the corrosion of stainless steel in the construction industry, many were the result of incorrectly processed material. An exception here though is the use in indoor swimming pools, road tunnels, power plant chimney stacks and other special areas where steels of the A4 grade (316) containing about 2% molybdenum are certainly not resistant and suffer at least pitting corrosion. In view of this, Hilti’s recommendation for use in, for example, road tunnel atmospheres and chlorinated indoor swimming pool atmospheres, are products made of highly corrosion-resistant material (HCR). They are resistant in these surroundings according to the latest level of knowledge, i.e. more than ten years of experience with road tunnels. Once again, the German general construction supervisory authority approval, DIBT Z-30.3-6, dated August 3, 1999 “Components and fasteners of stainless steels” specifies this material for fasteners used in indoor swimming pools and road tunnels.

Further processing of stainless steel fasteners must be avoided at all costs, such as heating, cold forming, welding, etc. Only then can the mechanical properties imparted to the steel by the manufacturer be guaranteed. Similarly, such follow-up treatment of stainless steels as coating, oiling, etc., must be avoided as the functioning, loading capacity and corrosion behaviour could be impaired by this. Furthermore, stainless steel should not be gripped or treated with tools, i.e. pliers, brushes, etc., made of plain-carbon steel or other materials, like brass, because particles left on the surface can initiate corrosion.

Designations of stainless steels

A range of designations (standards) for stainless steels exists in industrial countries. The most important ones have been given here for better understanding. The American Iron and Steel Institute (AISI) has a designation system that is used world wide. It consists of a number to which one of several letters are sometimes added.
200 – designates an austenitic steel containing chromium, nickel and manganese
300 – designates an austenitic steel containing chromium, nickel and, possibly, molybdenum
400 – designates ferritic and martensitic stainless steels

The additional letters (some shown below) indicate the following:
L = low carbon
N = nitrogen
Se = selenium / free machining
Ti = titanium
F = free machining
Nb = niobium

Similarly, the German system of numbering materials in accordance with DIN is used in several countries. Each number has five digits, such as 1. 4306.

The no. 1 means steel, the next two numbers 43 mean chemically resistant steels without Mo, Nb or Ti. And, the last two numbers 06 designate the exact alloy. In addition to designation 43, the following designations for stainless steel exist:

“40” = without Mo, Nb, Ti, Ni < 2,5 %
“41” = with Mo, without Nb or Ti, Ni < 2,5 %
“44” = with Mo, without Nb or Ti, Ni > 2,5 %
“45” = with Cu, Nb or Ti, Ni > 2,5 %

In Germany and other European countries, an abbreviated form of designating the chemical analyses of materials is also in use. (See DIN EN 10088.)

For example: 2 Cr Ni 19 11

X= High-alloy steel
2= Carbon content in 1 / 100%,
in this case: C= 0.02%
Cr= Chromium, in this case: 19%
Ni= Nickel, in this case: 11 %

This steel corresponds to the AISI type 304 L and the DIN material no. 1.4306.

Designation V1A (A1), V2A (A2) or V4A (A4):
In some countries (D, CH and A) the designation V2A (A2) or V4A (A4) has become accepted, especially in the construction industry. This designation can be traced back to the early days of stainless steel production. It is the brand designation of a well-known steel producer. Under the synonym A1 (V1A), for example, the austenitic chromium-nickel steels without molybdenum but with a relatively high sulphur content have been grouped together. V2A steels are understood to be the group of austenitic CrNi steels without molybdenum, whereas austenitic steels of the V4A grade contain at least 2% molybdenum. In a sense, therefore, this designation describes a certain class of resistance to corrosion.

Taking A2/70 as an example, the usual designations of fasteners made of austenitic stainless steels are explained in the following:

A = Austenitic stainless steel (also possible, F= ferritic, C= martensitic)
2 = Chromium-nickel steel (1= free-machining steel with the addition of S, 4 = CrNiMo steel)
70= Tensile strength of 700 N/mm^2 (strain hardened), (50= 500 N/mm^2 soft, 80= 800 N/mm^2 highly strain hardened; only the strength classification 45 (soft) and 60 (strain hardened) are possible with ferritic, stainless-steel fasteners.

In the DIBT approval, furthermore, further classes have been included (steel groups, such as A3, A5, KK, etc.).

Examples:
A3= Steel in the A2 group, but stabilised (weldable through alloying in Ti)
A5= Steel in the A4 group, but stabilised (weldable through alloying in Ti)
etc.

Material no.	DIN designation	ACI Manufacturer	Comment Steel grade / group
1.4301	X5 CrNi 18 10	304	A2 (DIBT)
1.4401	X5CrNiMo 17 12 2	316	A4 (DIBT)
1.4404	X2CrNiMo 17 12 2	316L	A4L (DIBT)
1.4571	X6CrNiMoTi 17 12 2	316Ti	A5 (DIBT)
1. 4565	X2CrNiMnMoNbN 25 18 54 4	---	A4 X- CR (powder-actuated fastening)
1.4462	X2CrNiMoN 22 5 3	318 LN	AK (DIBT)
1.4529	X1NiCrMoCuN 25 20 6	---	KK (DIBT) HCR (**H**ighly **C**orrosion **R**esistant)

Table 3: Stainless steels used mostly by Hilti for fasteners and connectors

Hilti HCR products (Highly Corrosion Resistant)

HCR products are made of a material recommended by Hilti since about 1994 for anchor fastenings made in atmospheres containing chlorides (road tunnels and indoor swimming pools) where safety is at stake. In view of experience from our own field tests, Hilti refuses to use other stainless steels for safety-relevant fastenings in these fields of application.

The development of pit depth in stainless steels tested for 96 months in the Mont Blanc Tunnel is shown in the following diagrams 4 and 5.

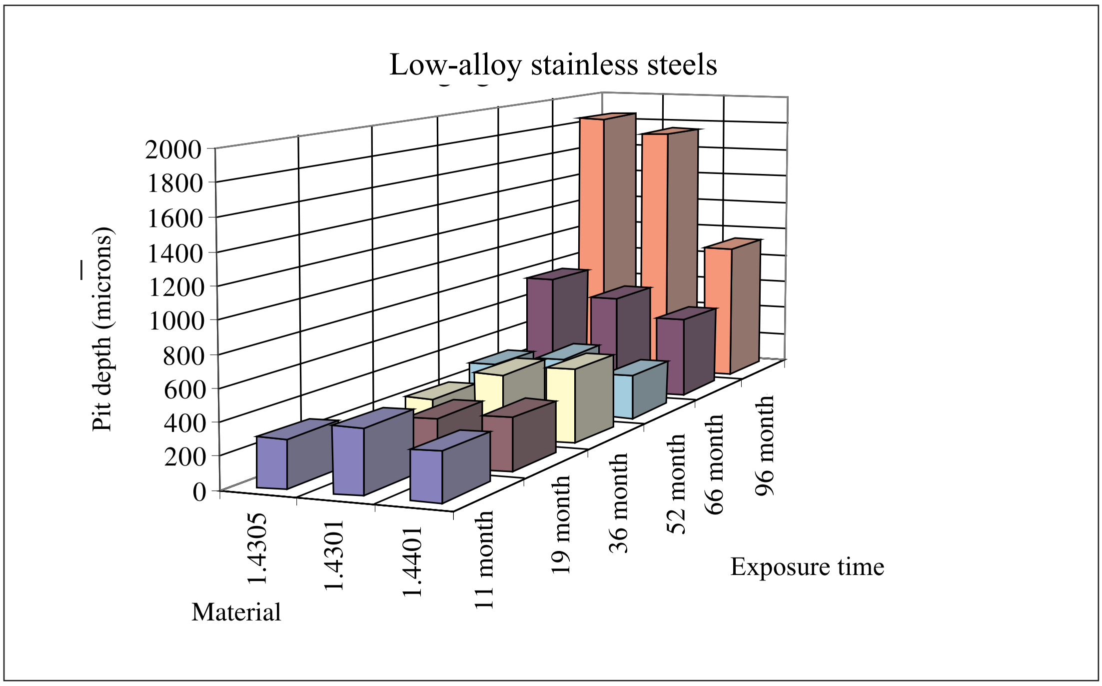


Diagram 4: Development of pit depth in austenitic materials 1.4305, 1.4301 and 1.4401 after 96 months of exposure in the Mont Blanc Tunnel

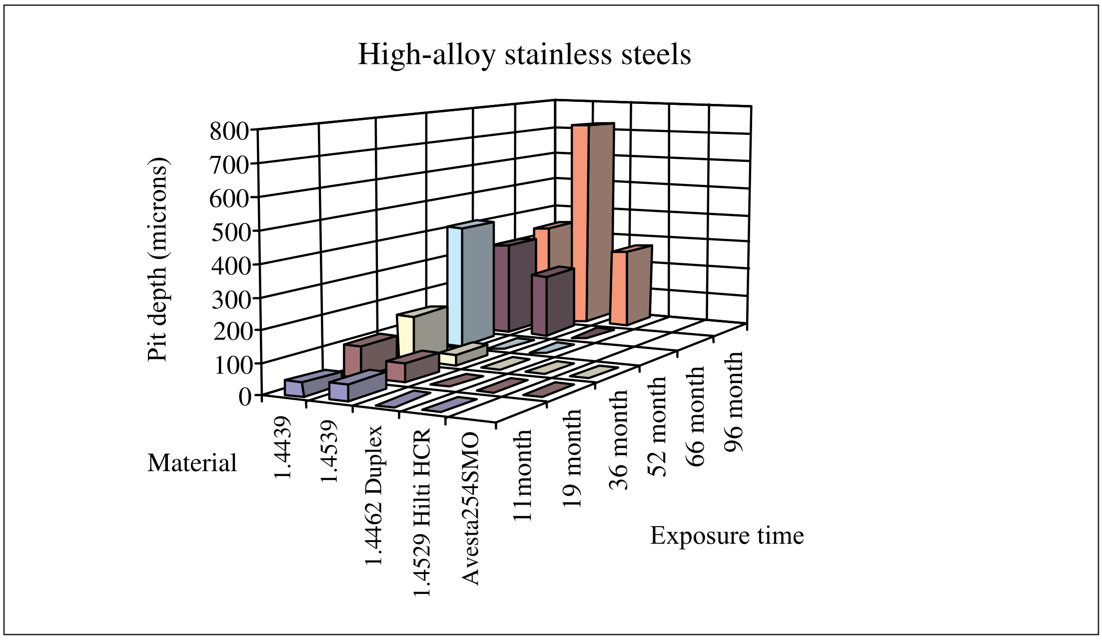


Diagram 5: Development of pit depth in high-alloy austenitic materials 1.4439, 1.4539, 1.4525 and Avesta 254 SMO as well as Duplex steel 1.4462 after 96 months of exposure in the Mont Blanc Tunnel

Whereas the A2 (304), A4 (316) steels and some high-alloy steels were completely non-resistant and suffered heavy corrosion, the Hilti HCR material proved to be absolutely resistant. Results of testing in six other Swiss road tunnels have confirmed these results. The tests are continuing.

Hilti X- CR direct fastening product (Corrosion Resistant)

X-CR material is a stainless steel of the A4 grade with corresponding resistance to corrosion and very high strength. It is used for powder-actuated fasteners (threaded studs and nails). This material was developed jointly by Hilti and a renowned steel producer. Despite the very stiff requirements that have to be met as regards mechanical properties, this material has a better corrosion behaviour in many areas than materials of the A4 grade.

Materials for special applications

In Hilti, we concern ourselves in depth with product applications in areas in which particularly corrosive and also very special conditions exist. In addition to field tests, of course, a whole series of laboratory and basic investigations have been carried out. The susceptibility of a material to pitting corrosion in a medium containing chlorides is governed to a great extent, among other things, by the maximum temperature to which it is subjected. The iron III chloride test according to ASTM G48-76 is suitable for determining the critical pitting and crevice corrosion of a material.

In the following table 4, some steels and nickel alloys have been tabulated according to decreasing resistance to corrosion during the iron III chloride test.

Material	Cr	Ni	Mo	N	Fe	Others
2.4602	**20.0-22.5**	**Rest**	**12.5-14.5**		**2.0-6.0**	**W:2.5-3.5**
1.4529	**19.0-21.0**	**24.0-26.0**	**6.0-7.0**	**0.10-0.25**	**Rest**	**Cu:0.5-1.5**
1.4462	**21.0-23.0**	**4.5-6.5**	**2.5-3.5**	**0.08-0.20**	**Rest**	
1.4539	**19.0-21.0**	**24.0-26.0**	**4.0-5.0**	**0.04-0.15**	**Rest**	**Cu:1.0-2.0**
1.4439	**16.5-18.5**	**12.5-14.5**	**4.0-5.0**	**0.12-0.22**	**Rest**	

Table 4: Materials arranged according to decreasing resistance during the iron III chloride test.

The term “ activator total ” of an alloy is closely linked with the iron III chloride test. Activator total is understood to be the summation of alloying elements contributing to resistance to corrosion multiplied by a certain factor. The following formula has long been known:

$$TA = \%Cr + 3.3 (\%Mo)$$

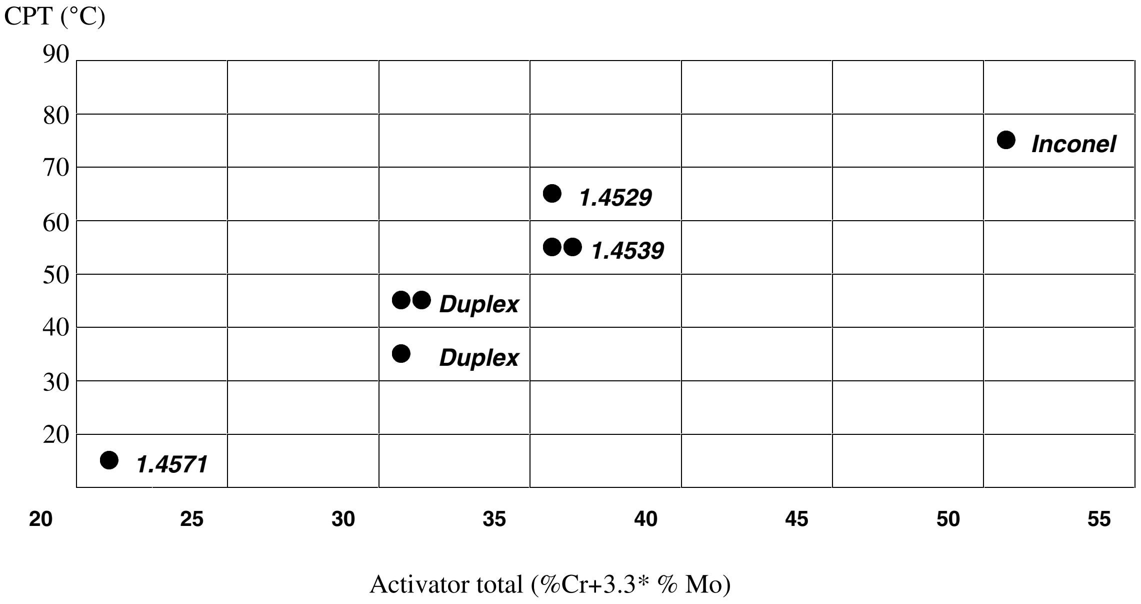


Diagram 6: This shows the relationship between activator total and critical pitting corrosion temperature. The higher the activator total of a material, the higher, for example, will be the critical pitting corrosion temperature, as a rule. This means that with increasing activator action, the resistance of a material at high temperature in the respective medium also increases.

On the basis of these considerations (activator total and critical pitting temperature) it may, in fact, be possible to estimate the corrosion behaviour of a material, but this cannot be applied on a one-to-one basis to applications in field practice where many different factors can influence the corrosion behaviour.

With the foregoing in mind, the well-known activator totals, also the “traditional” AT = %Cr + 3.3 %Mo, are only of minor importance for the respective application and can only be used as a guide. Thus, a material must be selected on the basis of the different aspects of its use.

If conditions are extremely corrosive, as, for example, in a road tunnel atmosphere, this “traditional” activator total formula is no longer valid. Consequently, an activator total specific to tunnels, $WS_{(Tunnel)}$, was calculated on the basis of field test results. In this activator total, molybdenum and nitrogen play a significant role along with other alloying elements.

In certain surroundings, where stainless steels corrode, materials of even higher resistance are used, such as titanium and some nickel-based alloys.

Designs allowing for corrosion

When configured, a component or design should make the greatest possible allowance for corrosion. In particular, crevices in a design should be avoided at all costs.

When using stainless steels, it is important for the passivation state to be upheld by allowing an oxidising agent, for example, oxygen in the air, to get to the metal surface. Oxygen diffusion can no longer take place unhindered in narrow crevices filled with a corrosive medium, and this permits an attack of corrosion. The narrower the crevice, the more critical will be the situation. The critical crevice width is in the order of several hundredths to tenths of a millimetre. In view of this, deposits of dust, for example, can often be more critical than the gap between an anchor and its hole wall. According to DIN 50900, this means locally accelerated corrosion in crevices. Often, a system automatically dictates crevices. As the schematic depiction of an anchor fastening in fig. 17 shows, differently ventilated zones must be expected. As a result, anodic (high rate of corrosion) and cathodic zones are produced on one and the same fastening.

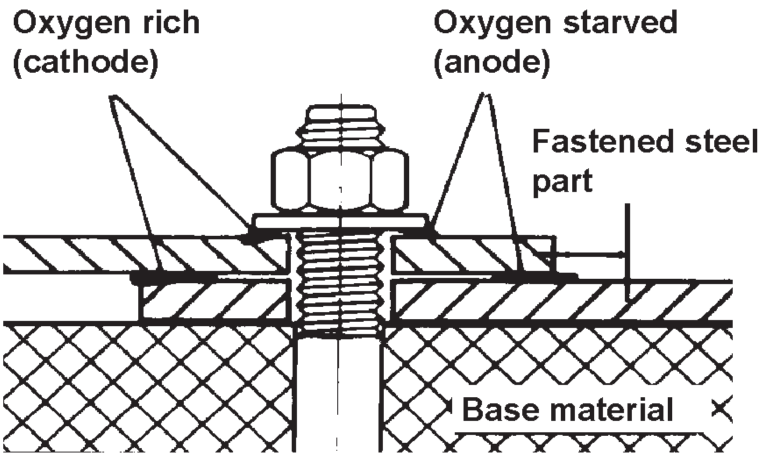


Fig. 17: Crevice situation with an anchor fastening

Avoidance of contact corrosion

Materials suitably resistant to an attacking medium must be used for fasteners if a reliable fastening solution is to be guaranteed. If two or more metals are combined and these are linked conductively with direct contact or contact through a medium, attention must be paid to their electrochemical compatibility. Every metal has a certain electrochemical potential which is dependent on the medium. The relative positions of chemical elements are shown in diagram 7, electrochemical / electromotive force series of elements.

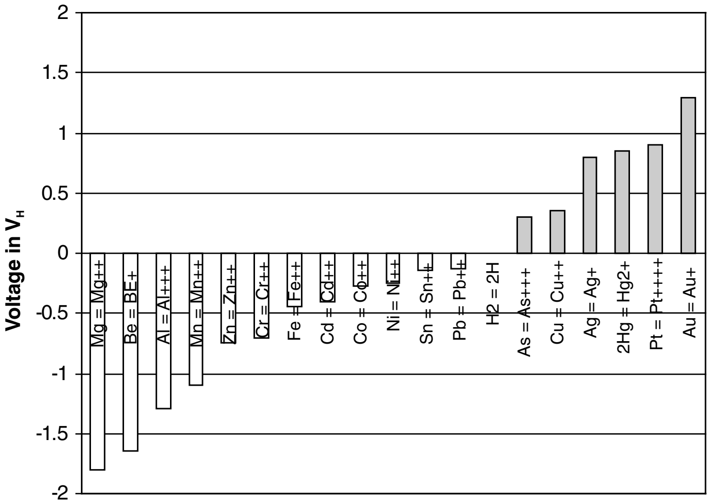


Diagram 7: Electrochemical / electromotive force series of elements

- The more negative, the greater is the tendency to transform to the ion state.
==> To dissolve
- The less noble (lower in the series) forces the more noble (higher in the series) out of their solutions.
==> The more noble deposits itself metallically, the less noble dissolves.
- Hydrogen is converted to the molecular state by the less noble metal.
==> These metals are soluble in acid.
Purely thermodynamic quantity

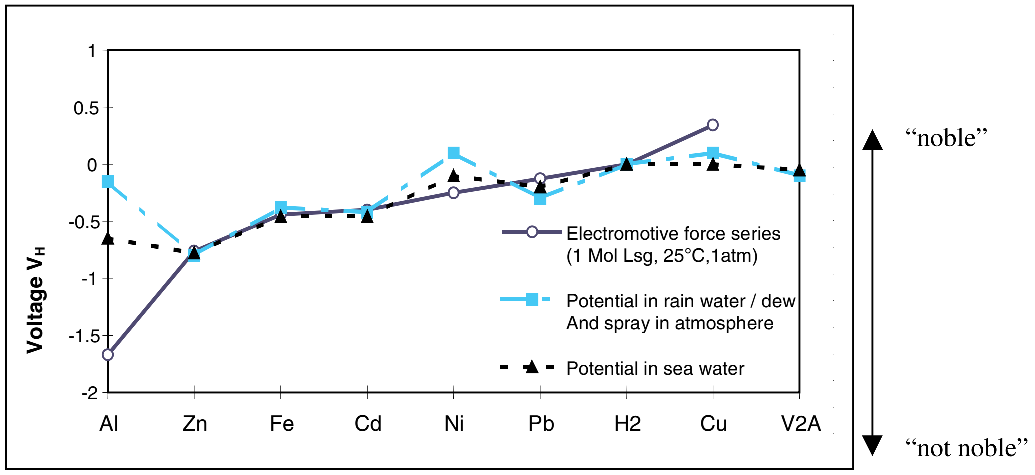


Diagram 8 shows the electrochemical behaviour of these elements / materials on the basis of a few examples and “medium conditions” (electrochemical / electromotive force series and practical series).

Taking aluminium (Al) as an example, it is clear to see that this metal reacts far more like a noble metal, due to its tendency to form a covering layer in the atmosphere, than this would be expected from the theory of the electromotive force series of elements. When estimating the probability of contact corrosion in practice, therefore, it is important to be accurately informed about the medium and the electrochemical potential of the material under consideration.

The ratio of surface areas of the linked metals is also crucial for the rate of corrosion. Here, it should be remembered that, from an electrochemical point of view, the less noble metal should always have a much larger surface area. In view of the fact that a fastener is normally always the smaller component and thus has a smaller surface area, the fastener should either be made of the same material as the part fastened or, if this is not possible, of a nobler material.

The following table 5 shows the suitability of the respective metal couple. It also shows which two metals in contact are permissible in field practice and which should rather be avoided.

Fastener Fastened part	El.-chem. galvanised	Hot-dipped galvanised	Aluminium alloy	Structural steel	Stainless steel	Brass
Zinc	○	○	○	○	○	○
Hot-dipped galv. steel	○	○	○	○	○	○
Aluminium alloy	●	■	○	○	○	○
Cadmium coating	●	■	○	○	○	○
Structural steel	●	●	●	○	○	○
Cast steel	●	●	●	●	○	○
Chromium steel	●	●	●	●	○	■
CrNi(Mo) steel	●	●	●	●	○	●
Tin	●	●	●	●	○	■
Copper	●	●	●	●	●	●
Brass	●	●	●	●	●	○

○ Slight or no corrosion of fastener
● Heavy corrosion of fastener
■ Moderate corrosion of fastener

Table 5: Metal couples dependent on medium

If an “unfavourable” combination of different materials cannot be avoided, suitable measures can be taken to avoid contact corrosion, for example electrical insulation using plastic parts, like washers, sleeves, etc.

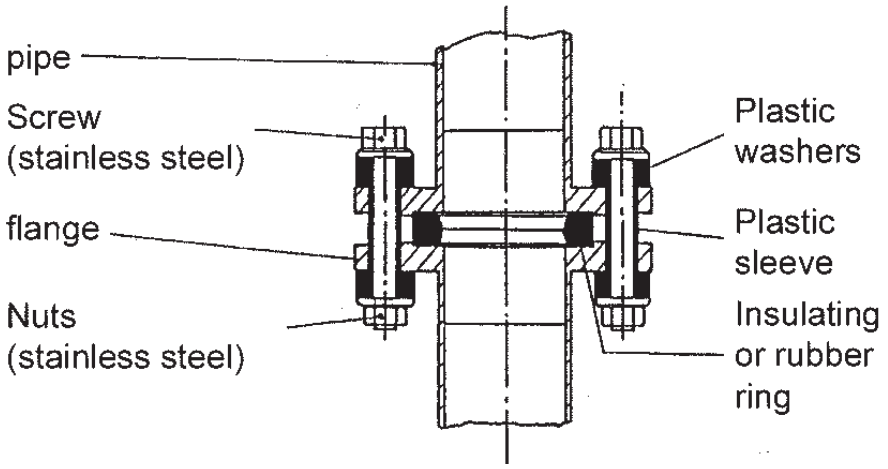


Fig. 18: Galvanic separation using plastic and rubber

If a fastening is under water, such as in waste water treatment plants, in rivers or in sea water, particular attention must be paid to electrical isolation of the fastener from the concrete reinforcement. Very extensive damage occurs repeatedly because such measures are not taken into account.

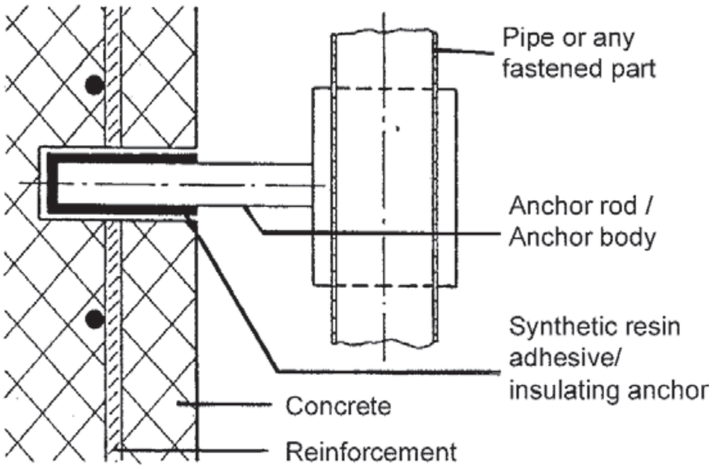


Fig.19: Galvanic separation using, for example HIT-BAR to avoid contact corrosion with reinforcement

5. When must corrosion be expected?

Corrosion must be expected when the properties of the metal component or entire structure (here, this includes the fastener, the base material and what is being fastened) do not meet requirements imposed by the surrounding conditions. To evaluate the risk of system corrosion, it is essential that a profile of anticipated or existing mechanical loading and chemical exposure is drawn up. This includes all marginal conditions and properties that influence the corrosion of a system.

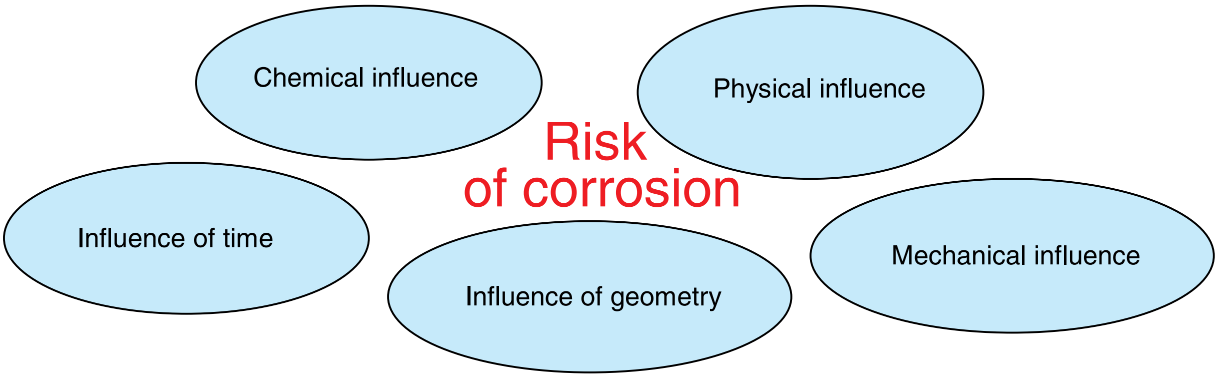


Fig. 20: Factors influencing the risk of corrosion

Chemical influence is understood to be the medium (surroundings). Also, the chemical composition, concentration and pH value must be allowed for.
Physical influence covers the temperature and temperature fluctuation affecting condensation conditions. This also includes pressure and radiation, potential difference and current flow. All have to be allowed for. Mechanical influence, for example, is static or dynamic stressing of a component. Flow direction and velocity of the medium and frictional conditions are also important mechanical influencing factors. Geometric influence can mean crevices, material couples and spreading of the medium (like a film, spatially). Where the influence of time is concerned, it is important to know the duration of exposure to the medium (all the time or only part of the time) or the types of loading.

6. Selection of suitable fastener

If a perfectly satisfactory and reliable fastening is to be guaranteed for an entire service life, the surrounding conditions, conditions in use and influencing factors resulting from them must be ascertained before a suitable fastener can be selected.

Climatic influence?
Mechanical influence?
Chemical influence?
Biological influence?
Electromagnetic influence?
Others?

↓

Microclimate

Fastener

A selection of suitable materials and systems for protection against corrosion must be made under consideration of the desired service life, technical safety aspects and, not to be forgotten, the appearance (colour, brightness, etc.). In this respect, applications are conceivable in dry inside rooms, outside and weathered in an industrial atmosphere or coastal atmosphere and even in special technical surroundings, e.g. waste water treatment plants, industrial installations, etc., not forgetting the earth’s various climatic zones. In view of this, each application must be evaluated separately and the findings considered when selecting a material with the required corrosion behaviour or the system necessary for protection against corrosion. Products must be designed in such a way as to avoid crevices and cavities where contaminants can build up. Allowance must be made for the electrochemical behaviour of linked materials when material combinations are used.

Another point of crucial importance when selecting a fastener or material in field practice, is the actual relevance to safety each time. Often, legislation, regulations and codes exist which must be observed by whoever carries out the fastening work.

It is important that the user or whoever does the work to be well informed about possible suitable solutions, but it is even more important that he or she is aware of the potential risk of using an unsuitable material. If any uncertainty exists, it is absolutely essential that you contact a corrosion specialist. Your local Hilti technical staff can provide you with the necessary information.

7. How does Hilti solve the corrosion problem in field practice?

The following general recommendation can be given for selection of the right material and system for protection against corrosion to be used in field practice.

CONDITIONS WHERE USED	MATERIAL / PROTECTIVE SYSTEM
• Inside rooms without humidity • With sufficient concrete coverage	**Carbon steels:** **- Electrochemically zinc plated to 5 – 10 microns**
• Damp inside rooms • Occasional exposure to condensation • Coastal areas • Slightly corrosive outside atmosphere	**Carbon steels:** **- Hot-dipped galvanised ≥ 45 microns** **- Sherardised ≥ 45 microns** **- Dacromet and/ or Delta Tone ≥ 10 microns** **Coated parts**
• Inside room with heavy condensation • Outside	**Austenitic CrNi steels**
• Outside industrial atmosphere without chlorides	**Austenitic CrNiMo steels** **with at least 2% Mo**
• Outside atmosphere with moderate chloride and sulphur dioxide content	**Austenitic CrNiMo steels** **with at least 4 % Mo** **and Duplex steel**
• Highly corrosive surroundings, e.g. in a road tunnel, indoor swimming pool, etc.	**Austenitic CrNiMo steels** **with at least 6 % Mo** **and special materials** **(Evaluate each case.)**

In the given surroundings, the material must be stable and resistant, guarantee a long, reliable service life and meet aesthetic requirements. In the following, some widely used materials and systems for protection against corrosion have been given, and the surrounding conditions in which fasteners made of these materials can, typically, be used have also been shown.

8. General recommendations

The selected applications have been arranged according to the following structure:

Building construction	• Rough initial construction / interior finishing
	• Façade / roof
M & E installations	• Pipe and electrical installations
	• Industrial equipment, etc.
Civil engineering	• Road construction and bridge building
	• Tunnel construction
	• Dock and waterway construction
Special applications	• Industry / chemical industry
	• Power plants
	• Chimney stacks of waste incineration plants, Composting facilities
	• Waste water treatment plants
	• Multi-storey car parks
	• Indoor swimming pools
	• Stadiums / sports facilities
	• Road tunnel construction

BUILDING CONSTRUCTION

Application	Marginal conditions	Recommendations
Initial construction		
Temporary fastenings: Forming, temporary fixtures, scaffolding	Outside and inside application	Electrochemically zinc plated or coated
Design-relevant fastenings: Brackets, columns, beams	Dry inside room without condensation	Electrochemically zinc plated to 5 – 10 microns
	Moist inside rooms with occasional condensation due to high humidity and temperature fluctuations	Hot-dipped galvanised / sherardised to min. 45 microns
	Frequent and lasting condensation (greenhouses), non-enclosed inside rooms or open sheds, halls, etc.	A4 (316) steels, possibly hot-dipped galvanised (Evaluate each case.)
Composite construction	Protection from alkalinity of concrete	Electrochemical zinc plating generally adequate
Interior finishing		
Partitions / drywalls, suspended ceilings, windows, doors, elevators, fire escapes, railings, etc.	Dry inside room without condensation	Electrochemically zinc plated to 5 – 10 microns

BUILDING CONSTRUCTION

Application	Marginal conditions		Recommendations
Façade / roof			
Profiled sheet metal, curtain wall cladding, fastening of insulating material, façade support framing	**Rural atmosphere** (without emissions), alpine atmosphere with very little air pollution	Inside application, outside application, insulating materials	Electrochemically zinc plated to 5 - 10 microns Hot-dipped galvanised / sherardised to min. 45 microns X- CR Dacromet / plastic, A4 (316) steels
	Town atmosphere High content of SO_2 and NO_x, chlorides from road salt can accumulate on parts not exposed to weather	Inside application, outside application, insulating materials	Electrochemically zinc plated to 5 - 10 microns (Evaluate each case.) Hot-dipped galvanised / sherardised to min. 45 microns X- CR, with chlorides HILTI HCR (Evaluate each case.)
	Industrial atmosphere High content of SO_2 and, under circumstances, other corrosive substances (without halogenides)	Inside application, outside application, insulating materials	Electrochemically zinc plated to 5- 10 microns A4 (316) steels, X- CR A4 (316) steels, X- CR
	Coastal atmosphere High chloride content, among other things, combined with industrial environment	Inside application, outside application, insulating materials	Electrochemically zinc plated to 5 - 10 microns Hilti HCR, possibly X- CR (Evaluate each case.)
Fasteners not directly exposed to weather: for example, chlorides and other contaminants can accumulate behind curtain wall façades and thus create more corrosive conditions. A4 (316) steels can suffer corrosion here.			Hilti-HCR and special materials

M & E installations

Application	Marginal conditions	Recommendations
Pipe and electrical inst.		
Pipe fitting, cable runs, air ducts	Dry inside rooms, no condensation	Electrochemically zinc plated to 5 - 10 microns
Electrical installations: Cable runs, lighting, aerials	Moist inside rooms, poorly ventilated rooms, cellar / basement shafts, occasional condensation due to high humidity and temperature fluctuations	Hot-dipped galvanised / sherardised to min. 45 microns
	Frequent and lasting condensation (greenhouses), non-closed inside rooms or open halls, sheds, etc.	A4 (316), possibly hot-dipped galvanised or sherardised (Evaluate each case.)
Industrial installations		
Crane rails, barriers, conveyors, machine fastening	Dry inside rooms without condensation	Electrochemically zinc plated to 5 - 10 microns
	Moist inside rooms, poorly ventilated rooms, cellars / basement shafts, occasional condensation due to high humidity and temperature fluctuations	Hot-dipped galvanised / sherardised to min. 45 microns
	Frequent and lasting condensation (greenhouses), non-closed inside rooms or open halls, sheds, etc.	A4 (316), possibly hot-dipped galvanised or sherardised (Evaluate each case.)

CIVIL ENGINEERING

Application	Marginal conditions	Recommendations
Road and bridge construction		
Pipe fitting, cable runs, traffic signs, acoustic walls, crash barriers, connecting structures	Exposed to weather (chlorides are washed off regularly) or indirectly weathered, e.g. pipes fitted to underside of bridges	Possibly, hot-dipped galvanised or sherardised, A4 (316) steels, stainless Duplex steel or austenitic steels with approx. 4 - 5 % Mo (Evaluate each case.)
	Frequent heavy exposure to road salt Highly relevant to safety	Hilti HCR
Tunnel construction		
Tunnel foils / sheeting, reinforcing mats, traffic signs, lighting, tunnel wall cladding, air ducts, ceiling suspensions, etc.	Of secondary relevance to safety	X- CR, Duplex steel, possibly also A4 (316) steels (Evaluate each case.)
	Highly relevant to safety	Hilti HCR
Docks / offshore		
Fastenings to quay walls, dock equipment, harbour installations	Secondary relevance to safety and temporary fastenings, high humidity, chlorides, frequent mixing with industrial atmosphere or alternating oil / sea water on a platform	Hot-dipped galvanised Hilti HCR, special materials
Offshore platforms		X CR and possibly A4 (316) steels (Evaluate each case.)
Under water: Where fastenings have to be made in / under water, there is often a sacrificial / cathodic protection system (impressed current). This must, of course, be taken into account when selecting a suitable material.		

SPECIAL APPLICATIONS

Application	Marginal conditions	Recommendations
Industry / chemical industry		
Pipe fitting, cable runs, connecting structures, lighting	Dry inside room Corrosive inside rooms, e.g. fastenings in laboratories, galvanic facilities, etc., very corrosive vapours, outside applications with very high SO_2 exposure and, additionally, corrosive substances (only acidic surroundings) Chemical industry	Electrochemically zinc plated to 5 - 10 microns (Evaluate each case.) Stainless steels, Hilti HCR; special materials A4 (316) steels and special materials (Evaluate each case.) (Evaluate each case.)
Power plants		
Fastenings relevant to safety	Extremely stiff safety requirements and long service life, highly relevant to safety	(Evaluate each case.)
Chimney stacks of waste incineration plants / composting facilities		
Fastening of, for example, ladder rungs, lightning conductors, etc.	On lower section of chimney stack On topmost section of chimney stack: Condensation of acids and often high chloride content and other concentrations of halogenides	Hot-dipped galvanised / sherardised to min. 45 microns and A4 (316) steels Special materials (Evaluate each case.)

SPECIAL APPLICATIONS

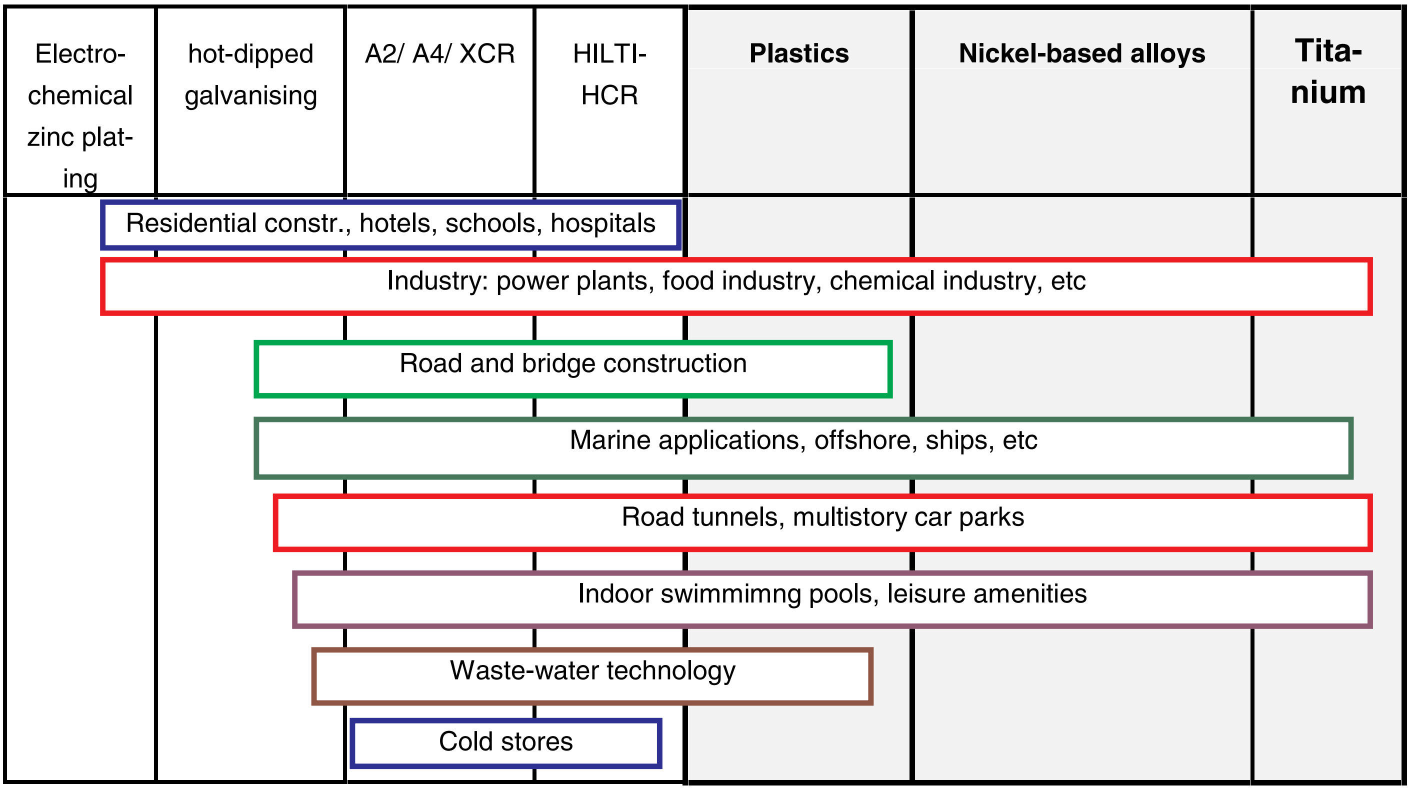
Application	Marginal conditions	Recommendations
Waste water treatment plants		
Pipe fitting, cable runs, connecting structures, etc.	Outside in atmosphere with high humidity, digester / sludge gas, etc.	Hot-dipped galvanised / sherardised, A4 (316)
	Underwater applications, community waste water, industrial waste water	Hilti HCR Special materials
Caution: As clarification tanks have a common means of grounding / earthing in most cases, it is absolutely essential that contact between fastener and reinforcement is interrupted or avoided. **Risk of contact corrosion**		
Multi-storey car parks		
	Large amount of chlorides carried in (road salt) by vehicles, many wet-dry cycles	Hilti HCR
Indoor swimming pools / other pools, etc.		
	Fastenings of secondary relevance to safety	Hot-dipped galvanised possible, Duplex steel, austenitic steels (approx. 5% Mo)
	Fastenings relevant to safety	Hilti HCR
Sports stadiums / facilities		
	Rural atmosphere	Hot-dipped galvanised / sherardised
	Town atmosphere Fastenings that can be checked	Hot-dipped / sherardised to min. 45 microns and A4 (316) steels
	Inaccessible fastenings	A4 (316) steels

9. Examples of applications and procedure for material selection

The following table shows the materials that can be used basically for the fields of application chosen as examples. Selection of a material suitable or necessary for a specific application in order that the desired service life and safety requirements are met, depends on the surrounding conditions and or special stipulations and regulations (approval authorities, safety standard authorities, etc). In view of this, electrochemically zinc plated parts can, for example, be sufficient for use in certain areas of the chemical industry, whereas highly corrosion-resistant materials might be necessary in others.

A general statement like
"only stainless steels can be used in the chemical industry"
is thus incorrect.

Problems that face users when selecting a material suitable for certain surroundings, are shown by the following chart.



Examples of applications

This table shows, by way of example but not complete, what variety of surrounding conditions can exist in a conventional house. In the food trade, the chemical industry and road construction, for example, this becomes much more complicated.

dry	dry, ”high“ temperature or temperature fluctuations (condensation)	high air humidity	acidic gasses	halogenides, e.g.. chloride from road salt, etc	others, e.g. various base materials like impregnated wood, etc	**Examples**	**Material recommendation**
	x	x				**Cellar/basement rooms**	**hot-dipped galvanised steel or A2**
	x	x	x	x		**underground garages/car parks**	**hot-dipped galvanised steel and Hilti - HCR**
X						**living quarters**	**electrochemically zinc-plated steel**
X						**attics/lofts**	**electrochemically zinc-plated steel**
		x	x	x	x	**special cases**	**Evaluate each case.**

Example: conditions inside a house

In field practice, all combinations of surrounding conditions are conceivable. Consequently, the list of some influencing factors is intended to indicate which circumstances are ”more or less insignificant“ for corrosion and which surrounding conditions should be classified as ”promoting corrosion“

Examples of applications

Dry surroundings	No electrolyte exists and thus the rates of corrosion are low to negligible. An exception here, dependent on material, is when strongly oxidising or reducing gases or mediums are present.
Frequent temperature fluctuations	Conditions for condensation which occur have considerable relevance to corrosion, depending on how frequent this is. As a rule, electrochemically zinc-plated steel is not good enough (short life expectancy). In such cases, hot-dipped galvanised steel gives the assurance of a longer life expectancy.
Frequent temperature fluctuation and polluted air, e.g. exhaust gases or salt	Conditions for condensation that occur have a considerable relevance to corrosion, depending on the frequency of occurrence. As a result, pollutant gases can concentrate on a surface and, in the course of time, form very strong acids on metal surfaces. In such conditions, an A4 (316) steel is generally adequate. If chlorides (or other pollutants) also come into play, e.g. from road salt, special steels or even special nickel-based alloys must be used. Possibly, the use of a hot-dipped galvanised component is best in such conditions (evaluate the individual case). From a safety point of view, hot-dipped galvanised steel should be given preference to an A4 (316) steel in any event in conditions of this kind because corrosion on hot-dipped galvanised steels can be seen with the naked eye, unlike that on stainless steels, and it can thus be identified in good time and the part possibly replaced (risk of stress corrosion cracking with A4 (316) steel). In places where components cannot be checked visually (behind facades and in many areas of tunnels, etc.) a resistant material should, however, always be used while allowing for any possible changes in the course of time.

10. Case study

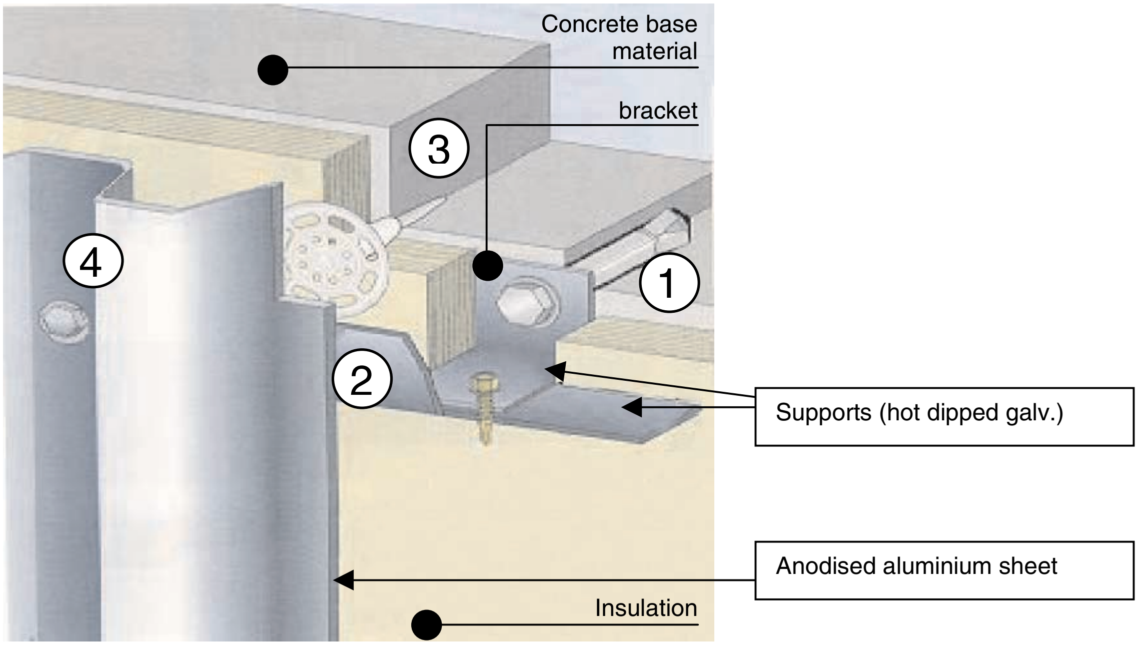
On the basis of an example from field practice, a facade installation is presented and a solution with powder-actuated fastening and anchor technology is shown. In this case, particular allowance is made for the following where the problem of corrosion is concerned:

1. the surrounding conditions
2. metals in contact
3. possible changes in corrosiveness in the course of time
4. special circumstances/possibilities, such as condensation, etc.

Fastening of a facade in a town: trapezoidal aluminium sheets fastened to concrete

Marginal conditions:
The facade is on a heated commercial building (sales hall) in a city in Central Europe. In recent years, traffic has increased and will increase further. Salt is strewn on roads in winter to free them from ice.
The metal cladding – anodised profiled aluminium sheets - begins at a height of 1.5 metres above the ground.

Construction details:



Recommendation and reasons

1. Fastening of entire facade to concrete

Solution: Anchors made of the (316) material A4.
Reasons: The surrounding conditions are slightly acidic and contain small amounts of chlorides. As the facade sheet metal is slightly above the ground (1.5 m) and, additionally, well protected from the weather from a design point of view (insulation, etc.), no extreme exposure to pollutants need be expected in this area. In addition, little dampness is anticipated, although condensation cannot be excluded. In view of this, a material of the A4 (316) grade (DIN 1.4404 or 1.4401) should be sufficiently resistant. Furthermore, a visual check is virtually impossible once the facade is in place. This is the main reason why a material of the A4 (316) grade is proposed (long life expectancy). An additional measure can be considered, namely galvanic separation of the hot-dipped galvanised support framing and the stainless steel anchors can be achieved by using plastic washers, thus hindering contact corrosion of the hot-dipped galvanised part. This measure is not absolutely essential though, owing to the favourable surface area ratio of the metals in contact (A4 (316) anchor = a noble part from an electrochemical point of view with a far smaller surface area than the less noble hot-dipped galvanised part).

2. Fastening of both individual parts of the hot-dipped galvanised support frame (2 brackets) using nuts and bolts

Solution: Sherardised screws and nuts or 4 (316) bolts and nuts with plastic washers on both sides
Reasons: In the case of A4 (316) bolts, this is the same as for fastening 1 above. As a low cost possibility, the sherardised version with a zinc layer of at least 45 µm should be given preference to the stainless-steel version. Contact corrosion is not a problem as zinc layers are involved on both the hot-dipped galvanised angles and the sherardised connector.

3. Insulating material installation using powder-actuated fastening

Solution: XIE-R (XCR- Material)
Reasons: X-CR material is predestined for this application. In this area, there are crevices and condensation can form on the nail due to temperature differences. Under circumstances, these damp phases can last for quite a time. The X-CR nail gives the assurance of a long life expectancy here and is thus a reliable fastening.

4. Fastening of trapezoidal aluminium sheets to support framing using direct fastening

Solution: X- CR studs or A4 (316) self-drilling screws with neoprene washer

Reasons: Anodised aluminium surfaces have a very noble behaviour from an electrochemical point of view because of the so-called passivation layers (oxide layer: a synthetically produced Eloxal layer in this case). The potential difference between the anodised trapezoidal sheet metal and the X–CR nail in the prevailing medium cannot be described as serious. Nonetheless, signs of contact corrosion around the fastening might appear. These would be unacceptable for purely aesthetic reasons. A metal washer on, for example, neoprene can avoid this.

11. Recommended reference literature

1. W. Stichel, „Korrosion und Korrosionsschutz in Schwimmhallen“, BAM- Forschungsbericht 126
2. W. Haase, „Zur Korrosion von Bauteilen aus nichtrostendem Stahl in Hallenbädern“, LGA Bayern, Materialprüfamt , Heft 6
3. G. Herbsleb und F. Theiler, Spannungsrisskorrosion nichtrostender austenitischer Chrom – Nickel- Stähle bei Raumtemperatur“, Werkstoff und Korrosion 40, 467
4. SIA- Studientagung „Korrosion und Korrosionsschutz Teil 2, Schutz und Sanierungsmethoden von Stahlbetonbauwerken“, Zürich, SIA- Dokumentation D021
5. SIA- Studientagung „Korrosion und Korrosionsschutz Teil 3, Einsatz von nichtrostenden Stählen im Bauwesen“, Zürich, SIA- Dokumentation D030
6. J. Löbel und M. Paduch: Wechselwirkungen zwischen technischen Oberflächen und Atmosphäre, VDI Berichte 721
7. SIA- Studientagung „Korrosion und Korrosionsschutz, Anker und Spannkabel“ Teil 4 Zürich, SIA- Dokumentation D030
8. S. Fitz, D. Hochrainer und H. Marfels, Immisionsratenmessung und Materialkorrosion“, VDI- Kommision Reinhaltung der Luft, Schriftenreihe, Band 11
9. SIA- Studientagung „Sicherheit und Dauerhaftigkeit von Befestigungselementen“, Zürich, SIA- Dokumentation D055
10. W.L. Plawer, „Korrosionsschutz durch Zink“, DBZ II 1.1
11. U. Heubner ed., „Nickel alloys and high- alloy special stainless steels“, Expert- Verlag, Sindelfingen
12. J.W. Olfield and B. Todd, „Stress Corrosion Cracking of Austenitc Stainless Steels in Atmospheres in Indoor Swimming Pools“, int. Conference : Stainless Steels`91 Tokyo
13. D. Binschedler und H.-D. Seghezzi, Korrosionsprobleme in der Befestigungstechnik“, Schweizer Ingenieur und Architekt 48
14. D. Bindschedler und P. Gschwend, „Prüfung auf wasserstoffinduzierte Versprödung“, Oberfläche – Surface 10
15. D. Bindschedler, „Korrosionssichere Profilblechbefestigungen durch den Einsatz von Direktmontageelementen“, Bauingenieur 63
16. Ulf Nürnberger, Korrosion und Korrosionsschutz im Bauwesen , Bauverlag
17. „Korrosionsbeständige Befestigungen in Strassentunnel“, Haselmair, Übleis, Böhni (ETHZ), Schweizer Ingenieur und Architekt 16/17- 93
18. „Stress Corrosion Cracking“ of Type 303 Stainless Steel in a Road Tunnel Atmosphere" Haselmair, Materials Performance , Houston June 1992, pp. 60-93
19. „Corrosion-resistant Fastenings in Road Tunnel – Field Tests, Verfasser: Böhni, Haselmair, Übleis, Structural Engineering International, Zürich 4/ 92 pp.253- 258
20. „Einsatz hochlegierter Spezialstähle für Korrosionsbeständige Befestigungselemente
    G. Felder, Boretius, Übleis, VDI- Berichte 1995 VDI – Werkstofftag

21. Longterm Trials with Fastening Elements in Road Tunnels, Tunnel 1997
    G. Felder, P. Jokiel, R. Mock, C. Allenbach and Prof. H. Böhni
22. Nichtrostende Stähle – Eine Übersicht Swiss INOX
23. Dechema Handbook vol. 7, VCH Verlagsgesellschaft ISBN 0-89573- 628- 4
24. B. Dolezal, Die Beständigkeit von Kunststoffen und Gummi, C. Hanser Verlag, München, Wien
25. Herbsleb, Ermittlung kritischer Lochfrasstemperaturen nach ASTM G48 an Grundwerkstoffen und Schweissverbindungen hochlegierter Werkstoffe MFI- Untersuchungsbericht
26. Richtlinien zum Korrosionschutz in Abwasserreinigungsanlagen, Schweizerische Gesellschaft – C6
27. Die neue bauaufsichtliche Zulassung Z-30.3-6 vom 3. August 1999 “Bauteile und Verbindungselemente aus nichtrostenden Stählen”

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