



SINTEF



Project Report

Corrosion of aluminium in marine environments

Reported issues and standards

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SUMMARY

This report summarizes:

- Standards and recommended practices from various standardizing bodies that covers the use of aluminium in marine environments
- Standards for corrosion testing and testing of coatings on aluminium
- Reported corrosion attacks on aluminum in marine environments and the root cause of the attacks

The report will be used as a guideline for further research in the MARINAL project and to identify gaps in the standards to be closed in the future.

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Table of contents

1	Introduction	5
1.1	Background	5
1.2	Objectives.....	5
2	Classification of the marine environment with respect to exposure zones.....	5
3	Standards and design codes on aluminium in marine environments	7
3.1	Overview	7
3.2	EN 1999-1-1.....	8
3.3	EN 1090-3.....	8
3.4	DIN 81249 – Corrosion of metals in sea water and sea atmosphere	9
3.5	NORSOK M-001, M-102 and M121	9
3.6	DNV	11
3.7	Recommendations from aluminium suppliers.....	11
4	Corrosion tests for aluminium relevant in marine environments.....	13
4.1	Corrosion tests for atmospheric conditions.....	13
4.1.1	ISO 9227 and ASTM B117 Salt spray tests.....	13
4.1.2	ISO 16701 Accelerated corrosion test involving exposure under controlled conditions of humidity cycling and intermittent spraying of a salt solution.....	14
4.1.3	ISO 7441 Corrosion of metals and alloys — Determination of bimetallic corrosion in atmospheric exposure corrosion tests	14
4.2	Corrosion tests for tidal- and splash zone	14
4.2.1	ASTM G44 Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution	14
4.2.2	ISO 11130 Corrosion of metals and alloys – Alternate immersion test in salt solution	14
4.3	Corrosion tests for submerged zone.....	14
4.3.1	ASTM G31 Standard Practice for Laboratory Immersion Corrosion Testing of Metals	14
5	Coating tests	15
5.1	Coating tests for atmospheric conditions	16
5.1.1	ISO 4623-2 Paints and varnishes — Determination of resistance to filiform corrosion — Part 2: Aluminium substrates (ASTM D 2803)	16
5.1.2	ISO 12944-9 Protective paint systems and laboratory performance test methods for offshore and related structures.....	16
5.1.3	ISO 11997-1 Determination of resistance to cyclic corrosion conditions — Part 1: Wet (salt fog)/dry/humid	17

5.2	Coating tests for immersion conditions.....	17
5.2.1	ISO 15711 Paints and varnishes — Determination of resistance to cathodic disbonding of coatings exposed to sea water	18
5.3	Standardized methods for evaluating coating degradation	18
5.3.1	ISO 4628 Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance.....	18
6	Some reported corrosion issues on aluminium in marine environments.....	19
6.1	Applications.....	19
6.2	Atmospheric conditions	20
6.2.1	Galvanic corrosion	20
6.2.2	Pitting corrosion	22
6.2.3	Crevice corrosion	23
6.3	Submerged conditions	24
6.3.1	Testing of corrosion inside steel-aluminium overlapping joints with CP	24
6.3.2	Aluminium – steel crevice corrosion	26
6.3.3	Galvanic corrosion between aluminium and steel	27
7	References	29
A	Appendix - DIN 81249 Corrosion of metals in sea water and sea atmosphere	31
B	Appendix – ISO 4628 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance	37

1 Introduction

1.1 Background

The main objective of the MARINAL project is to strengthen and extend the use of aluminium (Al) alloys in marine applications. Aluminium, with its high strength-to-weight ratio and good corrosion resistance when used correctly, has a high potential for extended use in marine constructions.

An important obstacle against extended use of aluminium in marine applications is uncertainty about the corrosion properties. Marine and offshore design codes and standards are focused on steel and do not provide the necessary information on how to use aluminium. Standardizing bodies have a focus on steel, and specifications for aluminium are either lacking or insufficient to ensure safe implementation of aluminium in a construction. Therefore, aluminium is often not even considered by marine engineers and designers. The focus of the project will therefore be fundamental studies of corrosion properties of standard aluminium alloys, including recycled alloys, in marine conditions and development of sustainable protection solutions.

This report summarizes our knowledge about corrosion problems with aluminium in marine constructions and provide an overview of available standards and design documents provided by various bodies like NORSOK, ISO, Eurocode, and DNV.

1.2 Objectives

The objectives with this report are to:

- Provide an overview of relevant standards about use of aluminium in marine constructions
- Provide an overview of standards for corrosion testing of aluminium alloys and testing of coated aluminium
- Describe typical corrosion attacks reported on aluminium in marine applications

The report will be used as a guideline for further research in the MARINAL project and to identify gaps in the standards to be closed in the future.

2 Classification of the marine environment with respect to exposure zones

Following the standards ISO 9223 [1] and ISO 12944-2 [2], the environmental conditions are classified in categories according to corrosion of bare metal during the first year of exposure. As shown in Figure 1, the maritime environment is classified in corrosivity categories exemplified by an offshore wind turbine mounted on a jacket substructure. The corrosivity categories were originally developed for steel but are now well established and useful also for aluminium.

ISO 9223 also contains information about how to classify environments according to corrosion rate on aluminium, but it does not take the large difference in corrosion resistance between various aluminium alloys into account. In that respect, ISO 9223 also exemplifies the general lack of knowledge about aluminium and the use of aluminium in constructions.

For further information about the various exposure zones and categories of corrosivity, we refer to ISO 9223 and 12944-2.

Offshore wind turbine with jacket

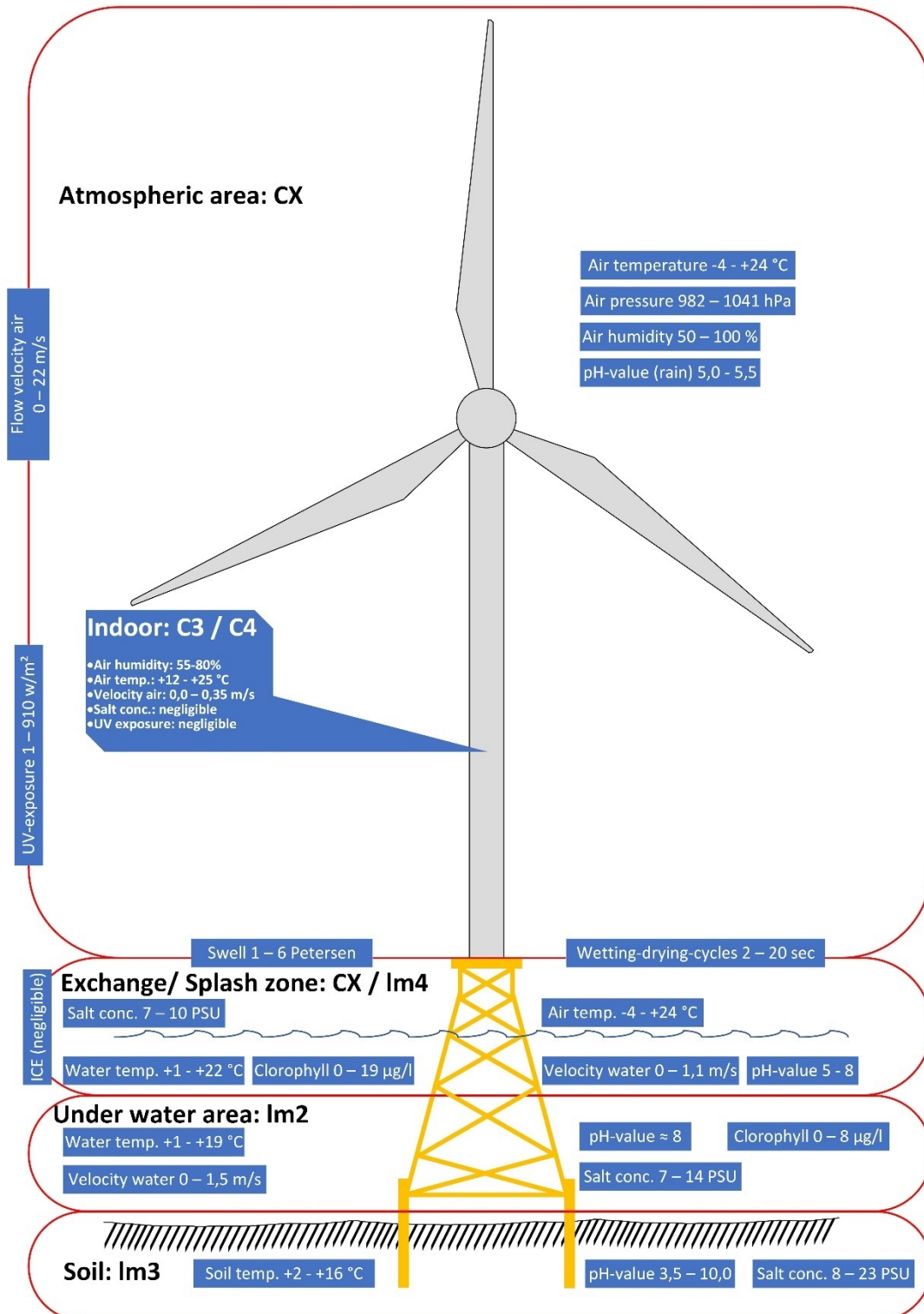


Figure 1. Corrosivity categories according to ISO 12944-2, exemplified by an offshore wind turbine on a jacket substructure

3 Standards and design codes on aluminium in marine environments

3.1 Overview

Table 1. Standards, specifications and guidelines covering the use of aluminium in marine environments

Standard	Covering	Comment
EN 1999-1-1: 2007 (E) Eurocode 9 Design of aluminium structures	Structural	Annex D gives recommendations about corrosion protection
EN 1090-3: Execution of steel structures and aluminium structures	Structural	Gives some requirements about bolting and sealing of crevices
DIN 81249-2: Corrosion of metals in sea water and sea atmosphere. Free corrosion in seawater	Maritime	Advice about alloys and their corrosion behaviour in seawater
DIN 81249-3: Corrosion of metals in sea water and sea atmosphere. Galvanic corrosion in seawater	Maritime	Advice about corrosion rates in seawater when connected to other metals
DIN 81249-4: Corrosion of metals in sea water and sea atmosphere. Corrosion in sea atmosphere	Maritime	Advice about corrosion mechanisms and corrosion rates in marine atmosphere
NORSOK M-001 Materials Selection	Oil and gas	Recommendations towards bolt materials and compatibility between aluminium and different materials for topside applications. Proposal for aluminum-steel joint design
NORSOK M-102 Structural aluminium fabrication	Oil and gas	Covers the requirements for the execution of aluminium structures used in offshore installations both atmospheric and submerged
NORSOK M-121, Aluminium Structural Material	Oil and gas	Selection of aluminium alloys, tempers for offshore installations both atmospheric and submerged
DNV-OS-E401 Helicopter decks	Oil and gas	Defining minimum requirements for design and materials selection
DNV-RU-HSLC (High Speed, Light Craft), Part 3 Structures, equipment, Chapter 3 Hull structural design, aluminium	Maritime	Specifies the requirements for aluminium alloys to be used in the construction of hulls and supporting structures

3.2 EN 1999-1-1

Eurocode 9 EN 1999-1-1: 2008 [3] specifies design of aluminium structures, including materials selection and corrosion protection. Table D.2 gives recommendations about need for protection against crevice and galvanic corrosion for metal to be joined to aluminium and fasteners (Annex D is informative). The recommendations depend on the exposure environment, which for marine atmosphere is classified as non-industrial, moderate industrial and severe industrial atmosphere, summarized in Table 2 below.

Table 2. Summary of Table D.2 in EN 1999-1-1: 2008 Eurocode 9 [3]

	Marine, non-industrial	Marine, moderate industrial	Marine, severe industrial
SS material	Small contact areas and areas which dry quickly may be assembled without sealing		Protection by coating of Al is required
SS bolt/rivet	Additional protection shall be considered, depending on time of wetness, risk for accumulation of corrosive species, lifetime and practicality of inspection	Protection by coating of Al is required	

Whether an oil platform is to be classified as marine industrial environment can be discussed. An industrial atmosphere is defined by Corrosionpedia as:

"an atmosphere in an area of heavy industry with soot, fly ash and sulfur compounds as the principal constituents."

According to this definition, an offshore platform will probably be defined as non-industrial marine industrial atmosphere. The main atmospheric release on the platform is from the gas power plant. The emission of sulphur compounds, soot and ash is low from gas power, and the exhaust gas will normally blow away from the platform. Small contact areas and areas which dry quickly can then be assembled without sealing. The word "small" is not defined in the standard, but we assume that the contact area is not small. Due to the risk for accumulation of salt and the generally high relative humidity offshore we must also assume that the contact area will not dry quickly. Hence, the contact area should then be sealed, described in Procedure X in the standard.

Whether additional protection according to this standard should also be applied at the SS 316 fasteners is not obvious. The bolts are easily inspected, which speaks against protection. However, time of wetness and risk for accumulation of salts, speaks for protection.

3.3 EN 1090-3

Section 10.3.3 "Contact surfaces of aluminium and steel or wood" in EN 1090-3: 2008 [4] states that:

"If protection measures are specified on the aluminium surface in cases of contact between aluminium components with parts made of steel, the aluminium surfaces shall be treated according to F.2."

Section 10 deals with surface treatment and F.2 describes coating. Hence, the standard specifies that when aluminium shall be insulated from steel, a coating shall be applied on the aluminium. However, EN 1090-3 does not say anything about whether aluminium shall be insulated from steel or not.

3.4 DIN 81249 – Corrosion of metals in sea water and sea atmosphere

DIN 81249 deals with the different corrosion phenomena of bare metal in marine atmosphere and in seawater [5]. The standard describes the corrosive behavior of different metals, including aluminium alloys. The descriptions reflect the state of corrosion after two years of storage under atmospheric conditions 25 m above the waterline. The 36 aluminium alloys mentioned in the standard are grouped in 6 groups AL1 - AL6, as listed in Table 3. These alloys are particularly important for hydromechanical structures. The corrosion of aluminum alloys is covered by Part 4 of DIN 81249, and a summary is given in Annex A of this report.

Table 3 Aluminum alloys DIN 81249-2:2013-05 [5]

Group	No.	Description	Group	No.	Description
AL1	1	EN AW-1080A [Al99,8 (A)]	AL3	1	EN AW-6060 [AlMgSi] ^a
	2	EN AW-1070A [Al99,7]		2	EN AW-6106 [AlMgSiMn]
	3	EN AW-1050A [Al99,5] ^a		3	EN AW-6005 A [AlSiMg(A)] ^a
	4	EN AW-1200A [Al99,0]		4	EN AW-6082 [AlSi1MgMn] ^a
AL2	1	EN AW-5005 A [AlMg1(C)]		5	EN AW-6061 [AlMg1SiCu] ^a
	2	EN AW-5051 A [AlMg2 (B)]		6	EN AW-6012 [AlMgSiPb]
	3	EN AW-5052 [AlMg2,5]	AL4	1	EN AW-7020 [AlZn4,5Mg1] ^{a,b}
	4	EN AW-5754 [AlMg3] ^a	AL5	1	EN AC-51100 [AlMg3(b)] ^a
	5	EN AW-5082 [AlMg4,5] ^a		2	EN AC-51300 [AlMg5]
	6	EN AW-5019 [AlMg5]		3	EN AC-51400 [AlMg5(Si)] ^a
	7	EN AW-3103 [AlMn1]		4	EN AC-51200 [AlMg3] ^a
	8	EN AW-3003 [AlMn1Cu]	AL6	1	EN AC-42000 [AlSi7Mg]
	9	EN AW-3105 [AlMn0,5Mg0,5]		2	EN AC-43300 [AlSi9Mg]
	10	EN AW-3005 [AlMn1Mg0,5] ^a		3	EN AC-44000 [AlSi11] ^a
	11	EN AW-3004 [AlMn1Mg1]	a	prefered in maritim structures	
	12	EN AW-5251 [AlMg2]	b	status: artificially aged	
	13	EN AW-5049 [AlMg2Mn0,8] ^a			
	14	EN AW-5454 [AlMg3Mn] ^a			
	15	EN AW-5086 [AlMg4]			
	16	EN AW-5083 [AlMg4,5Mn0,7] ^a			
	17	EN AW-5182 [AlMg4,5Mn0,4]			

3.5 NORSOK M-001, M-102 and M121

Section 4.10 "Galvanic corrosion prevention" in NORSOK M-001 describes connections between aluminium and steel in the following paragraph [6]:

"Direct contact between aluminum and steel (carbon steel and stainless steel) shall be prevented in marine environments.

The design shall ensure distance between aluminum and steel to avoid water wetting of the interface and ensure that water traps are avoided. All aluminum and steel (carbon steel and stainless steel) surfaces shall be segregated with pads made of non-metallic material. Proposed material shall be accepted by end user.

The combination shall be designed according to NS-EN 1090-3 and NS-EN 1999-1-1 to ensure the insulation material can withstand the loads. If it is not possible to apply a non-metallic insulation material, e.g. due to high loads, bi-metallic shims may be used as alternative. Couplings between aluminum and steel shall be isolated with (in order of decreasing preference):

- 1) non-metallic isolating spacers;
- 2) bolted bi-metallic plates.

Fasteners shall be made of stainless steel minimum type 316 SS grade 70 or 80 with minimum type 316 stainless steel plate washers used under both bolt head and nut. The plate washer shall not be in direct contact with the aluminum surface, i.e., segregated with a non-metallic material. When pre-tension and shear forces are required, non-metallic washers in fiber reinforced polymer shall be used.

To prevent galvanic corrosion due to water wetting of the aluminum and steel (carbon steel and stainless steel) connections, non-metallic shims and washers shall have an excess protrusion onto the aluminum surface to ensure distance.

All carbon steel contacting surfaces shall be coated."

NORSOK M-001:2014 allowed stainless steel in contact with aluminium, but this corrigendum from 2021 specifies that this is not acceptable anymore. Offshore experiences have shown cases of severe corrosion on aluminium in contact with stainless steel. Aluminium and steel shall now be segregated by non-metallic pads. If non-metallic pads cannot be used due to mechanical loading or other reasons, bimetallic shims/washers can be used. Both solutions are described in Figure 2 However, bimetallic shims/washers are not commercially available at present. A revision of the requirements is expected in near future, though non-metallic pads is still expected to be the preferred choice.

Section 6 in NORSOK M-102 describes bolted connections aluminium – aluminium, aluminium – steel and aluminium – stainless steel. It is stated that: "The quality of stainless steel bolts shall be A4-70, A4-80 or 25 Cr Duplex". In Table 9 in Section 6.4 "Aluminium - stainless steel connections", precautions for bolted aluminium-stainless steel connections are specified as function of exposure environment. For both internal dry environment and marine atmosphere it is specified no metal-to-metal protection. Hence, aluminium can be bolted to stainless steel without insulation. However, the document states that "There shall be no open crevice in a bolted connection (to avoid crevice corrosion). Cavities that are open after tightening of the bolts shall be sealed." No definition of the term "open crevice" is given.

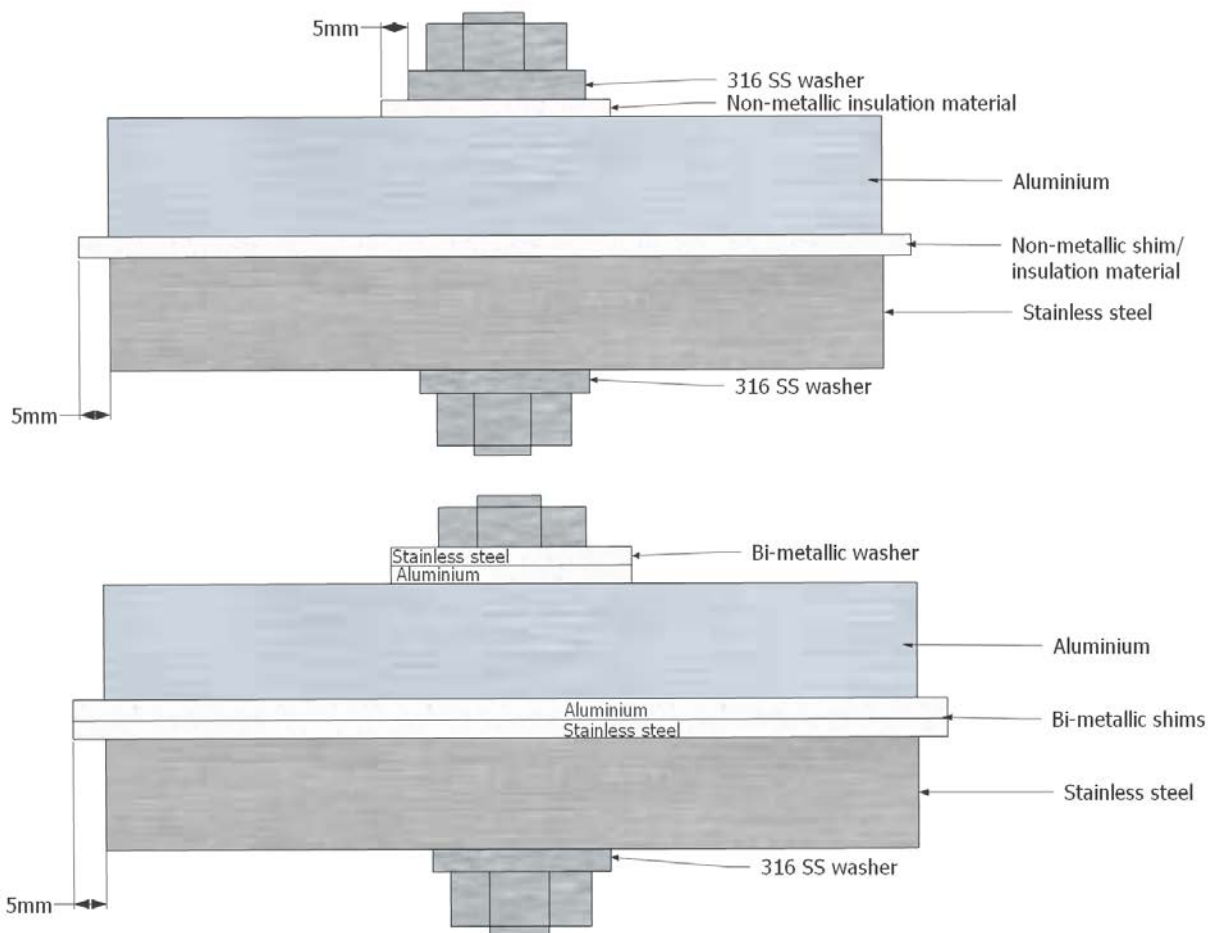


Figure 2. Illustration of the use of non-metallic washer/shim and bimetallic washer/shim in bolted aluminium – stainless steel joints according to NORSOK M-001 Amendment A1 of 2021

3.6 DNV

DNV-OS-E401 [7] provides requirements and recommendations to design of helicopter decks in aluminium or steel for use in offshore environments. The standard gives the following recommendations for steel and aluminium connections to prevent galvanic corrosion:

- Non-hygroscopic insulation material shall be applied between steel and aluminium.
- Bolts with nuts and washers shall be of stainless steel A4 or equivalent.

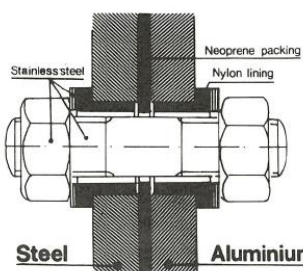
DNV rules for classification of hulls [8] also have a chapter on aluminium. The document briefly mentions corrosion protection and gives the same recommendations as DNV-OS-E401 for aluminum-steel connections.

3.7 Recommendations from aluminium suppliers

In 1993 Hydro Aluminium recommended to insulate aluminium from steel by neoprene shims in overlapping joints and nylon sleeves around stainless bolts. In the offshore O&G industry, this recommendation has rarely been followed, either due to strength requirements or costs. Instead, stainless steel shims have been used, see Figure 2.

ACCELERATING CORROSION EFFECTS

Galvanic Corrosion
IN A CORROSIVE ENVIRONMENT ALUMINIUM MUST BE INSULATED FROM OTHER METALS



Steel Aluminium

Crevice Corrosion
 Corrosion rate equivalent to general corrosion.

Intergranular Corrosion/Stress Corrosion Cracking
 None of the marine grade alloys are susceptible to these corrosion forms.

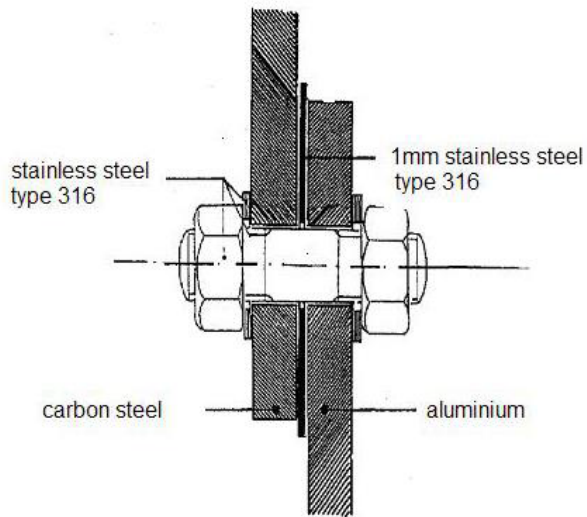


Figure 3. Left: Recommendation from Hydro Aluminium in 1993 about electrical insulation between steel and aluminium. Right: Current practice in the Norwegian offshore O&G industry, using EN1.4401 (AISI 316) stainless steel shims instead.

4 Corrosion tests for aluminium relevant in marine environments

This chapter summarizes standardized test methods and non-standardized exposure tests for evaluation of corrosion on aluminium in marine environments. The objective is to evaluate and select test methods for the project.

Table 4. Standard test methods relevant for testing and evaluation of coatings on aluminium

Standard	Covering	Comment
ISO 9223 Corrosion tests in artificial atmospheres — Salt spray tests	Marine atmospheric exposure	Developed as a corrosion test but has been extensively used for coatings also. Includes variants with acetic acid salt spray (AASS) and copper-accelerated acetic acid salt spray (CASS).
ASTM B117 Standard Practice for Operating Salt Spray (Fog) Apparatus	Marine atmospheric exposure	Similar to ISO 9223.
ASTM G85 Standard Practice for Modified Salt Spray (Fog) Testing	Marine atmospheric exposure	The standard describes various modified salt spray tests, including the seawater acidified test, cyclic (SWAAT)
ISO 16701 Accelerated corrosion test involving exposure under controlled conditions of humidity cycling and intermittent spraying of a salt solution	Marine atmospheric exposure	Specifies test method, reagents, and procedure for an accelerated atmospheric corrosion test
ISO 7441 Determination of bimetallic corrosion in atmospheric exposure corrosion tests	Marine atmospheric exposure	Determination of bimetallic corrosion of metals and coated metals in atmospheric exposure corrosion tests
ISO 11130 Corrosion of metals and alloys – Alternate immersion test in salt solution	Marine tidal- or splash zone exposure	Measures corrosion resistance of metals by an alternate immersion test in salt solution, with or without applied stress. For any type of metal or alloy.
ASTM G44 Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution	Marine tidal- or splash zone exposure	Similar to ISO 11130
ASTM G31 Standard Practice for Laboratory Immersion Corrosion Testing of Metals	Immersion exposure	The standard describes immersion testing in general, not only seawater
ASTM G4 Standard Guide for Conducting Corrosion Tests in Field Applications	Immersion or atmospheric exposure	Corrosion testing under operating conditions, either immersed or in atmosphere

4.1 Corrosion tests for atmospheric conditions

4.1.1 ISO 9227 and ASTM B117 Salt spray tests

Both standards describe continuous exposure to salt spray. ISO 9227 [9] includes exposure to acidic salt spray (ASS) and salt spray with copper ions (CASS) [10]. These variants are very aggressive to aluminium and will usually give significant corrosion on unprotected aluminium.

4.1.2 ISO 16701 Accelerated corrosion test involving exposure under controlled conditions of humidity cycling and intermittent spraying of a salt solution

The standard specifies a test method for accelerated atmospheric corrosion test constituting a 6 h exposure to a slightly acidified solution of 1 % NaCl twice weekly, followed by a condition of controlled humidity cycling between 95 % RH and 50 % RH at a constant temperature of 35 °C [11]. Compared to the continuous salt spray test, the cyclic exposure makes the test somewhat more realistic compared to field exposure.

4.1.3 ISO 7441 Corrosion of metals and alloys — Determination of bimetallic corrosion in atmospheric exposure corrosion tests

Galvanic corrosion under atmospheric conditions is characterized by a large potential drop between the anode and the cathode. The galvanic effect is therefore usually limited to a few mm distance from the contact point. The standard describes three methods:

- rectangular plates
- washers
- wire on bolt

Test procedures for the rectangular plate and washer test are described in the standard [12], while the wire on bolt test is described in ASTM G116 [13]. The standard describes how to derive the galvanic effect relative to uniform corrosion of the individual metal. A high corrosion rate does not necessarily mean that the galvanic corrosion rate is high.

4.2 Corrosion tests for tidal- and splash zone

4.2.1 ASTM G44 Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution

The test specifies 10 min immersion 50 min drying [14]. Alternatively, the immersion/drying times can be modified to simulate the tidal cycle, i.e. 6 h immersion in artificial seawater and 6 h drying in air.

4.2.2 ISO 11130 Corrosion of metals and alloys – Alternate immersion test in salt solution

The standard recommends 10 min immersion in 3.5 % NaCl solution and a 50 min drying period [15]. Solution temperature is 25 °C, while the temperature of drying should be 70 °C at < 50 % relative humidity. Other test conditions can be used in agreement between the interested parties.

4.3 Corrosion tests for submerged zone

4.3.1 ASTM G31 Standard Practice for Laboratory Immersion Corrosion Testing of Metals

The test describes procedures for laboratory immersion corrosion tests and factors that influence the result [16]. The general corrosion rate is determined by mass loss.

5 Coating tests

Table 5. Standard test methods relevant for testing and evaluation of coatings on aluminium

Standard	Covering	Comment
ISO 4623-2 - 2016 - Determination of resistance to filiform corrosion - Aluminium substrates	Filiform corrosion	Deals with the filiform corrosion only on aluminum substrate
ISO 11997-1 Determination of resistance to cyclic corrosion conditions — Part 1: Wet (salt fog)/dry/humid	Marine atmospheric exposure	Corrosion test simulating the cyclic conditions during atmospheric exposure, including concentration of salt during dry conditions
ISO 12944-9 Protective paint systems and laboratory performance test methods for offshore and related structures	Marine atmospheric exposure	Developed for ranking or pre-qualification of coating systems on steel. May be useful for aluminium substrate also.
ISO 15711 Paints and varnishes — Determination of resistance to cathodic disbonding of coatings exposed to sea water	Submerged coated surfaces	For steel substrates, but suitable for aluminium also. The method may also be used for investigating corrosion on submerged aluminium without paint.
ISO 4628 Part 1 – 10 Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance	Evaluation of degraded coating	Quantification of blistering, rusting, cracking, flaking, chalking, corrosion and delamination around scribe, and filiform corrosion

5.1 Coating tests for atmospheric conditions

5.1.1 ISO 4623-2 Paints and varnishes — Determination of resistance to filiform corrosion — Part 2: Aluminium substrates (ASTM D 2803)

Filiform corrosion (FFC) on coated aluminium normally requires a coating defect, presence of chlorides and a humid atmosphere to take place. Two distinctly different mechanisms of FFC propagation may occur in service. One form occurs by successive pitting events accompanied by mechanical lifting of the organic coating by voluminous corrosion products. The primary factors that control this type of FFC are wet adhesion of the coating and the pitting corrosion susceptibility of the pre-treated metal substrate. The second form of FFC occurs by rapid anodic undermining of the organic coating through selective dissolution of a thin, mechanically deformed and electrochemically active near-surface layer of metal. This type of corrosion attack can result in rapid cosmetic failures of painted aluminium products.

The ISO 2643-2 test is performed by introducing hydrochloric acid to two scribe marks (perpendicular to and parallel with the extrusion/rolling direction) on a coated panel, followed by exposure in a test cabinet at 40 °C and a relative humidity of 82 % [17]. The susceptibility to FFC is evaluated by measuring both the longest and the most frequent filament length from the scribe after a certain test duration, typically six weeks (1000 h). The method has proved to correlate better with the type and extent of corrosion attack observed in field tests than acidified salt spray testing does.

5.1.2 ISO 12944-9 Protective paint systems and laboratory performance test methods for offshore and related structures

This test was developed for testing corrosion creep from a scribe in the coating on steel substrate [18]. The test is rather laborious since the samples must be moved between the salt spray cabinet, UV/condense cabinet, and freezer three times per week. The test consists of 25 cycles, i.e. 25 weeks or 4200 hours. The test may very well be used for testing coatings on aluminium as well, but the degradation from scribe may rather be filiform corrosion than scribe creep corrosion. In that case, ISO 4623-2 for filiform corrosion is simpler, faster and probably give better correlation to field performance.

5.1.3 ISO 11997-1 Determination of resistance to cyclic corrosion conditions — Part 1: Wet (salt fog)/dry/humid

This test resembles to some degree ISO 12944-9, but without the UV radiation and the freeze-thaw cycle [19]. The same advantages and disadvantages as for ISO 12944-9 are probably valid for this test also.

Table 6. Test cycles in ISO 11997-1

Parameters	Cycle A	Cycle B	Cycle C	Cycle D
Constituents of the test cycle	1. Salt spray	1. Salt fog	1. Salt fog	1. Salt spray
	2. Dry	2. 100 % RH	2. Dry	2. Wet
	3. Wet	3. (50 ± 20) % RH	3. (75 ± 15) % RH	3. Hot dry
			4. 95 to 100% RH	4. Warm dry
Duration of the test cycle	240 h (30 cycles), 480 h (60 cycles), 720 h (90 cycles) or 1440 h (180 cycles)	840 h	1000 h	168 h (28 cycles)
pH	Between 6.0 and 7.0	Between 6.0 and 7.0	Between 6.0 and 7.0	Between 6.0 and 7.0
Spray solution constitution	50 ± 10 g/L of NaCl	50 ± 10 g/L of NaCl	0.31 ± 0.01 g/L of NaCl with 4.1 ± 0.01 g/L of (NH ₄) ₂ SO ₄	50 ± 10 g/L of NaCl

5.2 Coating tests for immersion conditions

A number of tests have been developed and standardized for coatings on submerged steel with cathodic protection [20]. Coatings on submerged steel are susceptible to cathodic disbonding, which is tested. Susceptibility to blistering will also be revealed. Coatings on aluminium are probably not susceptible to cathodic disbonding, since the disbonding is caused by very high pH under the coating. On aluminium the alkaline environment instead will cause corrosion of the aluminium. Polarization of aluminium below -1200 mV vs Ag/AgCl will cause severe corrosion [21], so accelerated cathodic disbonding tests with potentials below this limit cannot be used, e.g. ASTM G8 [22]. Besides, the cathodic reaction is very slow on aluminium due to the electrically insulating surface oxide.

5.2.1 ISO 15711 Paints and varnishes — Determination of resistance to cathodic disbonding of coatings exposed to sea water

This test has been developed for evaluating the resistance of organic coatings on metallic substrates against cathodic disbonding [23]. The test conditions are as follows:

Electrolyte	Artificial seawater or natural seawater
Coating damage	10 mm diameter circular holiday
Polarization method	Sacrificial zinc anode or impressed current
Polarization potential	-1050 ± 5 mV vs SCE with impressed current -1040 ± 10 mV vs SCE with sacrificial anode
Temperature	23 ± 2 °C
Duration	26 weeks

Hence, except for the temperature, the conditions are similar to field conditions, and the test is hardly accelerated at all. The test may also be used for testing corrosion on submerged aluminium without coating, e.g. alkaline etching around stainless steel bolts.

5.3 Standardized methods for evaluating coating degradation

5.3.1 ISO 4628 Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance

There is no standard for evaluation of coating damages specifically for aluminum, but ISO 4628 will be useful also for aluminium [24].

6 Some reported corrosion issues on aluminium in marine environments

6.1 Applications

The table below lists an overview of some applications of aluminium in marine environments, typical alloys used and reported corrosion issues.

Table 7. Typical marine applications of aluminium in various industries

Industry	Applications	Typical alloys	Types of corrosion reported
Oil & gas	Helideck Living quarters Railings Actuators Lamp reflectors Shielding walls Seismic sensors	6082 5083	Galvanic corrosion in contact with steel structure and bolts General corrosion and pitting corrosion on actuators due to use of Cu containing alloys
Maritime vessels	Hulls on boats/small ships	5000 and 6000 series	
Offshore wind towers and substations	Turbine tower access equipment Platform Railings Cable trays	6082	None
Research	Buoys	6082	None

6.2 Atmospheric conditions

In this section various corrosion issues with aluminium in atmospheric conditions are presented. Most of them are taken from the offshore O&G industry, reported by Egil Sandsbakk in 2014 [25].

6.2.1 Galvanic corrosion

Figure 4 to Figure 7 shows various examples of galvanic corrosion on aluminium caused by steel and stainless steel.



Figure 4. Galvanic corrosion on aluminium around stainless steel bolts (A4). Close-up to the right [25].



Figure 5. Galvanic corrosion on aluminium around EN1.4404 shims in a bolted joint [25].



Figure 6. Galvanic corrosion around galvanized bolt with nylon sleeve. The zinc has corroded away and the nylon sleeve has degraded, so that the bolt steel is in direct contact with the aluminium and causes galvanic corrosion [25].



Figure 7. Galvanic corrosion at a connection between an aluminum signage on the right and a steel structure on the left connected by a stainless steel bolt.

6.2.2 Pitting corrosion

Figure 8 shows pitting corrosion on aluminium (the surface has been cleaned and painted after the attack) caused by exposure to wet passive fire protection.



Figure 8. Pitting corrosion under passive fire protection (PFP). The PFB absorbed water and the aluminium surface was constantly wet, resulting in severe pitting corrosion [25].

6.2.3 Crevice corrosion

Figure 9 and Figure 10 show crevice corrosion on aluminium. In Figure 9 two aluminium surfaces are bolted together. Al-Al crevices are usually not susceptible to crevice corrosion, so the corrosion may originate from trapped water inside the bolt hole. In Figure 10 the crevice corrosion occurs under a steel plate bolted to the aluminium. The steel was painted to prevent corrosion on the aluminium, but the paint has degraded so that the steel can act as cathode for the crevice corrosion.



Figure 9. Crevice corrosion in Al-Al bolted joint, and galvanic corrosion around A4 bolt [25].

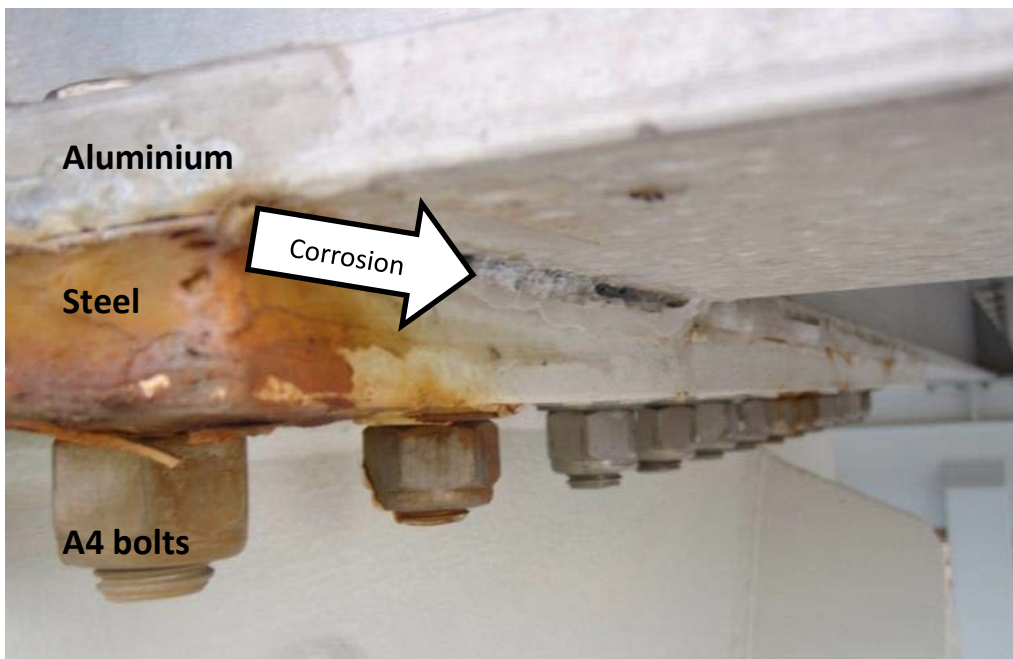


Figure 10. Corrosion in crevice between aluminium and steel in bolted joint [25].

6.3 Submerged conditions

Reported corrosion on submerged aluminium has mainly been inside crevices between steel and aluminium. Cathodic protection (CP) may in theory result in alkaline etching around steel attached to the aluminium, but this has not been reported so far. Excessive polarization by using magnesium anodes or too high current in impressed current CP (ICCP) systems will cause corrosion of aluminium. The main use of aluminium subsea has been on instrumentation and ROVs. In many cases the aluminium has been anodized to very thick oxide layers, typically about 50 μm , to be protected even without CP.

6.3.1 Testing of corrosion inside steel-aluminium overlapping joints with CP

SINTEF and NTNU have investigated submerged aluminium-steel joints under cathodic protection [26,27]. The assembly used is shown in Figure 11. A crevice gap of 100 μm between the two metals was made by applying 100 μm thick tape along three sides in the assembly (Figure 11e). Cathodic polarization inside the crevice would result in alkalization of the electrolyte and alkaline corrosion of the aluminium. However, given the narrow crevice between the steel and the aluminium, CP will probably reach less than 1 mm inside the crevice. The corrosion observed in the tests have therefore most likely been galvanic corrosion. Figure 12 shows corrosion on aluminium inside the crevice after termination of the test.

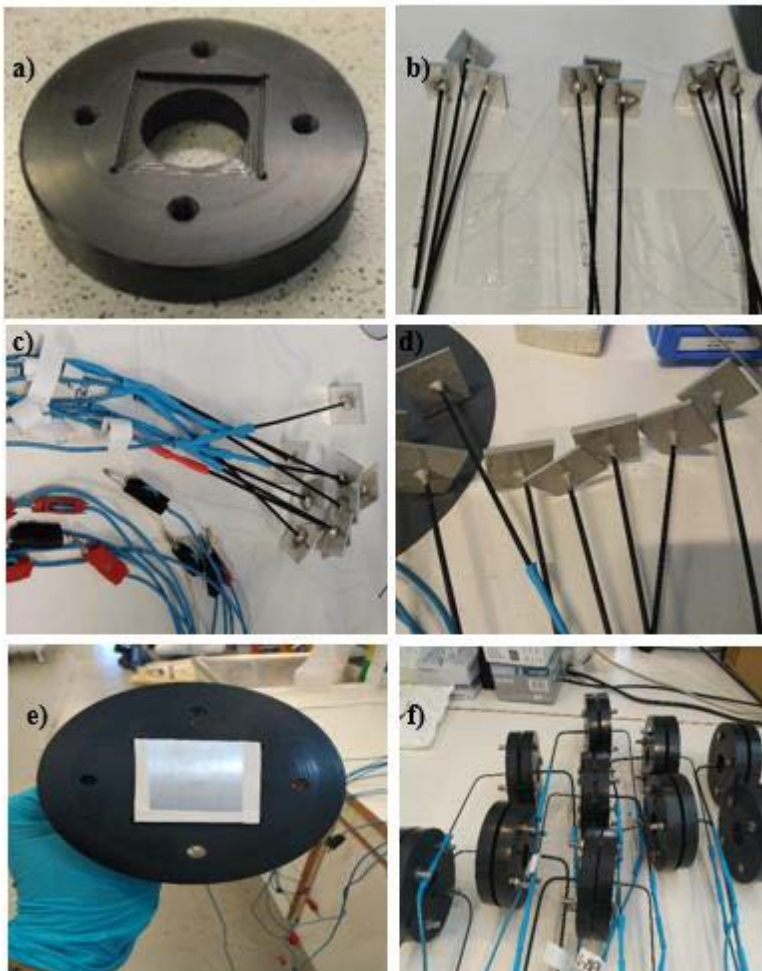


Figure 11. Test setup for studying corrosion of aluminium in Al-Fe crevices under cathodic protection.

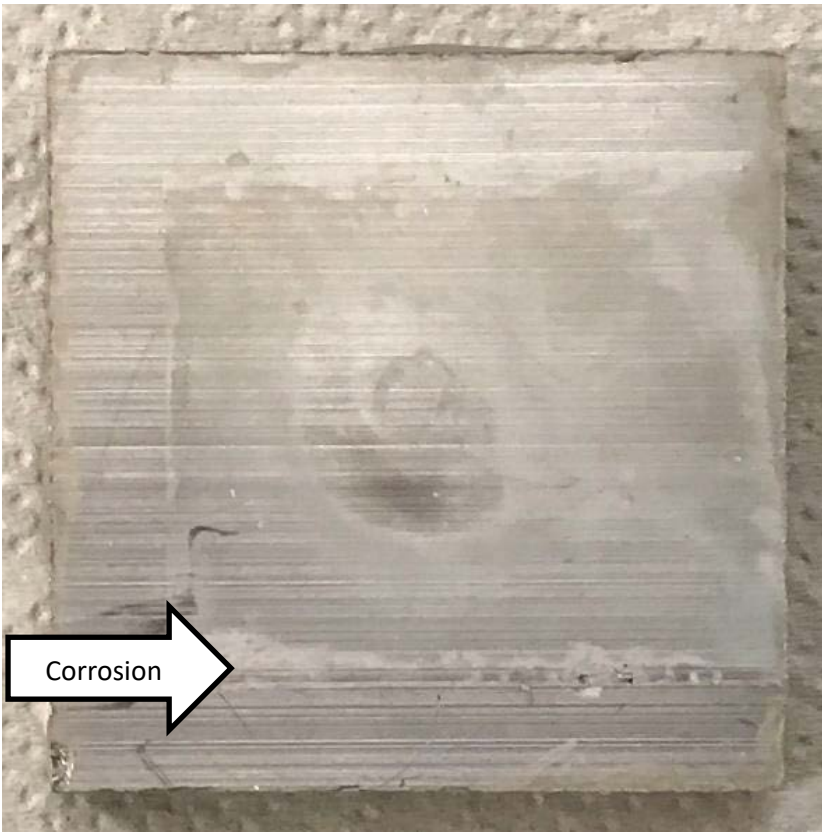


Figure 12. Corrosion of 6082 in Al-Fe crevice under CP in seawater after 105 days exposure.

6.3.2 Aluminium – steel crevice corrosion

Corrosion in crevices between steel and aluminium has been reported on subsea ROVs (remotely operated vehicle). ROVs must be light to increase the payload during operation, so aluminium is used for several parts on most ROVs. An ROV is typically immersed for 1 to 10 days and stored on deck or a harbor between operations. After immersion the ROV shall be washed with fresh water, but this may not always be the case. During operation it is hanging from a crane on the ship when lowered to the work site, and then moving from the crane with thrusters powered through an umbilical. There are anodes on the ROV, but also electrical contact to the ship hull, so CP may also be received from ICCP on the ship.

Figure 13 shows corrosion around stainless bolts in cast aluminium. The aluminium has been anodized to 50 μm oxide thickness and dyed black. The attacks initiate around the bolts and spread over the entire crevice with time. In the image it is difficult to distinguish between corrosion and aluminium oxide spreading inside the crevice.

The attacks may initiate both during immersion and atmospheric storage. CP will likely not penetrate very deep inside the crevice. A rule of thumb say that external CP will reach three pipe diameters into a pipe. This may also be valid for a crevice, i.e. that CP will penetrate 3 crevice mouth openings inwards. This would be a rather short distance in most cases, so the attacks we see in the image are probably galvanic corrosion enhanced by the cathodic efficiency of the steel. The anodizing may be mechanically damaged in the crevice by the bolt or the flanging material and direct the attack to these damages.



Figure 13. Crevice corrosion on anodized aluminium inside crevice against stainless steel.

6.3.3 Galvanic corrosion between aluminium and steel

Figure 14 and Figure 15 show galvanic corrosion between aluminium and steel. Trapping of aggressive electrolytes may have played a role here as well. The anodizing may not be an advantage since galvanic corrosion will be directed to cracks and other damages in the oxide.



Figure 14. Galvanic corrosion and alkaline etching around stainless steel parts screwed into anodized aluminium



Figure 15. Severe galvanic corrosion on anodized aluminium.

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A Appendix - DIN 81249 Corrosion of metals in sea water and sea atmosphere

A.1 Uniform corrosion

Uniform corrosion or general corrosion is shown in Figure 15. The corrosive attack takes place nearly over the whole surface exposed to the corrosive environment and is characterized by a quasi-uniform corrosion rate. Uniform corrosion of aluminium is normally so slow that there are no risks for significant material loss. Exceptions are high flow rate conditions or pH outside the passive range, which can result in dissolution of the protective surface oxide.

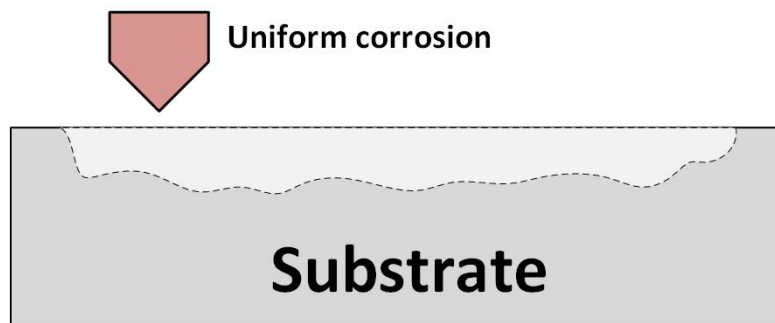


Figure 16. Uniform corrosion

A.2 Galvanic corrosion

Galvanic corrosion of aluminium occurs when the aluminum is in electric and electrolytic contact with a more noble metal or other effective cathode materials (e.g. graphite). Bolts and rivets used for joining aluminum are often made of stainless steels (material groups FE1 and FE2 in DIN 81249-2) to minimize galvanic corrosion. DIN 81249-3 deals especially with galvanic corrosion in sea water. Table 8 shows the risk of galvanic corrosion between the various groups of aluminum alloys (AL1 – AL6) with various other groups of metals and aluminium alloys. UE3 is thermally sprayed aluminium and aluminium-zinc alloys (TSA).

The table shows the increase in corrosion rate when connecting the various aluminium alloys to different metals. Especially in combination with copper and nickel alloys, the table shows high increase in corrosion of aluminum. According to the table titanium shall have almost no influence on the aluminium corrosion rate but given the cathodic efficiency and the noble nature of titanium, this should be questioned. Titanium dioxide is an n-type semiconductor and permits reduction reactions on the oxide surface. Hence, a behavior like stainless steel is reasonable to expect when connected to aluminium.

By combining the groups AL1, AL2, AL3, AL5 and AL6 with 7000 series alloys or TSA the corrosion rate decreases moderately.

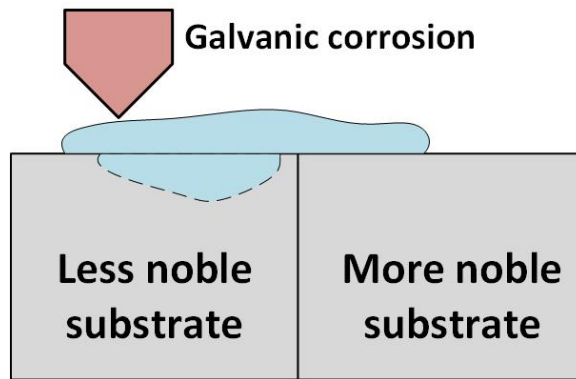


Figure 17. Galvanic corrosion

Table 8. Influence of galvanic corrosion velocity caused by several material combination according to DIN 81249-3

Material to be assessed subgroup																								In contact with material of the subgroup			
FE 1 to FE 3			FE 4 FE 5			CU 1 to CU 7			AL 1 AL 2 AL 3 AL 5 AL 6 UE 3 Part 1			AL 4 UE 3 Part 2			NI 1 NI 2			TI 1 to TI 3			UE 1				UE 2		
>	=	<	>	=	<	>	=	<	>	=	<	>	=	<	>	=	<	>	=	<	>	=	<	>	=	<	
			X	X	XX	O	O	X	O	X	X	X	X	X	O	O	O	O	O	O	X	X	XX	XX	XX	XX	FE 1 to FE 3
I	I	II				I	I	I	X	X	X	X	X	XX	O	O	O	O	O	O	I	I	I	XX	XX	XX	FE 4, FE 5
I	O	O	X	XX	XX				XX	XX	XX	XX	XX	XX	O	O	O	O	O	O	I	O	O	XX	XX	XX	CU 1 to CU 7
O	O	I	I	I	I	I	I	II				O	X	X	I	I	I	O	O	O	I	I	I	X	X	X	AL 1, AL 2, AL 3, AL 5, AL 6, UE 3 Part 1
I	I	I	II	II	II	II	II	II	II	O	I	I			I	I	I	O	O	O	I	I	I	O	O	X	AL 4, UE 3 Part 2
O	O	O	X	X	XX	O	O	X	X	X	XX	X	XX	XX				O	O	O	O	O	O	XX	XX	XX	NI 1, NI 2
O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O				O	O	O	O	O	O	TI 1 to TI 3
O	O	O	X	X	X	O	O	O	X	X	X	X	X	XX	O	O	O	O	O	O				X	X	XX	UE 1
O	O	O	II	II	II	II	II	II	I	I	I	O	O	I	I	I	I	O	O	O	I	I	I				UE 2

Empty fields signify that there is no assignment.
 > The exposed surface of the material is large in comparison to that of the material it is combined with.
 = The exposed surface of the material is approximate the same as that of the material it is combined with.
 < The exposed surface of the material is small in comparison to that of the material it is combined with.
 II The corrosion of the material is considerably reduced.
 I The corrosion of the material is reduced.
 O The corrosion of the material is practically not reduced.
 X The corrosion of the material is intensified.
 XX The corrosion of the material is considerably intensified.

A.3 Pitting

Pitting is a localized corrosion mechanism acting on passive materials like aluminium, see Figure 18. Pitting corrosion starts in the surface and extend into the metal from there. In contrast to uniform corrosion, the extent of the attack will not show on the surface of the metal. The extent of the damage will usually be evaluated by investigating a cross section of the pit or by weight loss measurement. Despite little visible corrosion in the surface, the attack may extend deep into the material. The pit may threaten the structural integrity of the substrate by acting as a notch for fracture or fatigue.

Alloys with a high concentration of elements like copper and iron that form noble intermetallic particles have increased susceptibility to pitting corrosion. The standard DIN 81249 – 4 shows different rates of corrosion for the various AL-groups as mentioned in 3.4. The alloys of the groups AL1 – AL5 have a maximum pitting corrosion rate of 0,02 mm to 0,15 mm after two years in the splash water zone. For the alloys of the group AL6 a rate of 0,02 mm to 0,1 mm within the same period was measured.

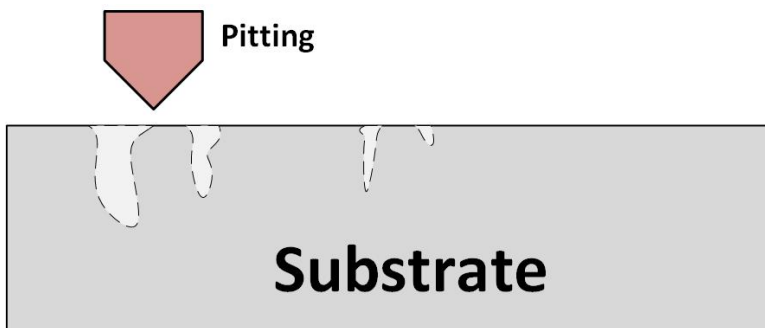


Figure 18. Pitting

A.4 Shallow pit formation

While pitting gives narrow but deep attacks, wide and shallow attacks can also occur with a geometry as indicated in Figure 19. To emphasize the difference to pitting corrosion this phenome is called shallow pit formation. The difference between pitting and shallow pit corrosion is not that clear. The alloys of AL4 rather tend to be attacked by shallow pit formation, while the groups AL1 to AL3 and AL5 to AL6 are more susceptible to pitting corrosion.

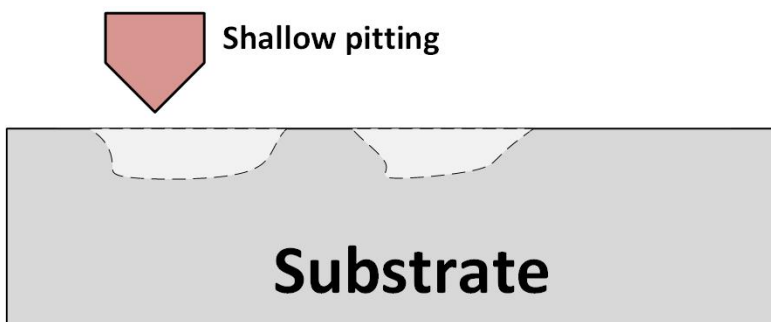


Figure 19. Shallow pit formation.

A.5 Crevice corrosion

Crevice corrosion is localized corrosion taking place in a crevice, as illustrated in Figure 20. Oxygen depletion inside the crevice results in formation of a galvanic cell, where the inside of the crevice becomes anode and external surfaces act as cathode. Aluminium to aluminum crevices or crevices against electrochemically inert materials are normally not sensitive to crevice corrosion due to the low cathodic reaction rate on aluminium. However, crevices to more noble materials like steel or stainless steel can result in severe crevice corrosion as shown in this report. The damage initiates in the aluminum substrate at the crevice opening and spread inwards with time. According to the standard DIN 81249-4 a thick anodized layer may improve the resistance against crevice corrosion, but cracks in the oxide (the oxide is brittle) may result in concentrated corrosion attacks in the cracks.

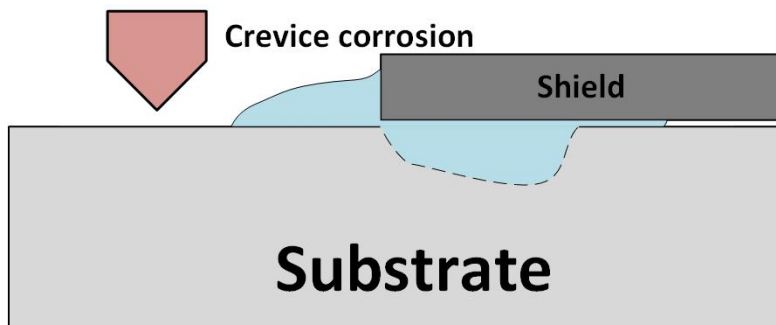


Figure 20. Crevice corrosion.

A.6 Intergranular corrosion

Intergranular corrosion (IGC) occurs at the grain-boundaries at the surface and continues along the boundaries into the substrate as shown in Figure 21. The susceptibility to IGC depends mainly on the thermo-mechanical processing and alloying elements present. As for pitting corrosion, IGC may be driven by more noble alloying elements, typically copper, segregating at the grain boundaries, acting as an efficient cathode. However, in magnesium containing alloys, typically containing more than 3.5 % magnesium, formation of a Mg-rich phase at the grain boundaries may also result in IGC.

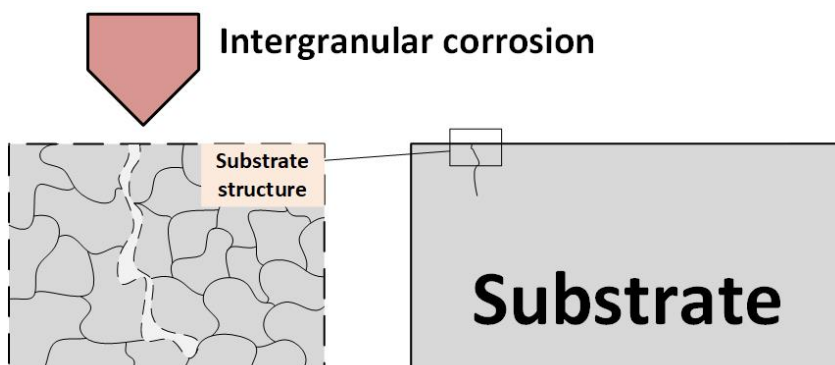


Figure 21. Intergranular corrosion.

A.7 Corrosion fatigue

Corrosion fatigue is a process where cyclic loading and corrosion results in cracking, as illustrated in Figure 22. Where dry fatigue has a lower stress threshold for fatigue, corrosion fatigue does. In addition, the number of cycles to fracture is reduced. Mainly the high strength aluminum alloys in the 2000 and 7000 series are vulnerable to corrosion fatigue. Any notch in the material may serve as an initiation point for fracture, and in corrosion fatigue the notch is typically a corrosion attack. In dry fatigue, the fatigue life is mainly the time to formation of a notch and initiation of the fatigue crack. In corrosion fatigue, the notch will typically be formed at an early stage, and the fatigue life will be more dependent by the crack growth rate. In general, the alloys of the Groups AL1 – AL6 are not susceptible to corrosion fatigue. Is this correct?

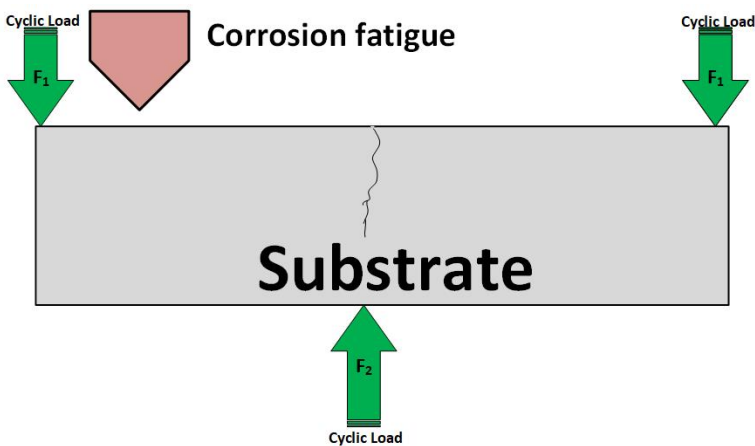


Figure 22. Corrosion fatigue.

A.8 Stress corrosion cracking

Stress corrosion cracking is caused by the combined action of static stress and corrosion, as illustrated in Figure 23. As for corrosion fatigue, mainly the high strength aluminium alloys in the 2000 and 7000 series are susceptible to stress corrosion cracking. The stress may be from external loading of the material, or from internal stress after e.g. welding. In general, the alloys of the Groups AL1 – AL6 are not susceptible to stress corrosion cracking.

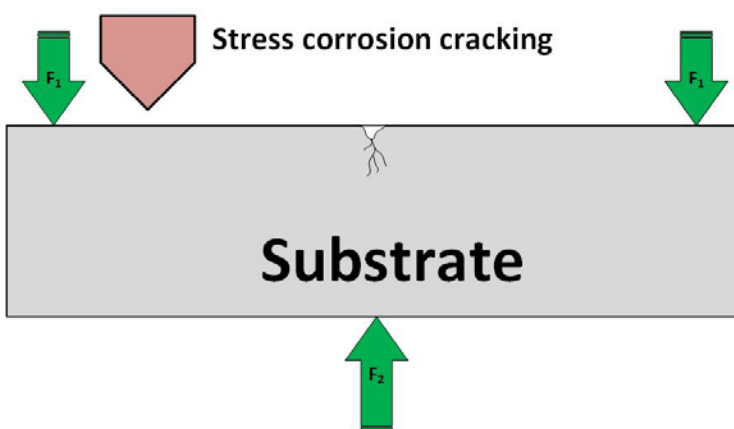


Figure 23. Stress corrosion cracking.

A.9 Exfoliation corrosion

Exfoliation corrosion is a type of intergranular corrosion that occurs in rolled and extruded aluminium alloys with directional structures. The attacks propagate along the grain boundaries and a wedging effect of the corrosion products opens cracks in the material.

According to DIN 81249 only the aluminum material group AL4 (EN AW-7020) is vulnerable for exfoliation corrosion.

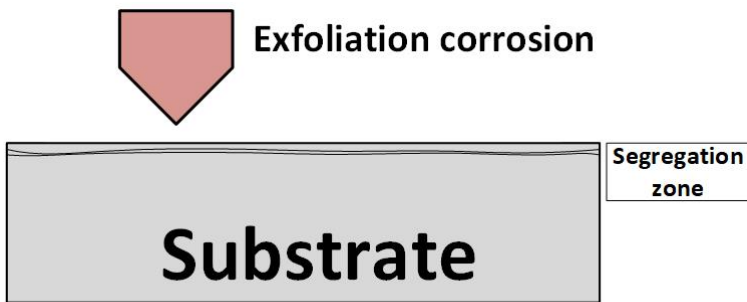


Figure 24. Exfoliation corrosion.

B Appendix – ISO 4628 Paints and varnishes - Evaluation of degradation of coatings - Designation of quantity and size of defects, and of intensity of uniform changes in appearance

B.1 Blistering

Blistering is a coating damage that typically is caused by insufficient cleaning before the coating application. Remnants of salt on the surface will cause osmotic blistering during exposure to freshwater or condensed water. Blistering is also typically found on submerged structures, where penetration of sodium ions through the film will initiate cathodic oxygen reduction and formation of NaOH. The osmotic power of NaOH is comparable to NaCl. ISO 4628 uses exemplary photos of coatings with blistering as a qualitative characteristic to assess the degree of blistering. The blistering is evaluated by blister density and size, as shown in Table 8. ASTM D714 has a similar evaluation method, but with a different notation.

Table 9 Assessment of blistering by quantity and size in ISO 4628 and compared to ASTM

Density		Size	
ASTM	ISO	ASTM	ISO
None	0		
-	1	-	1
Few	2	8	2
Medium	3	6	3
Medium-dense	4	4	4
Dense	5	2	5

B.2 Rusting

Rusting is when corrosion initiates below the coating and rust penetrates the coating. It is characterized by uniform corrosive attack over a surface or parts of it. Rusting is evaluated by the share of the surface that is affected, as shown in Table 10. ASTM D610 describes a similar method for evaluation of rusting, which is included in the table for comparison.

Table 10 Assessment of rusting by determining the share of rusted areas

Degree of rusting	Rusted area [%]	ASTM rust scale (ASTM D610)
Ri 0	0	10
Ri 1	0,05	9
Ri 2	0,5	7
Ri 3	1	6
Ri 4	8	4
Ri 5	40 – 50	1 to 2

B.3 Cracking

Cracking of the coating is a damage with several possible triggers, but internal stress in the coating is usually the failure mechanism. The assessment of cracking uses three characteristics: quantity, size and depth. The

gradual distinction of these criteria is shown in Table 11, Table 12 and Table 13. ASTM D661 also describes evaluation of cracked coatings, and ISO 4628 includes a comparison.

Table 11 Assessment of cracking – evaluation of quantity

Rating	Quantity of cracks
0	none, i.e. no detectable cracks
1	very few, i.e. small, barely significant number of cracks
2	few, i.e. small but significant number of cracks
3	moderate number of cracks
4	considerable number of cracks
5	dense pattern of cracks

Table 12 Assessment of cracking – evaluation of size

Rating	Size of cracks
0	not visible under $\times 10$ magnification
1	only visible under magnification up to $\times 10$
2	just visible with normal corrected vision (up to 0,2 mm)
3	clearly visible with normal corrected vision (larger than 0,2 mm up to 0,5 mm)
4	large cracks, larger than 0,5 mm up to 1 mm wide
5	very large cracks generally more than 1 mm wide

Table 13 Assessment of cracking – evaluation of depth

Rating	Depth of cracks
a	surface cracks which do not fully penetrate the top coat (i.e. checking)
b	cracks which penetrate the top coat, the underlying coat(s) being substantially unaffected
C	cracks which penetrate the whole coating system

B.4 Flaking

Flaking is when an intact coating delaminates from the underlying coating or direct from the substrate and falls off in flakes. Flaking is caused by lack or loss of adhesion, which can be caused by many phenomena, for example:

- Exceeding overcoating interval. The first coat has cured to an extent where the second coat cannot form chemical bonds.
- Contamination of the surface of the first coat before the second coat is applied. Amine blushing is an example, where excess amine curing agent in an epoxy separates in the surface.
- The first and the second coat are incompatible with each other and cannot form bonds.

Table 14, Table 15 and Table 16 shows assessment of flaking paint.

Table 14 Assessment of flaking – evaluation of flaked area

Rating	Flaked area [%]
0	0
1	0,1
2	0,3
3	1
4	3
5	15

Table 15 Assessment of flaking – evaluation of size

Rating	Size of flaking
0	not visible under × 10 magnification
1	up to 1 mm
2	up to 3 mm
3	up to 10 mm
4	up to 30 mm
5	Larger than 30 mm

Table 16 Assessment of flaking – evaluation of depth

Rating	Depth of cracks
a	coat(s) flaking from underlying coat
b	the whole coating system flaking from substrate

B.5 Chalking

Chalking occurs on coatings exposed to sunlight and UV radiation, which degrades the binder. Especially epoxies have a high susceptibility to chalking under the influence of UV radiation. Epoxies are therefore usually protected with a UV resistant topcoat unless they are exposed subsea or in darkness with no UV radiation. The degraded binder, fillers and pigments remain on the surface to form a powdery substance with a consistence like chalk which gave the phenomenon its name. Following the standard ISO 4628 there are two different methods to assess the effect of chalking. Both methods use the same rating scheme which is shown in Table 17.

Table 17 Assessment of chalking – evaluation of degree of chalking

Rating	Degree of chalking
0	unchanged, i.e. no perceptible chalking
1	very slight, i.e. just perceptible chalking
2	slight, i.e. clearly perceptible chalking
3	moderate, i.e. very clearly perceptible chalking
4	considerable, i.e. pronounced chalking
5	severe, i.e. intense chalking

Tape method

The tape method removes the powder from the dried surface with regular transparent adhesive tape. The tape is at least 15 mm wide and 40 mm long. The tape needs to be transparent to show the amount of adhering degraded paint. The removed tape is examined against a contrasting background, black or white depending on what gives the best contrast. The degree of chalking is assessed from 1 – 5 with reference pictures shown in ISO 4628.

Velvet method

The velvet method does not use adhesion but friction to remove the powder from the test surface. The velvet is pushed gently with the index finger against the surface and rotated once through an angle of 180°. Afterwards the degree of chalking is assessed by the amount of powder that remains on the velvet by using the rating scale.

B.6 Filiform corrosion

Filiform corrosion is thread-shaped corrosion attacks under a coating, typically found on coated aluminium in aggressive environments. The attacks start at bare metal, e.g. cut-edges, mechanical damages or weaknesses in the film. In lab testing, a scribe line is made in the coating and corrosion is initiated in a chloride containing environment. Dripping diluted hydrochloric acid in the scribe will effectively initiate the corrosion. The filaments will grow during exposure in humid environment. ISO 4628-10 describes how to measure maximum or average filament length on test panels after filiform corrosion testing.