CORROSION DETECTION AND DIAGNOSIS

E. Bardal
Norwegian University of Science and Technology, Norway

J. M. Drugli
SINTEF Materials Technology, Norway

Keywords: Corrosion monitoring, inspection methods, corrosion failures, detection, failure description, analysis, diagnosis, corrosion forms, further examination.

Contents

1. Introduction
2. Inspection Organization
3. Inspection, Detection and Monitoring Methods
4. Treatment and Analysis of Inspection Results
5. From Diagnosis to Determination of Solutions(s), Recommendations and Preventive Actions
Glossary
Bibliography
Biographical Sketches
To cite this chapter

Summary

This article is introduced by a presentation of different conditions and situations in which corrosion attacks are detected. Inspection and detection procedures depend strongly on the expected risk and consequences of failure as well as on various service conditions.

In the first half of the article, inspection organization and programs are briefly dealt with. This is followed by a more detailed review of inspection, detection and monitoring methods, which comprises visual inspection, radiography, ultrasonic testing, eddy current technique, magnetic particle inspection, the use of liquid penetrant, the electric field signature method, acoustic emission, leak detection, corrosion monitoring methods and pigging devices.

The second half of the article comprises the treatment and analysis of inspection results. Included in this are the various steps of description and evaluation of observations and conditions. It is shown how corrosion diagnosis can be based upon the description of attack and the service conditions. An important part of this is the classification of corrosion, where the corrosion forms are characterized by the appearance of the attack, possibly combined with information about the most significant service conditions. Characteristic features and conditions of the various corrosion forms are presented.
Possible need for further analysis by external experts and advanced laboratory equipment is briefly commented upon. Finally, the way from diagnosis to determination of solutions, recommendations and preventive actions is summarized.

1. Introduction

Corrosion can cause serious failures, which lead to large economic loss, sometimes combined with environmental pollution, or risk of personnel injuries. The most important steps in order to hinder or reduce the extent of such failures are sufficiently early detection, proper diagnosis and effective prevention measures.

Corrosion attacks are detected under quite different conditions and situations:

- When the expected risk and/or consequences of corrosion failure are great, systematic, periodic inspection, or continuous corrosion monitoring, has to be carried out. For such equipment, for example, for pressurized vessels and pipes, inspection techniques and intervals are often defined by legal code requirements. Code regulations and specifications ensure that proper materials are selected, that a responsible design of the equipment is obtained, and that adequate fabrication methods are used. When the equipment has been installed on the site, operating procedures, maintenance procedures, inspection and control shall ensure safe performance and operation of the particular items. The main objective of the periodic inspection is to determine whether the equipment is still conforming to the safe design parameters. It has to be established whether corrosion, erosion or abrasion has consumed the “corrosion allowance” or if there are indications of mechanical or corrosion-influenced cracking that can lead to failure. If the quality, periodicity, and extent of inspection or monitoring are carried out efficiently, the probability of detecting attacks before they cause serious failures is very high.
- The inspection schedules for medium consequences of failure are set by proprietor policy in response to real safety and cost factors.
- In other cases, the consequences of corrosion are minor, or significant corrosion may not be expected. When corrosion attacks are developed in such cases, they are usually detected casually, or in inspection routines for other purposes, but sometimes they are not detected before leakage, fracture, malfunction or some other indication of damage occurs.

The inspection program (see Section 2) and methods (Section 3) depend very much on the aforementioned conditions and situations, but also on type of structure, equipment, design, and process. In systematic inspection and monitoring, a range of techniques of varying sophistication are used.

The diagnosis, i.e., the identification of the form of corrosion and the ascertainment of the cause of it (Section 4), is based on the inspection results, the knowledge of materials data and service conditions, and qualified analysis of this information.

The final goal of the detection and diagnosis is to facilitate decisions on appropriate repair/replacement and corrosion prevention measures, which may include improved
materials selection or design, change of environment, electrochemical protection, or use of a coating.

2. Inspection Organization

Inspection plays an important role in modern engineering. As indicated, it shall start even before the equipment is fabricated by: checking materials selection, drawings, welding procedures, and capability of producers and suppliers. The fabrication and the acceptance of the finished product would also be inspected and quality controlled.

To be able to perform the inspection in a systematic way, an inspection program has to be worked out. The program shall specify the frequency of inspection, timing, and recording of service and equipment condition. To devise a proper inspection program, knowledge of the process and the material performance is needed. The inspection of the various parts of the system and the type of inspection methods shall be specified. The frequency of inspection shall be evaluated, based both on the risk of failure occurring and on the consequences if failure occurs. It is recommended that critical equipment operating at high pressure and/or at severe corrosive conditions shall be inspected at least once a year.

Experiences from similar equipment, or from previous inspection of the same equipment, will often give valuable information about the most critical sites for corrosion attacks. These sites must then be inspected more frequently than sites where the probability for corrosion damage is less. Critical sites may, for example, be bends, welds, or obstacles in pipe systems with corrosive medium flowing in the system. It is important that the inspection department has access to the past history of the equipment or of similar units, so that a proper inspection may be made.

The individual inspector or inspection department has to be reliable. Quality control or assurance programs shall involve professional licensing for inspection personnel. Inspection personnel, who are educated and trained in inspection techniques, such as radiography, ultrasonics, magnetic particles, and dye penetrants, should be certificated by government or institutions. The inspection and quality control is the foundation of a good preventive maintenance program.

3. Inspection, Detection and Monitoring Methods

3.1. Overview

In Table 1, the most important inspection methods and their relative ability to detect corrosion defects are summarized.

(0) The method is not used, or it is not applicable.
(1) The method is possible, but not suitable.
(2) The method is suitable, however, there are other methods that are preferable.
(3) The method is suitable.

©Encyclopedia of Life Support Systems (EOLSS)
Some monitoring methods are also listed in Table 1. These can give an indication of the corrosion rates.

In the following sections, a brief summary of some inspection and monitoring methods is given. Detailed descriptions can be found in books listed in the bibliography.

3.2. Visual Inspection

Visual inspection in the simplest form can be performed without any accomplishing aids when there is physical access to the object. The experienced inspector can often determine the type of corrosion, such as general corrosion, pitting corrosion, crevice corrosion, weld and heat affected zone corrosion, and erosion corrosion from visual inspection. The degree of corrosion can be measured and described and documented by use of sketches or photographs. For exact measurements of local corrosion penetration caused, for example, by pitting corrosion, various types of mechanical or optical measuring instruments can be used.

Material thinning due to general corrosion may be difficult to determine exactly, without use of additional non-destructive inspection methods, such as ultrasonics.

*Special probes for inspection of small tubes, for example, in heat exchangers

<table>
<thead>
<tr>
<th>Method</th>
<th>Ability to detect crack-like defects</th>
<th>Ability to detect general corrosion and pits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accessible surfaces</td>
<td>Non accessible</td>
</tr>
<tr>
<td>General inspection methods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual inspection</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Radiography</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ultrasonic, manual</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Ultrasonic, automatic</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Eddy current</td>
<td>2</td>
<td>1 (3*)</td>
</tr>
<tr>
<td>Magnetic particle</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Liquid penetrant</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Acoustic emission</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Leak detection</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Field signature method</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Corrosion probe monitoring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight loss coupons</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Electric resistance</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Linear polarization resistance coupons</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Electrochemical impedance</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 1. Inspection and Monitoring Methods
Initial cracks caused by stress corrosion or corrosion fatigue, are often difficult to detect visually. If such defects are likely, then methods to make the cracks visible are needed (magnetic particles, liquid penetrant, eddy current). Mirrors, boroscopes, flexible fiber-optic instruments, or small video cameras can be used together with light sources, to look inside small pipes or narrow spaces in the equipment.

3.3. Radiography

- Radiography makes use of the penetrating quality of short wave electromagnetic beams, which may be X-rays generated by X-ray equipment or γ-rays from radioactive isotopes. These beams are similar to light, but are not visible. The wavelengths are much shorter and the energy much higher and thus the beams are able to penetrate solid materials, including metals. When the beam passes through a test specimen, some energy is absorbed in the material. The thicker the material, the larger the amount of energy absorbed. Furthermore, different materials attenuate the beam to various degrees. For example, air and corrosion products are much more easily penetrated than solid metals. The principle of radiography is shown in Figure 1.

![Figure 1. The Principle of Radiography](image)

The beam from X-ray equipment or an isotope penetrates a piece of metal, and the amount the beam is attenuated depends on the thickness of the material, and hence the intensity of the transmitted beam varies with position. A photographic film at the back side of the specimen will, after development, be dark behind the thin parts where the transmitted beam intensity was high, and light behind the thick parts of the specimen where the intensity was low, i.e., pits and thinning of the material will be visible as dark
areas on the film. Pit depths and the degree of thinning can be determined to a certain degree by density measurements of the film and use of proper geometrical correction factors. Radiography is commonly used for control of weld quality, because most weld defects can be detected by this method.

The minimum variation of the thickness in the direction of beam that can be detected is ~1–2% of the sample thickness, which means that narrow cracks are difficult to detect if they are oriented in directions other than parallel to the beam. Another limitation of radiography is that both sides of the part must be accessible. However, the interior of pipes can be investigated by the so-called double wall technique.

Advantages of radiography in the assessment of corrosion are:

- The radiograph is a permanent record, which, if required, can be evaluated later by more competent personnel than the operator.
- The inside of complex small parts, which are not accessible, can be evaluated.

The radiograph can give some indication of the nature and degree of attack.

3.4. Ultrasonic Testing

Ultrasonic testing utilizes sonic waves (also known as elastic stress or acoustic waves) with higher frequency (1–6 MHz) than human beings can hear. Ultrasonic waves propagate quite easily in liquids and in solid materials, but not in gas. In solids and in liquids, the ultrasonic pulses will be propagated and reflected in a way almost analogous to light. When the ultrasonic pulses reach the back wall of the test specimen, they are reflected. The pulses will also be reflected by inhomogeneities in the test specimen. The time taken for the sound to transverse the thickness of a specimen and return to the probe is usually displayed on an oscilloscope and reflects the distance the pulse has traveled and thereby the thickness of the specimen. The principle of ultrasonic testing is shown on Figure 2 (see Composite Defects and their Detection). Ultrasonic equipment is widely used for crack detection and for thickness measurements of in-service equipment that may suffer from erosion or corrosion. Due to small size of the equipment and because it is easy to operate, ultrasound is very suitable for field inspection.

The acoustic pulses are both generated and detected by piezoelectric crystals. The most commonly used probes are normal probe, angle probe and the double crystal probe (separate transmitter and receiver). In addition, there are numerous special probes.

The three ultrasonic techniques that have been used are: (a) the pulse/echo, (b) transmission, and (c) resonance methods. The basic technique is the pulse/echo technique.

A more sophisticated technique is the ultrasonic holography. When using holography, both probe and the electronic processing of the signal are more advanced than ordinary pulse/echo techniques, and this makes it possible to get three-dimensional images of the corroded surface. Automatic ultrasonic scanning and recording techniques combined
with computer techniques are also able to produce three-dimensional maps of the corroded surface, which means that documented pictures of the corrosion attacks can be given.

![Figure 2. The Principle of Ultrasonic Testing using Pulse/Echo Technique and Normal Probe](image)

(a) normal probe, (b) angle probe

### 3.5. Eddy Currents

Eddy current is a useful technique for the monitoring of cracking and pitting corrosion processes for all types of metallic materials. The technique depends on the eddy currents produced in the surface of a metallic object placed in a field of a coil, fed with an alternating current (typically 10 kHz). At a crack or a pit, the eddy currents are disturbed, producing a change in the back EMF of the existing coil or in a secondary coil, which can be detected and amplified for visual display or a sound signal. Eddy current is restricted to a small layer in the surface of the metal, called the skin depth. If the metal is much thicker than this, the thickness of the metal cannot be determined, although of course the technique may be employed to detect surface defects. For ferromagnetic materials such as mild steels, the skin depth is small, typically 2.5 mm at about 50 Hz. Eddy currents can also be used for thickness measurements of non-conducting surface layers on metallic materials. Moreover, special equipment has been developed to examine small tubes, for example, in heat exchangers.

### 3.6. Magnetic Particle Inspection (MPI)

Magnetic flaw detection can only be applied to ferromagnetic materials, and relies on the distortion that the surface defect imparts to a magnetic field. The distortion is detected by a magnetic powder, or a suspension of a magnetic powder in a liquid
carrier, such as paraffin, covering the surface. Fluorescent magnetic inks have also been employed to improve the sensitivity of the technique. The magnetic particles will concentrate at the magnetic perturbations associated with flaws at the surface, and hence make defects in or close to the surface visible. The test specimens can be magnetized by several methods. The simplest way is to send an electric current through the material. The specimen can also be magnetized with electromagnets. Both direct current (DC) and alternating current (AC) can be used for magnetization. DC increases the probability for detecting defects underneath the objects surface. The method is specially suited for revealing narrow cracks close to the surface or in the surface, for example, cracks caused by stress corrosion cracking or corrosion fatigue, which can be very difficult to detect visually.

3.7. Liquid Penetrant

Some liquids, for example, paraffin, have the ability to penetrate into very narrow cracks. This ability can be used to locate cracks in the surface of all types of metallic materials. A penetrating liquid is applied to the surface to be investigated and will penetrate into flaws and cracks. After the superfluous liquid is removed, a developer is added, which sucks the penetrant out of the cracks and makes them visible. The developer has high contrast to the penetrating fluid, which can be dyed a bright red color, or it can be fluorescent and thus shown up by ultraviolet light.

This method is commonly used for detection of surface cracks, especially for materials where MPI cannot be used.

3.8. The Electric Field Signature Method (FSM)

This is a method developed by CorrOcean ASA from the commonly used principle of electrical resistance (ER) determination applied for corrosion monitoring of probes.

A current is impressed through the object and the potential drop between several electrodes fixed directly to the outer surface, e.g., on a spool piece in a pipe system, is measured. Changes in the geometry, in the form of cracks, general corrosion, erosion corrosion, or pitting will impair the potential field in the metal. These measurements are compared to previous measurements, and the development of corrosion or cracks can be recorded. A computer usually treats the results before they are presented.

3.9. Acoustic Emission

Acoustic emission monitoring is the analysis of the ultrasonic waves generated by dynamic events, such as deformation and cracking, occurring in the material under investigation. Thus, stress corrosion cracking, hydrogen embrittlement and corrosion fatigue can be detected. However, acoustic emission cannot indicate the size of a defect, only whether a defect is growing or not.

Acoustic emission sensors can be located at some distance from the defect, because the acoustic waves propagate easily in metallic components. Structures can therefore be monitored from relatively few fixed sensors. The location of the defect can be revealed...
if several sensors are fixed to the structure in a special pattern and the times of arrival of an acoustic wave recorded at the different sensors. The method has fewer problems with access and scanning than other inspection methods.

3.10. Leak Detection

Leaks in pressure vessels can be detected by a number of methods. Thermography can provide remote temperature monitoring, and is capable of detecting leaks if the leaking fluid has a temperature different from the ambient. With this technique, large areas of a plant can be examined simultaneously from a remote position. The data can be presented in the form of a visual display, using color notation, which can be superimposed on an optical image if necessary. (Leakage can be detected by acoustic emission techniques, because a leakage from a pressure vessel will create ultrasound.)

In addition, leak detection can be used to indicate when the corrosion allowance of pressurized equipment has been consumed by uniform or erosion corrosion. A small hole is drilled from the outside into the item's wall, so that only the corrosion allowance is left. When the corrosion allowance of the wall has been consumed by corrosion, a small leakage will occur and give a warning.

Thermography is also employed to evaluate the condition of insulation, to locate product flow problems and failures of electrical components.

3.11. Corrosion Monitoring

The aggressiveness of the environment can be measured more or less continuously by recording the corrosion rate of coupons or probes installed in the system. If the material in the coupons or probes is the same as in the equipment, the results can indicate corrosion rates of the equipment. The coupons must be mounted correctly so that they experience similar conditions to the equipment being monitored. The most common monitoring methods are:

- Weight loss coupons. The weights of the coupons are recorded at certain time intervals.
- Electric resistance probes. The electric resistance of the probe is increased by corrosion.
- Linear polarization resistance (LPR). Electrochemical test method.
- Electrochemical impedance. Electrochemical test method.

3.12. Pigging Devices

Equipment for internal examination of pipes and tubes have been developed, based on a number of techniques such as ultrasonic, eddy currents, spring loaded calipers, magnetic flux, induction and combination of techniques. The measuring equipment is fixed to a body, known as a pig, that follows the flowing medium in the pipeline. The data are often recorded and stored in the pigs and can be analyzed after the pigs are removed.
from the pipe. When this technique is to be used, the pipes have to be supplied with launching devices for the pig.

4. Treatment and Analysis of Inspection Results

4.1. Description and Evaluation of Observations and Conditions

When corrosion failure or unacceptable corrosion attack have been detected, the first step should be to estimate the cost of repair or replacement and the consequence of new attack after such repair. This will affect the decision on extent and content of further investigations. In many cases, the preliminary examination is sufficient to decide that a relatively simple action is adequate to solve the problem. In more complex cases, more extensive examinations have to be carried out.

Before a complete diagnosis can be made, all relevant data and information must be collected and evaluated; this includes:

- Description of the construction/equipment as regards location, shape, dimensions, relationships between components, age and delivering company.
- Description of the appearance of the attack both before and after surface cleaning, by means of photographs, sketches, text and quantitative expressions. Both distribution and intensity (depths) of attacks must be documented.
- Evaluation of data from physical and chemical detection methods, as described in Section 3.
- Reports on service conditions such as continuity/intermittence and duration of service, temperature, pressure, flow conditions and rates, chemical composition of the corrosive environment, possible mixture of phases, mechanical loads and effects, as well as the variation of the mentioned physical, chemical and mechanical conditions. Operation by personnel and possible operational irregularities should also be included.
- Data of corroded material and possibly other materials in the plant with some connection to the former. Such data must include composition and possible welding, cold work, heat treatment, surface treatment, etc.

4.2. Diagnosis Based on Description of Attack and Service Conditions – Definition of Corrosion Forms

Corrosion is often classified by corrosion forms characterized by the appearance of the attack, possibly combined with information about important service conditions. The benefit of such classifications is that a real corrosion attack can usually be identified as a certain form of corrosion, by means of a simple visual examination, by the naked eye, by a magnifying glass or a microscope. Because each form of corrosion has its characteristic conditions and causes that are well known to the corrosion engineer, it is often possible to make the diagnosis after such an examination (supported by information on material and service conditions).

Using this approach, one can define the following forms of electrochemical corrosion:
(a) Uniform or general corrosion.
(b) Galvanic or two-metal corrosion.
(c) Thermogalvanic corrosion.
(d) Crevice corrosion, including deposit corrosion.
(e) Pitting corrosion.
(f) Intergranular and exfoliation corrosion.
(g) Selective corrosion, selective leaching.
(h) Erosion corrosion.
(i) Cavitation corrosion.
(j) Fretting corrosion.
(k) Stress corrosion cracking.
(l) Corrosion fatigue.

The corrosion forms are briefly described in the following section, with particular emphasis on appearance of attack, material characteristics and service conditions. Some of the corrosion forms are schematically illustrated in Figure 3.


### 4.3. Characteristic Features and Conditions of Various Corrosion Forms

#### 4.3.1. Uniform (General) Corrosion

In this form of corrosion, the attack is relatively evenly distributed all over the surface. It occurs typically under the following conditions:

- the material is a metal or alloy that is not liable to form protecting surface films in the environment in question,
- electrochemical corrosion is the only deterioration process (which rules out cases of, e.g., erosion corrosion, where a mechanical process contributes),
• the anodic and the cathodic reaction both occur all over the surface, but not at the same positions at the same moment (the two reactions may steadily change position). Closely connected to this is:
• that the concentration of the electrolyte does not vary significantly over the metal surface.

4.3.2. Galvanic (Two-metal) Corrosion

When a more noble metal or alloy is in metallic contact with a less noble one, the corrosion rate of the latter is higher and that of the former is lower than when the two materials are separated. A necessary condition for galvanic corrosion is that there is an electrolytic connection between the two metals, as shown in Figure 4. The increase in corrosion rate of the less noble material is the galvanic corrosion rate (represented by galvanic corrosion current $I_{\text{galv}}$ in Figure 4.

Furthermore, one of the most important factors in galvanic corrosion is the area ratio between the more noble and the less noble material. The larger this ratio is, the more intense is the galvanic corrosion.

![Figure 4. Galvanic Corrosion](image)

The practical ranking of nobleness of the materials is given by the position in the galvanic series, i.e., their corrosion potential in the actual environment, as shown for seawater at 10 and 40 °C in Figure 5.
4.3.3. Thermogalvanic Corrosion

A temperature gradient in a material exposed to a corrosive environment may cause a galvanic element and consequently lead to a form of corrosion called thermo-galvanic corrosion. The hottest parts will normally act as dominating anodes with increased corrosion, while the colder parts are cathodic seats, which are protected. When analyzing such a case, it must be taken into account that the temperature may affect both the anodic and the cathodic reactions.

4.3.4. Cervice and Deposit Corrosion

This is localized corrosion concentrated in crevices or under dense deposits of corrosion products, dirt, sand, leaves and marine fouling. The crevice must be wide enough for
liquid to penetrate into it. But, as a consequence of the mechanism, it must also be narrow; a condition for the corrosion to start is that the liquid in the crevice is depleted of oxygen. This means that the liquid in the crevice must be stagnant and the diffusion of oxygen into the crevice must be slower than the consumption of \( \text{O}_2 \) in the crevice.

When crevice corrosion has been initiated the anodic reaction inside the crevice is mainly balanced by a cathodic reaction on the adjacent external surfaces. A condition for crevice corrosion is therefore that there is access of electrolyte and an oxidizer (usually oxygen) to the external surfaces.

The most typical cases of crevice corrosion are found on materials which are originally passive or easily passivated (e.g., stainless steels, aluminum, unalloyed or low alloy steels in alkaline solutions), when these materials are exposed to dissolved, aggressive species like chlorides, which can destroy the passive oxide locally. Conventional stainless steels, such as AISI 316, 304, are liable to deposit corrosion in stagnant or slowly moving seawater.

A special type of crevice corrosion is the so-called filiform corrosion, which may occur on steel, aluminum and magnesium underneath protecting films of more noble metals, lacquer, enamel or phosphates.

### 4.3.5. Pitting Corrosion

Pitting corrosion occurs on more or less passivated metals and alloys in corrosive media containing chloride, bromide, iodide or perchlorate ions.

The electrochemical condition is that the corrosion potential exceeds a critical potential, the pitting potential, which depends on factors like material, concentrations of aggressive species, pH and temperature. The corrosion form is characterized by pits with a radius of the same order of magnitude or less than the pit depth. The pits may have different shapes, as shown in Figure 6. Deep pits may develop without being detected, because they are narrow and often covered by corrosion products. The number and size of pits may vary greatly between different materials and from one area region to another on a given material. On a material like aluminum, e.g., in seawater, a large number of small pits may develop. In contrast, many stainless steels (SS) have relatively high resistance against pit initiation and therefore, usually only few pits are formed. However, when a pit on SS has been formed it may grow rapidly, and the attack becomes serious.
4.3.6. Intergranular Corrosion (IC) and Exfoliation Corrosion

Intergranular corrosion is localized attack on or at the grain boundaries (g.b.), with little or no attack on other parts of the surface. This is a dangerous form of corrosion, because the cohesion between grains can be reduced so much that tensile stresses cannot be transferred; the toughness of the material decreases markedly at a relatively early stage, and fracture can occur without warning. Grain may fall out, and cause pits, which may not necessarily have any significant consequence.

The reason for intergranular corrosion is galvanic elements due to difference in concentration of impurities, or alloying elements between grain boundary regions and the rest of the metal or alloy. Intergranular corrosion may, for example, take place under the following conditions: secondary phase of AlFe at g.b. in technical grades of aluminum; increased concentration of Zn at g.b. in brass, and reduced amount of chromium in solution at g.b. in stainless steels. A familiar case is intergranular corrosion in conventional austentic stainless steels with 0.06–0.08% C, particularly after welding. It is avoided if the carbon content is reduced to <0.03% (as in AISI 304 L and 316 L). IC is also experienced in nickel alloys, magnesium alloys and cast Zn-alloys, and is common in marine and other salt containing environment. Intergranular corrosion occurs without tensile stresses, which separates this form from intergranular stress corrosion cracking (see later).
A special form of corrosion in aluminum alloys is exfoliation corrosion, which usually propagates along the grain boundaries parallel to the surface. It is most familiar in AlCuMg-alloys, but it has also been observed in AlMg-, AlZnMg- and AlMgSi-alloys. The intensity of exfoliation corrosion increases when the solution becomes slightly acid and when it is coupled to more noble metals.

4.3.7. Selective Corrosion (SC) (Selective Leaching)

Selective corrosion occurs in alloys where one element is less noble than the others. The less noble element is removed from the alloy, leaving a porous material of little strength and ductility. Regions that have suffered selective corrosion are often covered by corrosion products and have exactly the same shape, and thus the attack may be difficult to discover. Serious material damages may therefore occur without warning.

The most common example of SC is selective corrosion in brass, where Zn is dissolved and copper is left in place (dezincification). After cleaning the surface, such corrosion is easy to identify, because the dezincified regions have a characteristic red copper color, in contrast to the original yellow brass color. Two different types of this corrosion form exist (Figure 7): uniform dezincification (favored by high Zn content and acid corrosion media), and localized dezincification (favored by somewhat lower Zn content and neutral, alkaline and slightly acid solutions). The same corrosion forms and types may develop in aluminum bronzes (dealuminizing) in acids and strongly polluted seawater. Silicon bronzes may suffer from selective dissolution of silicon. Graphitizing of gray cast iron is another example of selective corrosion, in which iron is dissolved and graphite is left on the material.

![Figure 7. (a) Uniform and (b) Local Dezincification of Brass](image)

4.3.8. Erosion Corrosion

When there is relative movement between the corrosive medium and the metal, the metal surface is often affected by mechanical forces leading to increased corrosion denoted erosion corrosion. The usual mechanism is that layers of corrosion products, or deposited salts resulting from the corrosion reaction, are worn away, dissolved or prevented from being formed, so that the material surface becomes clean and more active.
Erosion corrosion is promoted by high velocities, liquid-gas and liquid-particle mixtures, and geometrical elements in the flow system, which lead to disturbance turbulence, and impingement (see Figure 8). The result is grooves and pits with a pattern determined by the flow direction and local flow conditions.

Most sensitive to erosion corrosion are materials, which under stagnant conditions are largely protected by corrosion products of relatively low strength and adhesion to the metal (lead, aluminum, copper and their alloys, and unalloyed and low alloy steels). Most copper alloys have critical velocities below 4–5 m/s in seawater. Stainless steels, titanium and nickel alloys have much higher erosion corrosion resistance.

![Figure 8](image.png)

**Figure 8.** (a) Impingement and (b) Turbulence Erosion Corrosion

### 4.3.9. Cavitation Corrosion

Cavitation corrosion, or rather called cavitation erosion if the contribution of corrosion is small, is caused by high flow velocities and varying fluid dynamic conditions leading to rapid local pressure fluctuations. It takes place in a wide range of equipment such as water turbines, pumps, propellers and on the external side of wet cylinder linings in diesel engines; the latter case is due to vibration of the cylinder wall.

Cavitation damage is characterized by deep, narrow pits normal to the surface, localized close to each other or grown together over smaller or larger areas, often leading to a spongy appearance (Figures 9 and 10). The edges of the pits are usually very sharp.
Figure 9. External Cavitation Corrosion on Wet Cylinder Lining of Cast Iron in Diesel Engine
(Photograph courtesy of: Erling Abusland, SINTEF Corrosion Center)

Figure 10. (a) Cavitation Corrosion on Propeller of Nickel Aluminum Bronze on a High-speed Ship; (b) Close-up of the Damage
4.3.10. Fretting Corrosion

Contrary to the other forms of corrosion dealt with in this chapter, fretting corrosion is not to be considered as electrochemical corrosion. It is included here because it can take place at ambient external temperature, just as the electrochemical forms.

Fretting corrosion takes place at the interface between two parts, which are vibrating with very small amplitudes relative to each other. Depending on the situation, fretting may cause seizing of originally movable components, and in other cases, loss of tolerances and loosening of parts that are considered fixed, e.g., pressed-on wheels.

Fretting corrosion is dependent on access of oxygen, but not of water. The visual result is discoloring of the attacked surfaces and formation of pits or grooves. In many cases, fatigue cracks may be initiated from the surface attacks.

4.3.11. Stress Corrosion and Hydrogen Assisted Cracking

Stress corrosion cracking can be defined as crack formation and growth as a result of simultaneous static tensile stresses and corrosion. The tensile stresses may be due to external loading, centrifugal forces or temperature differences, or they may be residual stresses caused by cold working, welding or heat treatment. The cracks are roughly speaking oriented normal to the tensile stresses, may grow intergranularly or transgranularly, and may be more or less branched. If they are not detected in time, they will lead to rapid, unstable fracture.

Stress corrosion cracking has been observed for many different combinations of materials and environments. A mechanism operating for several material—environment combinations is hydrogen embrittlement due to atomic hydrogen, which is produced at cathodic areas and diffuses into the material. This form of stress cracking is termed hydrogen assisted or hydrogen induced cracking, often simply called hydrogen embrittlement.

4.3.12. Corrosion Fatigue

Corrosion fatigue (CF) is crack formation and growth due to simultaneous fluctuating stresses and corrosion. Just as for stress corrosion cracking, only the tensile stresses cause corrosion fatigue. The difference between these two deterioration forms is that one originates from static and the other from fluctuating stresses. Any environment, which may cause some kind of surface corrosion, will cause CF when the stress conditions are present.

It is well known that fatigue crack surfaces in non-corrosive environment have typical beach marks. Corrosion fatigue also usually leads to beach marks, but these may be less visible because they might have been attacked by corrosion and possibly covered by corrosion products. CF cracks are in most cases transgranular, and are often branched in...
contrast to ordinary dry fatigue cracks. The various stages of the crack development are shown in Figure 11.

![Figure 11: The Different Stages in Corrosion Fatigue Crack Development](image)

4.3.13. Corrosion under some Special Environmental Conditions

A type of corrosion that occurs in soils and sometimes in water due to externally induced electric current is stray current corrosion. A typical example is corrosion caused by current, originating at an electric installation and flowing in and out of a buried pipeline.

A different cause of corrosion on steel in soils is sulfate reducing bacteria, which are operating under anaerobic conditions. A second example of biologically assisted corrosion is particularly experienced on more corrosion resistant materials, like stainless steels in seawater. An aerobic bacterial film developed on the surface catalyses the cathodic reaction strongly, and promotes both initiation of localized corrosion and an increase in the corrosion rate.

High temperature corrosion is not covered here, but is described in some of the books in the bibliography.
4.4. Further Analysis

Sometimes the reasons for the corrosion attack may be complex and difficult to sort out on the basis of simple visual observations, or with the resources available in the industrial company or division. It may be necessary to consult external experts who have more advanced equipment available. Further examination may include light or scanning microscopy of surfaces and cross-sections, photography, chemical analyses of materials, corrosion products and scales, and various mechanical tests.

5. From Diagnosis to Determination of Solutions(s), Recommendations and Preventive Actions

Based upon use of the inspection system and detection methods described in Sections 2 and 3, evaluation of inspection results and conditions, and possibly further analysis as outlined in Section 4, the diagnosis can be made, i.e., the form and cause of corrosion are determined. In books of corrosion technology, various solutions are recommended for each corrosion form. The company’s corrosion engineer or the external expert has to make a technological and economic evaluation of the actual case before he/she can recommend one specific solution and possible alternative(s) to this.

Sometimes, failures may have occurred due to human error. If this is the case, steps must be taken to avoid repetition. Improvement in routines of supply and labeling of materials, information on experienced failures, and further education of technical personnel, may be appropriate.

Glossary

AC: Alternating current.
CF: Corrosion fatigue.
Corrosion diagnosis: Identification of the form of corrosion and the ascertainment of the cause of it.
Corrosion form: Type of corrosion defined by the appearance of the attack, possibly combined with information about important service conditions.
Corrosion potential: Rest potential, zero current potential, electrode potential at zero external current.
DC: Direct current.
ER: Electrical resistance
FSM: Electrical field signature method.
Galvanic series: Series of corrosion potentials of different materials in a given environment.
IC: Intergranular corrosion.
LPR: Linear polarization resistance.
LPR method: An electrochemical test and monitoring method.
MPI: Magnetic particle inspection.
SC: Selective corrosion.
Bibliography


Biographical Sketches

**Einar Bardal** graduated at the Faculty of Mechanical Engineering of The Norwegian Institute of Technology in Trondheim, Department of Materials and Metal Forming in 1964, and obtained his dr.ing. degree with a scientific investigation in corrosion at the same department in 1968. He was senior lecturer from 1969 to 1977 and part time professor in materials properties 1979-94 at this department.

He was initiator of SINTEF Corrosion Centre and head of the centre 1975-94. Since 1994 he has been professor in Corrosion and Coating Technology at the Norwegian University of Science and Technology, Trondheim, Department of Machine Design and Materials Technology, and in the same period scientific adviser at SINTEF Materials Technology. In 30 years he has been responsible for corrosion education at the faculties of Mechanical Engineering and Marine Technology at the university. Bardal has published a large number of papers in corrosion, corrosion fatigue and surface technology. He is member of the Norwegian Academy of Science and Technology, and was winner of Statoil's research prize in 1993 and the European Federation of Corrosion Medal 2001. He has been member of several international committees and was chairman of the European Corrosion Congress in 1997 (Eurocorr’97)

**John M. Drugli** is educated at Trondheim Technical College as mechanical engineer in 1958. He was engineer at the Ship Towing Tanks and the Cavitation Tunnel, Division of Marine Hydrodynamics, Norwegian Institute of Technology till 1961. In the time period 1962-1970 he accomplished courses in Physical Metallurgy, Welding, Metallurgy and Metals Working and Corrosion at the Norwegian Institute of Technology in Trondheim. He was laboratory engineer at the same institute from 1961 to 1976. After
that time he worked as Research Scientist and from 1990 as Senior Research Scientist at SINTEF Corrosion Centre. He has background in research work in the fields of Welding and Welding Metallurgy, Materials Testing, Corrosion and Corrosion Testing with particular emphasis on experimental techniques, evaluating of materials, cathodic protection design and material selection for various corrosion conditions. Drugli has published more than 30 papers in corrosion, corrosion testing and material selection. He was winner of SINTEF’s research prize in 1995.

To cite this chapter