partner in material technology and innovation	TITLE **REVIEW OF STRUCTURAL CONNECTIONS OF DISSIMILAR METALS – PREVENTION OF GALVANIC CORROSION; PRACTICE AND EXPERIENCE**
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1 GENERAL

1.1 Introduction

This document provides the best practices to avoid galvanic corrosion between two of these three materials: aluminium, carbon steel and stainless steel, specifically for offshore oil and gas platforms; however, it is also applicable for other industries. The recommended practices and guidelines proposed in this document are specified for different geometry and position of connections.

The guidelines are for bolted connections where design is based on shear force. Bolted connections based on pre-stress and friction forces are not, to our knowledge, used for these types of structural connections in the offshore oil and gas industry.

These guidelines are not intended to exclude solutions and new technologies, provided the avoidance of galvanic corrosion can be ensured for the design lifetime. This document is produced to Petroleumstilsynet, but is not a part of the regulations.

1.2 Motivation

Reduced integrity of structural connections over time poses a reduced safety level in oil and gas operations. Petroleumstilsynet (PTIL) has highlighted this to the industry (1,2). The experiences of galvanic corrosion of aluminium connected to carbon steel or stainless steel on existing oil and gas platforms, and the continual increase in the use of aluminium on newer facilities are the primary reasons for the establishment of this recommended practice. In addition, the existing requirements do not clearly detail the measures for preventing galvanic corrosion and this is another reason for the development of this document. The bid request from PTIL (translated from norwegian) is stated below:

1. Operating experience with different connections between steel and aluminum
    a. Distinction between tension and friction couplings (Non-prestressed and prestressed joints) when choosing bolted solutions. Review of existing requirements and experiences.
    b. The description shall be such that it can be used as a basis for assessing the goodness of the connections / assemblies based on requirements for installation and operation.
2. Sketch of a "design guideline" for connections between aluminum and steel:
    c. Detailed drawings
    d. Good design solutions / examples
        i. Life expectancy of technical solutions
    e. Poor design solutions / examples
3. Report for publication on ptil.no
    i. Discussion of draft report with the PSA

ii. Discussion with professional experts

1.3 Abbreviations

Table 1. Abbreviations

6Mo	Austenitic Stainless steel Type with minimum 6% Molybdenum
CS	Carbon Steel
HDG	Hot dip galvanized
HVAC	Heating, ventilation, and air conditioning
NCS	Norwegian Continental Shelf
PTFE	Polytetrafluoroethylene
RHS	Rectangular Hollow Section
SS	Stainless Steel
Ti	Titanium

2 REVIEW OF REQUIREMENTS

The requirements to avoid galvanic corrosion in offshore specifications or in NORSOK standards have not been clear. In 1988, when the HVAC units for Sleipner A project were being designed, it was debated if the cooling units could be made of 6Mo tubing and cooling fins made of aluminium. A test was carried out at DNV, and in order to accelerate the test, it was decided to carry out the test submerged in sea water. After 6 weeks it was concluded that the combination was acceptable. The effect of surface area of the anode (fins) being much larger than the cathode (tubes) was not discussed. In such cases, the combination of aluminium and stainless steel in submerged condition has turned out to work satisfactorily. However, the large anode surface area will not help, in cases above seawater.

NORSOK M-001 specifies requirements for avoiding galvanic corrosion, and it is one of the most referenced NORSOK standards in the Norwegian Continental Shelf (NCS). The requirement for 'Material selections' in NORSOK M-001, Rev 4 (2004) was:

For connections between Aluminium and steel, the following apply:

• *bolts, nuts and washers shall be stainless steel type 316;*
• *the direct contact between aluminium and carbon steel shall be prevented by application of an insulation system, e.g. an organic gasket or equivalent. Alternatively the two materials may be separated by a 1 mm stainless steel barrier;*

When it comes to stainless steel versus aluminium, the requirements are not clear.

The next M-001 revision (rev 5 from 2013) is discussing stainless steel, however, requirements are still unclear. The section 4.10 stated (3):

Direct contact between aluminium and carbon steel shall be prevented in marine environments. Aluminium and steel (carbon steel and stainless steel) surfaces shall in general be segregated with pads made of non-metallic materials such as rubber. For combinations carrying high loads type 316 SS shims can be used in between carbon steel and aluminium. Fasteners shall be made of type 316 SS grade 70 or 80 with type 316 SS plate washers used under both bolt head and nut. The plate washer shall not be thinner than 4 mm.

Still, in 2014, 316 SS shims can be used towards aluminium. And carbon steel, stainless steel and aluminium surfaces shall "in general" be separated. Since NORSOK is not clear, operators and design contractors have been obliged to issue more or less tailormade guidelines.

3 CORROSION AND BASIS FOR RECOMMENDED PRACTICE

Corrosion is a natural process driven by the tendency of elemental composition of materials, mostly metals, to return to their most thermodynamically stable state. Generally, the corrosion process is slow which enables the use of different materials, such as aluminium and stainless steel, in different applications without any problem in structural integrity. However, certain conditions can rapidly increase the corrosion rate of materials affecting the structural integrity and design lifetime of structures. This section describes two phenomena, galvanic corrosion and crevice corrosion, responsible for material deterioration when two dissimilar metals are in contact in the presence of electrolyte and oxygen.

3.1 Galvanic corrosion

Galvanic corrosion is a form of corrosion which occurs when two different metallic materials are electrically connected in a presence of an electrolyte and oxygen. An electrolyte is a conductive solution which facilitates the ionic movement, and seawater or water containing ionic salts is considered as a strong electrolyte due to its high conductance. Two electrically connected metals in an electrolyte have different electrochemical potential and this potential difference provides a stronger driving force for the dissolution of more electrically negative metal (less noble) and this phenomenon is called galvanic corrosion. Generally, the oxygen consumes the electrons from less noble metals and forms anionic compound which combines with cations of less noble metals resulting in the corrosion product. This is the simple explanation of corrosion process which is also shown in equation (I – III) and figure 3.

In the case of any connections between two of these three materials, aluminium, carbon steel and stainless steel, aluminium has the higher negative electrochemical potential which makes it anode. Therefore, aluminium always corrodes when connected to carbon steel or stainless steel, and in the connection between carbon steel and stainless steel, carbon steel acts as anode and corrode first as shown in figure 1.

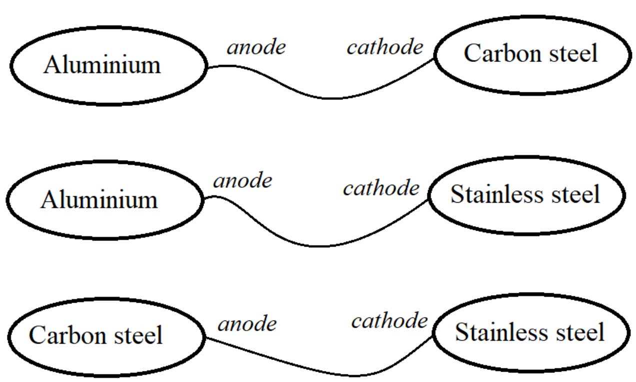


Figure 1: Roles of metals in galvanic corrosion process.

This can be illustrated from figure 2 where the electrochemical potentials for different materials in seawater is presented. Aluminium alloys act as anode and corrode first when connected to most of the metals besides zinc and magnesium.

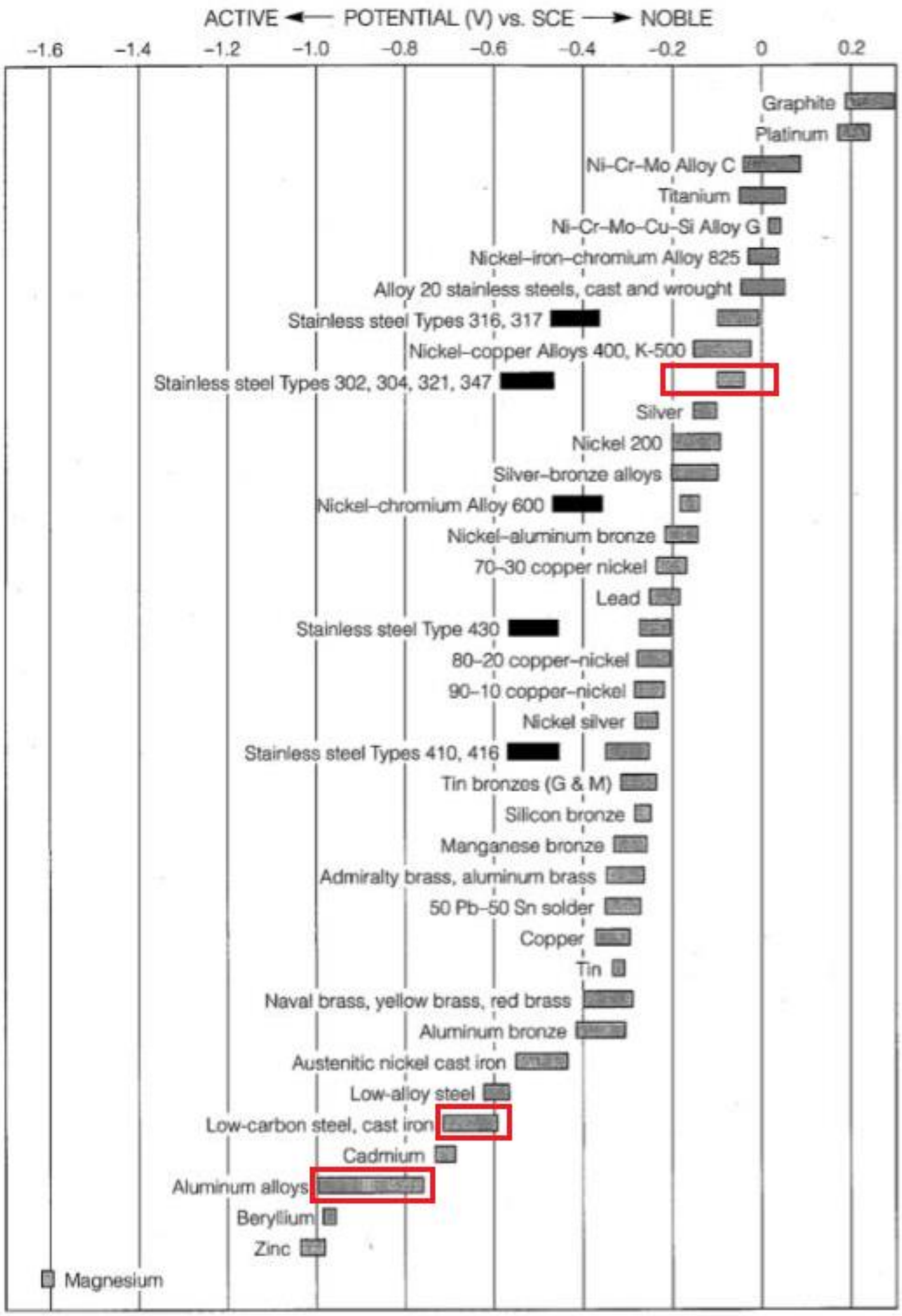


Figure 2: Galvanic Series in seawater (4).

The process of galvanic corrosion is illustrated in figure 3.

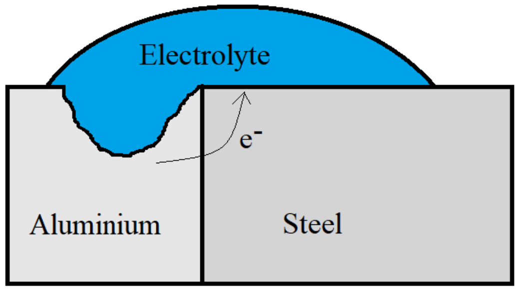


Figure 3: Schematic of galvanic process.

The chemical reactions that take place on aluminium surface is:

At anode: $Al \longrightarrow Al^{3+} + 3e^-$ (I)

At cathode: $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$ (II)

Total reaction: $Al^{3+} + 3H_2O \longrightarrow Al(OH)_3 + 3H^+$ (III)

Aluminium hydroxide $Al(OH)_3$ precipitates on the aluminium surface as white sludge.

3.2 Crevice corrosion

Crevice corrosion refers to the localized attack immediately adjacent to crevice or gap between two joining metallic surfaces which is normally large enough to entrap a liquid but too small to allow its flow (5,6). Crevices can be formed at metal-metal junctions or metal-nonmetal junctions such as space between metal and gasket, rivet, bolts heads, etc. Figure 4 illustrates a crevice corrosion on a crevice or gap between two metal surfaces. Generally, the crevice corrosion rate increases with the increase in electrochemical potential difference between two metals, and therefore, crevices between aluminium and steel surfaces allow for higher corrosion rate.

The crevice corrosion mechanism is similar to uniform or pitting corrosion, however, it is localized only in the crevices where electrolyte is present. The anodic and cathodic reactions in such cases are (5,6):

At anode: $M \longrightarrow M^{n+} + n^{e-}$ (IV)

At cathode: $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$ (V)

M represents the corroding material in the crevice. When chloride ions are present in an electrolyte, the situation worsen leading M^+ to attract Cl^- forming metal chlorides which hydrolyzes to form metal hydroxide and hydrochloric acid.

$$MCl + H_2O \longrightarrow MOH + HCl \qquad (VI)$$

The formed hydrochloric acid destroys the passive film resulting in the accelerated rate of dissolution of the metal in the crevices. The acidity increases, and pH can easily be lower than 3-4. The effect of formation of galvanic cell (two dissimilar metals connections in the presence of an electrolyte) to crevice corrosion is that the potential difference will provoke an early start of crevice corrosion, and the potential difference will enhance the corrosion rate inside the crevice by draining off large amount of electrons.

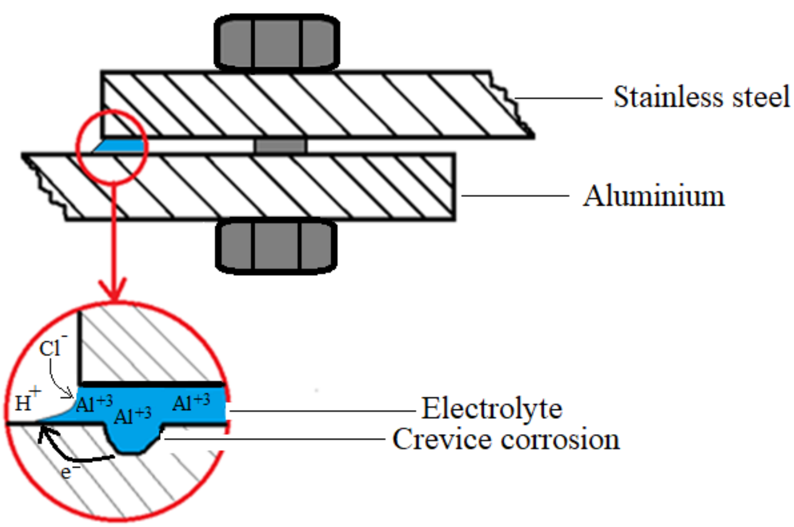


Figure 4: Schematic of crevice corrosion induced by the formation of a galvanic cell.

3.3 Reason for increased number of galvanic corrosion incidents/maintenance reports

In order to reduce maintenance and costs, and increase the life time of oil and gas producing platforms, carbon steel is more and more replaced by aluminium and stainless steels. Ladders, handrails, cable trays, access platforms, pipe supports, walls, tanks, etc. are today made of aluminium and stainless steels. This shift in material selection, has caused an increased number of galvanic corrosion reports. Painted carbon steel surfaces will limit galvanic corrosion current when connected to aluminium. Stainless steel surfaces are unpainted, and when the surfaces are wet, either caused by sea water sprays, rain-water or by condensation, high galvanic corrosion currents can be formed on meeting surfaces. A clean metal surface is hydrophilic, meaning a continuous film of water can stay on the surface. The water film will not "pearl" or be "drained off". The thickness and electrical resistivity of the water film will control the galvanic currents. In order to address the effect of galvanic corrosion, as shown in next section, a typical water film thickness of 0.1 mm – 1 mm can be considered. The electrical resistivity to be used is as for sea water, about 28 Ωcm. The electrical resistivity will be higher based on rain-water, or lower if water with salt have evaporated over a period of time (due to heating from neighbouring areas or due to sun radiation).

3.4 Termination of galvanic corrosion by PTFE

A water film of w = 10 mm, thickness = 1 mm, and assumed length of 100 mm, can cause a galvanic current of 10 mA/m^2 x 10 mm x 100 mm = 0.01 mA. This is based on a small passive current on stainless steel surface of 10 mA/m^2. If the meeting surface is 1 mm x 10 mm, the corrosion current can be 0.01 mA/(1 mm x 10 mm) = 1000 mA/m^2, which can cause a corrosion rate of about 1 mm/year.

In case of a stainless steel nut of 10 mm "head length", the galvanic current can be 10 mA/m^2 x 10 mm x 10 mm = 0.001 mA. If the meeting surface is 1 mm x 10 mm, the corrosion current can be 100 mA/m^2, which can cause a corrosion of 0.1 mm/year. The schematic of water film is presented in figure 5. Considering the fact that corrosion products have a volume of 8 – 14 X volume of the metal, the corrosion can be judged as serious even after a few years.

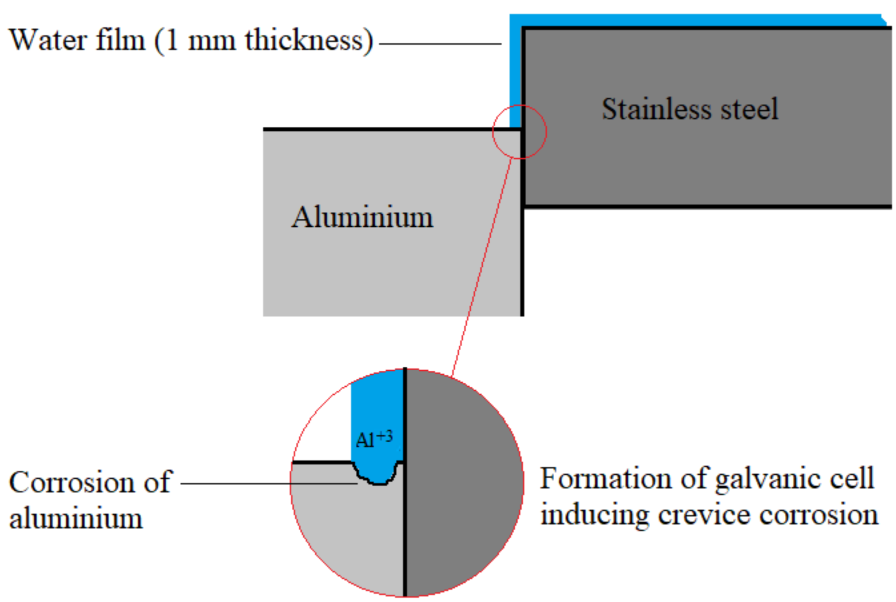


Figure 5: Schematic showing galvanic corrosion of aluminium in the presence of water film.

In the above text, galvanic current has been discussed. Normally a passive metal “does not corrode” due to a passive current. However, the various metals have different “corrosion” potentials as shown in figure 2. When aluminium is connected to stainless steel, the potential on aluminium surface will be raised from -900 mV (SCE) to a potential in between -900 mV and 0 mV. Table 2 shows potential differences or driving potentials between the three metal combinations. The higher the driving voltage, the higher is normally the risk for galvanic corrosion. At 0 mV (SCE) or at – 600 mV (SCE), the passive film on aluminium is not stable when Cl^- ions are present and cannot protect aluminium connected with stainless steel or carbon steel from galvanic corrosion.

One way of eliminating galvanic corrosion, is to remove or break the water film between the two alloys. A painted surface will reduce galvanic corrosion, due to a reduction of alloy surface in contact with the water film. Another solution to break the water film, is to apply surfaces where water cannot stay, by using a water repellent paint. Polyethylene and PTFE make surfaces hydrophobic or water repellent. Neither water nor water-containing-substances can wet PTFE.

By applying PTFE, water films are disrupted or removed, and galvanic corrosion can be terminated. PTFE coating on stainless steel washers will prevent galvanic corrosion between 316 nut or bolt head and the aluminium the bolt is connecting.

Table 2: Potential Difference

Alloy combinations	Potential difference (mV)
Al – stainless steel	850
Al – carbon steel	240
Carbon steel – stainless steel	610

3.5 Basis for the proposed recommendation to prevent galvanic corrosion

The proposed recommendation to prevent galvanic corrosion, are prepared considering the following points:

- High driving voltages exist between alloys of aluminium, carbon steel and stainless steel.
- High driving voltages will cause galvanic corrosion between alloys.
- Crevice corrosion between alloys will be accelerated by effect of galvanic corrosion.
- Only crevice and galvanic corrosion are focused on. Other types of corrosion may be present.
- Surfaces are covered by salt due to wind, rain, condensation, temperature effects, and solar radiation.
- Vertical surfaces are impacted as well as horizontal surfaces.
- PTFE will break continuous water films.
- Bolts connecting aluminium, carbon steel, stainless steel, and all combinations of these shall be fixed by stainless steel bolts to ISO 3506-1 grade A4-80, unless higher alloyed

bolts are required, for example 25Cr, see reference 9. Washers shall be of 316 SS with dimensions given by recognized standards as ISO 7090 or equivalent (8). Washers are of two types; 316 SS and PTFE coated 316 SS with PTFE thickness of 10 – 20 micrometers.

- Bushings in non-metallic materials, as proposed by reference 9, is not recommended due to structural instability and experienced lifetime of bushings.
- Insulating materials are preferably 3 – 4 mm thick neoprene rubber, alternatively 3 – 4 mm thick PTFE pads. If space does not allow, PTFE pads of 1 – 2 mm thickness can be used.
- Compressive yield strength of PTFE is roughly about 12 MPa, and the steel is tightened to about 100 - 150 MPa. In all cases, the surface area of PTFE is minimum 10 times more than the bolt area, and, therefore, the compression of PTFE should not be of any issue. For instance, a typical pad of 150 mm x 100 mm gives the area of 15000 mm^2 and 4 off 13 mm bolts give the total area of 530 mm^2 which means the pad area is 28 times the bolt area.
- Insulating materials or PTFE pads shall have a lifetime equal to or higher than the design lifetime of the structure.
- The insulating material shall have an extrusion of min 5 mm, unless specified otherwise.
- In case non-metallic pads cannot be used due to high forces, bimetallic plate shall be used. Sealing compound shall be applied between bimetallic plates and the structural material to avoid water ingress.
- On pads with heavy equipment and requiring high torque, 1 mm PTFE should be used.
- Shims of 316 SS can be used provided Sealing compound is applied on the side that is connected to aluminium or carbon steel, and Sealing compound shall also be applied on outer surface in order to avoid water ingress.
- Sealing compound is always used between two alloys, in the bolt holes and at external corners to avoid water ingress.
- For horizontal surfaces, two washers shall be used in order to address the issues regarding higher thickness of water film and possibility of local damages in PTFE when nut is tightened. The lower shall be PTFE coated 316 SS. The upper can be 316 SS without coating.
- In cases where two washers are specified, one PTFE coated 316 SS and another uncoated 316 SS, the latter can be replaced by PTFE coated 316 SS if this ease logistic or reduce total cost.
- All 316 SS nuts in this document shall be locking nut of type Nyloc.
- Thickness of washers shall be in accordance to applicable bolt standards, and not as specified in M-001 section 4.10: ‘The plate washers shall not be thinner than 4 mm.’

4 TYPICAL CONNECTION DETAILS

Several types of connections can be found in the offshore oil and gas platform. In this section, typical connections between two of these three materials, aluminium, carbon steel and stainless steel are presented.

4.1 Welded connections

Welded connections are preferred where high loads are expected. Explosion cladded tri-plate can be used when a welded connection is preferred to bolted connection. The details on welded connections and recommended measures are presented in section 6.1. A metallographic picture of a tri-plate connection is shown in figure 6.

Figure 6: An example of a tri-plate connection.

4.2 Handrails

Aluminium handrails are normally connected to stainless steel, and galvanic corrosion is a common phenomenon if proper insulation is not provided between them. A schematic of such connection in shown in figure 7. Details on guidelines for avoiding galvanic corrosion on such connections are presented in section 6.2.

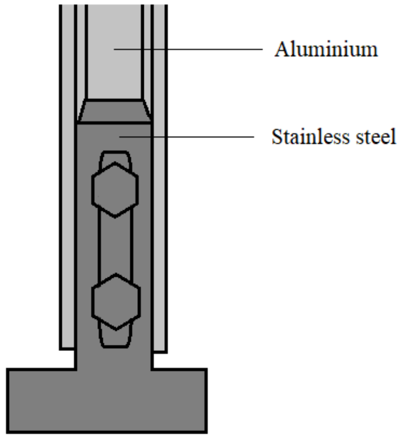


Figure 7: Schematic of connection between stainless steel and aluminium handrails support.

4.3 Ladders

The connection of aluminium ladders on carbon steel or stainless steel is common. The connections type for ladder can be similar to horizontal and vertical bolted connections as shown in section 4.5 and 4.6, respectively. A schematic of aluminium ladder connected to stainless steel is shown in figure 8. Details on avoiding galvanic corrosion on ladders are presented in section 6.3.

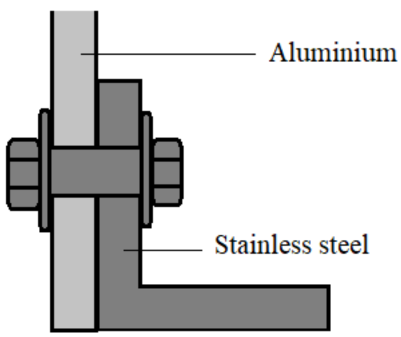


Figure 8: Connection between aluminium ladder and stainless steel.

4.4 Stairs and access platforms

The use of aluminium connected to stainless steel and/or carbon steel is common in oil and gas platform. There is evidence of galvanic corrosion on such cases and proper insulation is required between stainless steel and aluminium. A schematic of such connection is presented in figure 9. Details on avoiding galvanic corrosion on stairs and access platforms are presented in section 6.4.

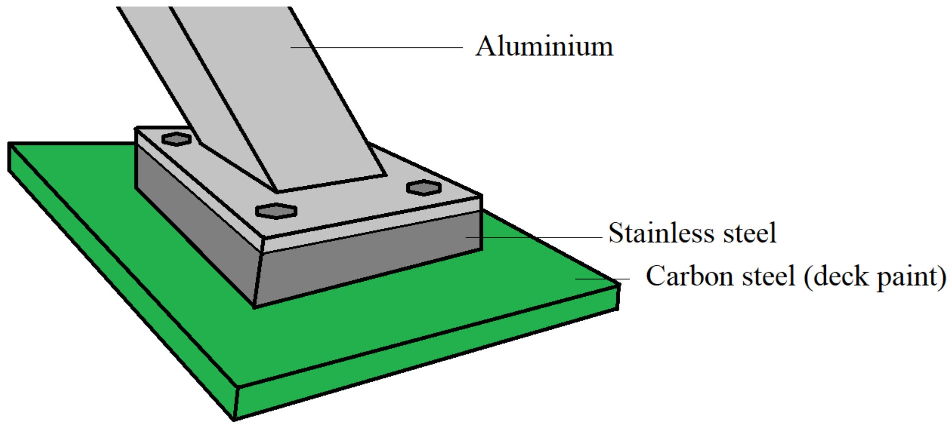


Figure 9: Stair and access platform.

4.5 Horizontal bolted connections

The schematics of normal horizontal bolted connections between any two of three materials, aluminium, carbon steel and stainless steel, are presented in figure 10. The details on avoiding galvanic corrosion on horizontal bolted connections are presented in section 6.5.

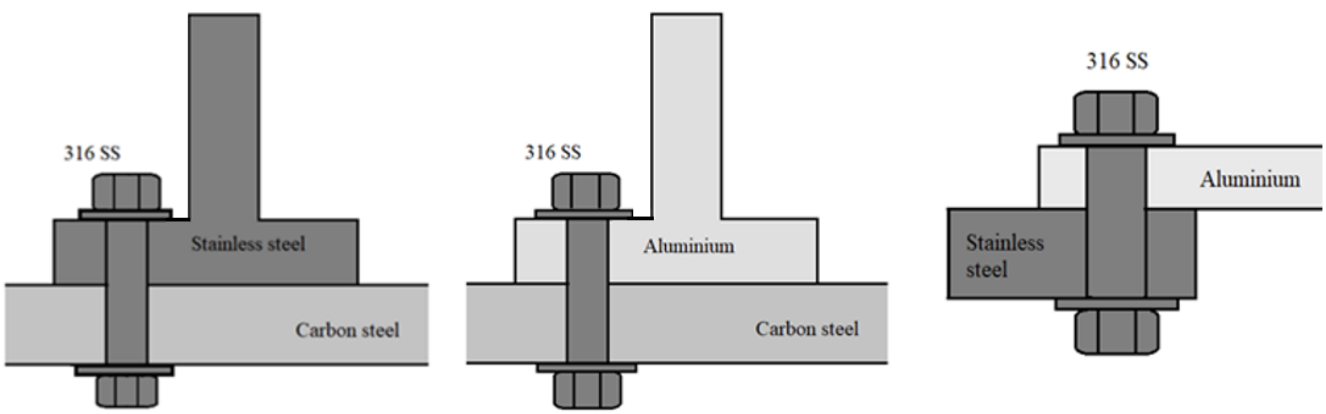


Figure 10: Typical horizontal bolted connections.

4.6 Vertical bolted connections

The vertical bolted connections between any two of three materials, aluminium, carbon steel and stainless steel, are shown in figure 11. The details on avoiding galvanic corrosion on vertical bolted connections are presented in section 6.6.

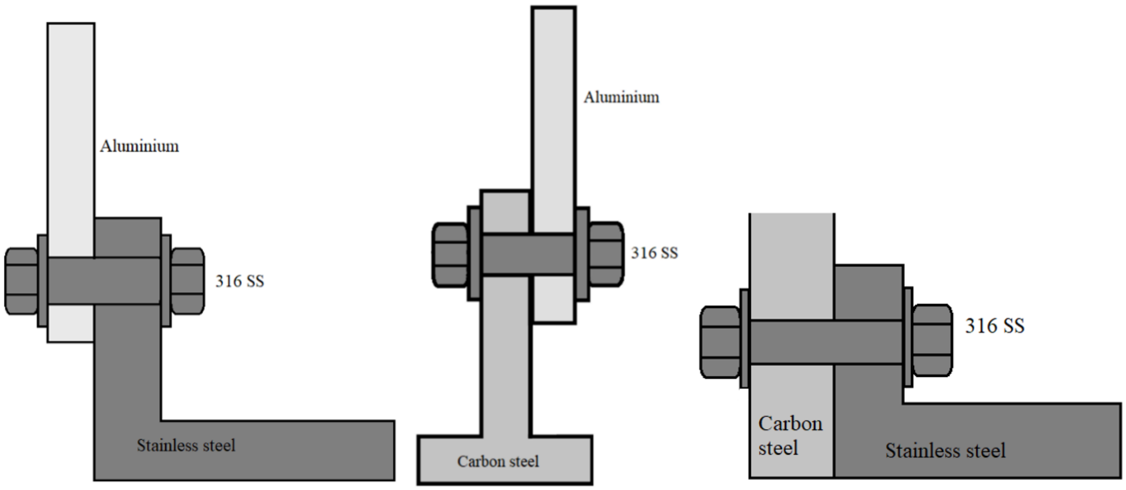


Figure 11: Typical vertical bolted connections.

4.7 Gratings and fasteners

A schematic of grating connected to the underlying structure (steel plate or RHS profiles) is shown in figure 12. Details on avoiding galvanic corrosion on gratings are presented in section 6.7.

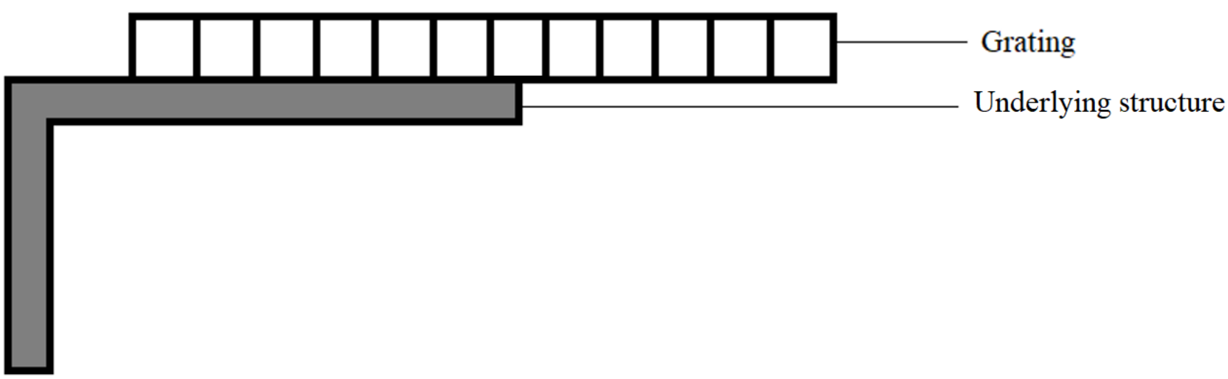


Figure 12: Schematic of grating connected to steel plate.

The schematic of fasteners used in gratings are shown in figure 13.

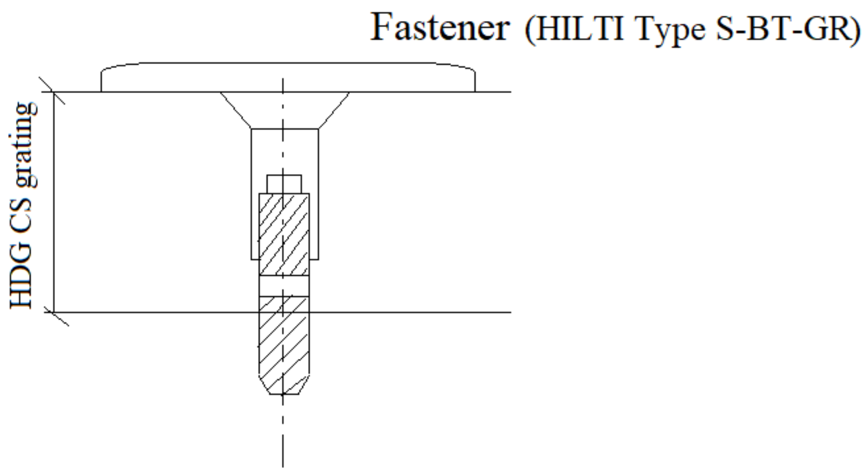


Figure 13: Grating fastener HILTI Type S-BT-GR (stainless steel).

5 EXPERIENCES

Experiences from oil and gas platforms indicate that the galvanic corrosion of aluminium frequently occurs and the current requirements does not ensure the full protection against galvanic corrosion, specifically for aluminium structures. For every typical connection mentioned in section 4, the evidence of galvanic corrosion was collected from offshore platforms, with few and many years in operations, are illustrated in this section.

Figure 14 shows aluminium handrail connected to stainless steel without insulation. The build-up pressure due to corrosion products has caused fracture of the cast aluminium components.

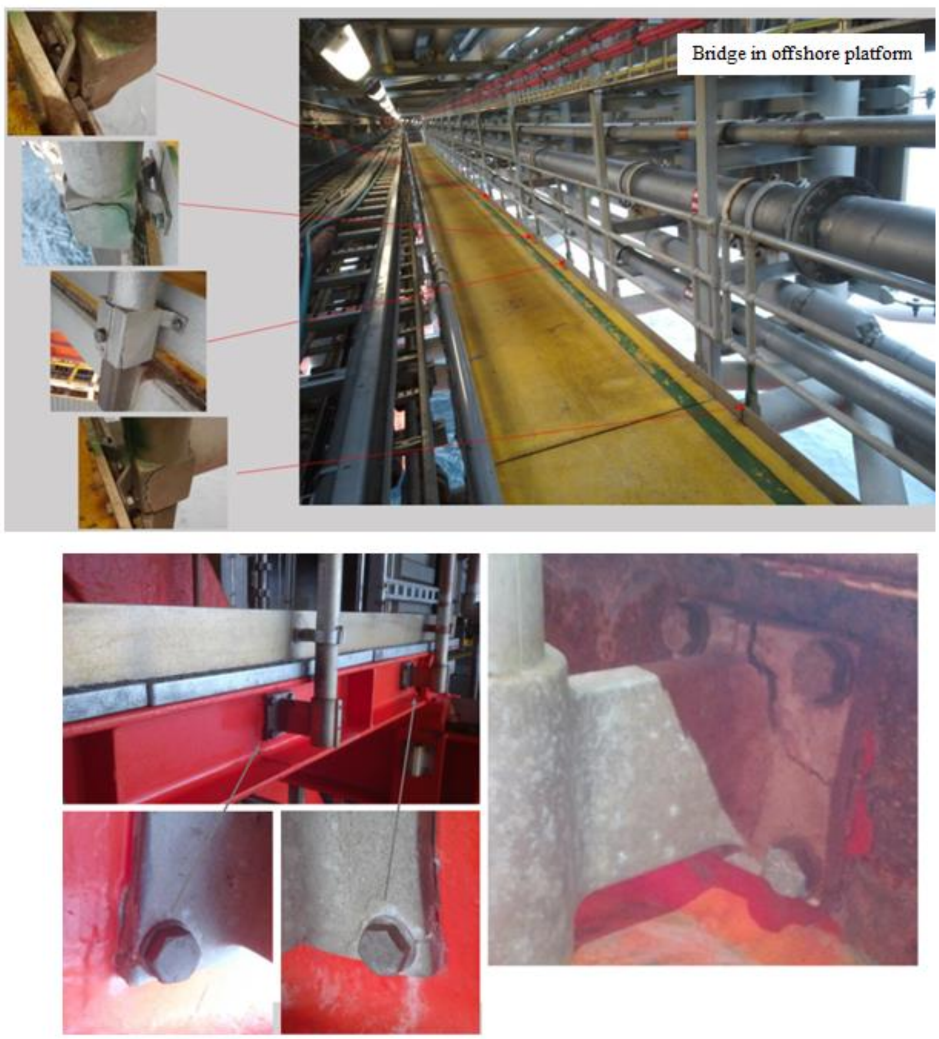


Figure 14: Fracture of cast aluminium component of handrails connected to stainless steel without insulation.

Figure 15 shows galvanic corrosion between aluminium and carbon steel due to the lack of insulation.

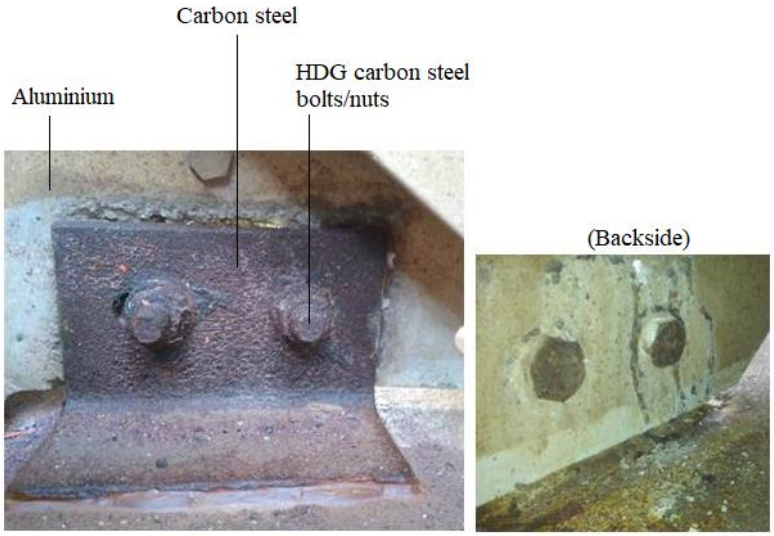


Figure 15: Corrosion of aluminium connected to carbon steel without insulation.

Figure 16 shows galvanic corrosion of stair and access platforms.

Figure 16: Corrosion in stair and access platform.

Figure 17 shows galvanic corrosion on bolted connections.

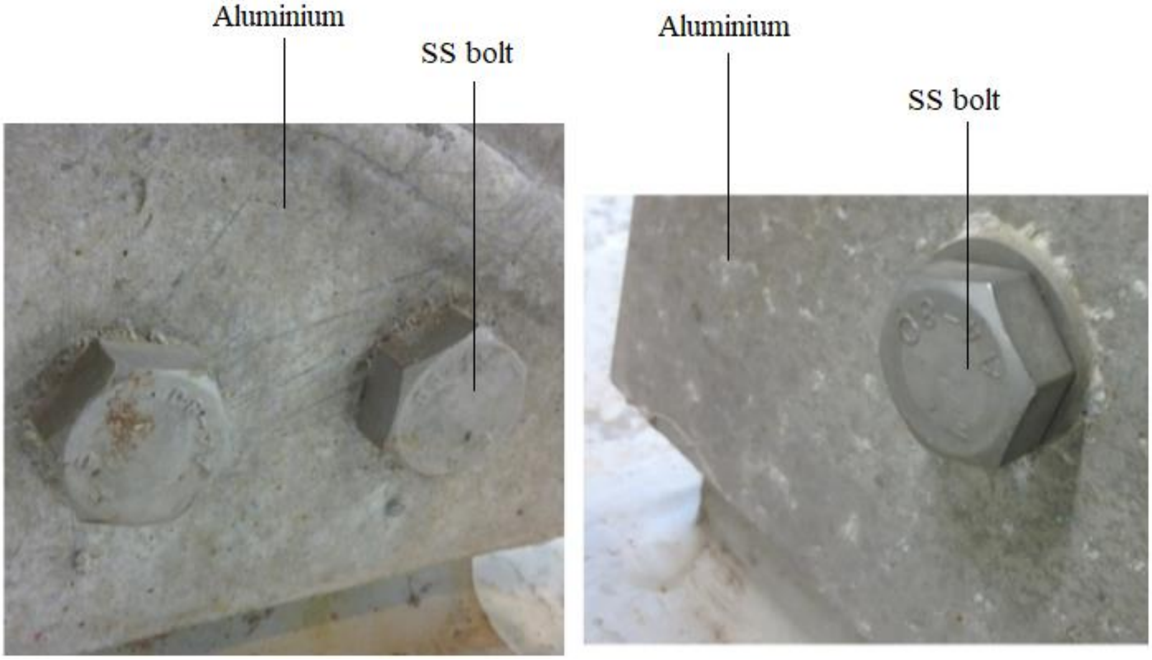


Figure 17: Corrosion on bolted connections.

Figure 18 shows corrosion on gratings fasteners.

Figure 18: Galvanic corrosion of fasteners.

Figure 19 shows the aluminium stairs where 316 SS bolt washers are connected directly to the aluminium. This solution will lead to crevice corrosion unless the nut and head are insulated from the aluminium surface.

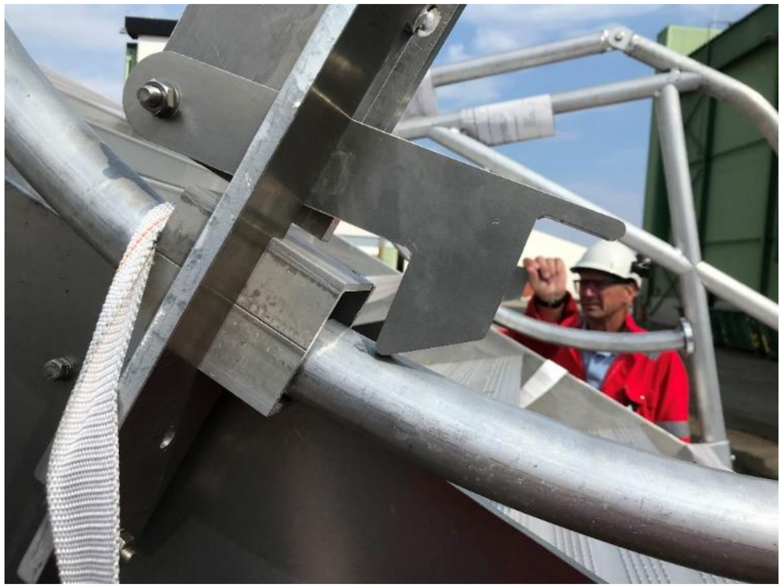


Figure 19: SS bolts washer connected directly to aluminium.

Figure 20 shows bolts used on Gudrun Helicopter deck (1). The tolerances bolt diameter versus hole diameter, are not optimal. This may cause bolts to vibrate and loosen. In addition, water can penetrate and collect in the annulus, causing galvanic corrosion. One of the solutions, and the preferred solution, was to inject epoxy resins through a small hole drilled in the bolt head. The epoxy resin prevents ingress of water and galvanic corrosion, and minimizes the risk for vibrations and loosening of bolts. Another solution would be to use plastic sleeves inside the bolt hole, see table 6. The plastic sleeves can be used as an alternative to applying sealant to bolt holes. The plastic sleeve will prevent galvanic corrosion and reduce vibrations.

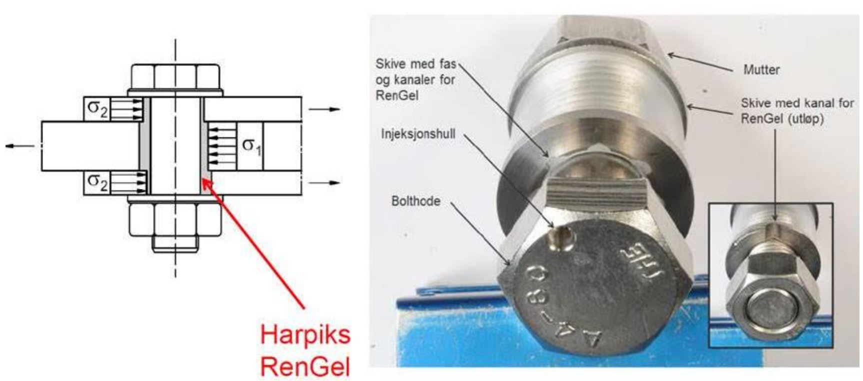


Figure 20: Injection hole on bolt head for injecting epoxy resin (1)

In fabrication, during erection, it is important to control the size of the bolt and bolt hole for the correct tolerances. If a sleeve configuration is not used, a sealing compound should be added in the bolt hole prior to inserting the bolt.

6 RECOMMENDED GUIDELINES FOR TYPICAL CONNECTIONS

6.1 Welded solutions

The tri-plate can be built up by use of explosion cladding the layers. The plate is typical 2 m x 6 m, with thickness of 31 mm, as shown in figure 21.

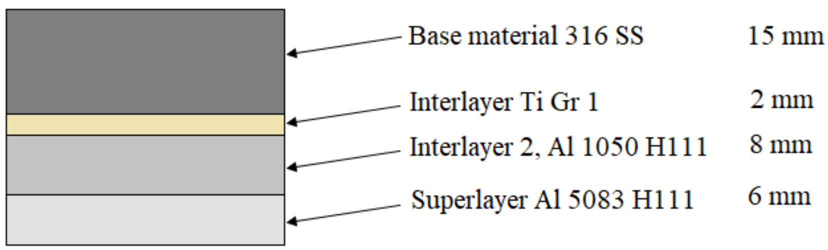


Figure 21: Explosion cladded tri-plate.

By using tri-plates, with 14 – 15 mm thickness on 316 SS side and Al side, strong fillets welds can be made. The load bearing capacity is however based on the strength of pure Al 1050 grade. If 316 SS is welded to stainless steel, paint is not required, and if it is welded to carbon steel, the total weld including the tri-plate edge shall be painted.

Another example is shown in figure 22, where Al is explosion welded to structural steel.

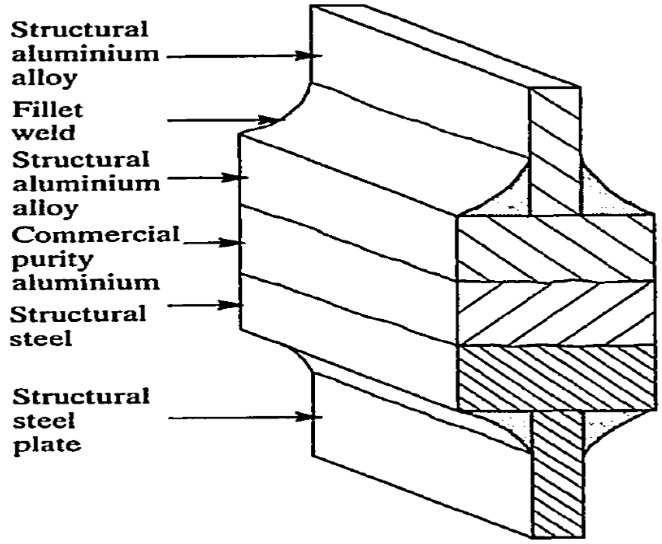
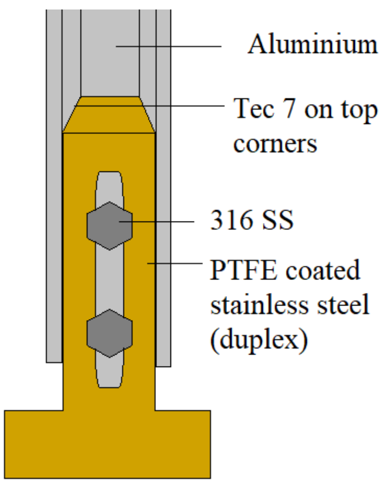


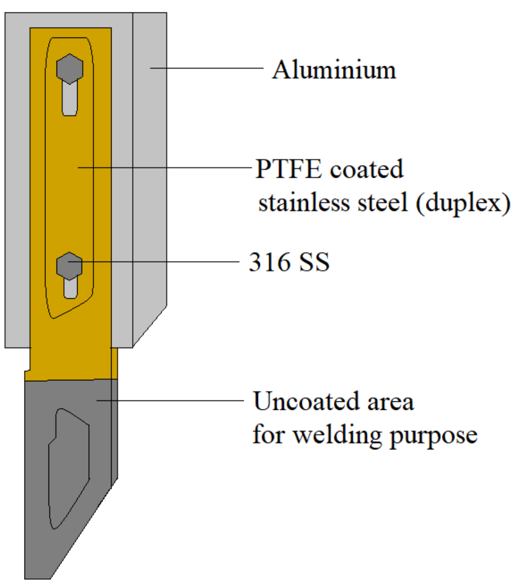
Figure 22: Use of an explosively bonded transition joint for the fastening, by welding, of aluminium alloy to steel (6).

6.2 Handrails

The recommended measures for avoiding galvanic corrosion on aluminium handrails connected to carbon steel or stainless steel are presented in table 3.

Table 3: Recommended measures for avoiding galvanic corrosion on handrail connection.

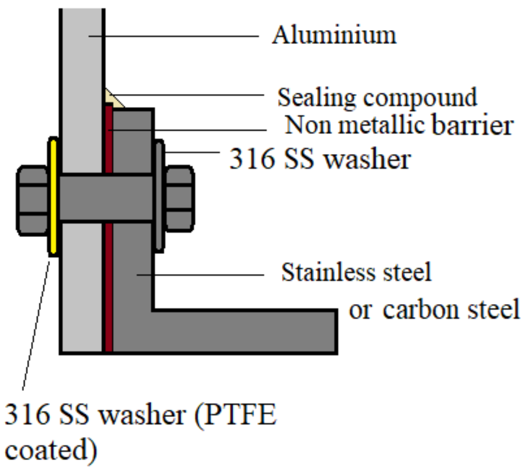
<table>
<tr><th>Handrail connection</th><th colspan="2">Recommended measures</th></tr>
<tr><td rowspan="5">


</td><td>1</td><td>Stainless steel (duplex) shall be coated with PTFE, at least one layer (15 µm), at the connecting area. The potential damage of the coating can give small cathodic area which will still limit the galvanic corrosion.</td></tr>
<tr><td>2</td><td>It must be ensured that the welding zone shall be free from the PTFE coating (refer second figure on left)</td></tr>
<tr><td>3</td><td>Sealing compound sealer shall be applied on top corners of connection in order to avoid the ingress of water.</td></tr>
<tr><td>5</td><td>Bolts details shall follow sections 6.5 and 6.6.</td></tr>
<tr><td>6.</td><td>See also section 6.9 for PTFE details.</td></tr>
</table>

6.3 Ladders

The recommended measures for avoiding galvanic corrosion on aluminium ladders connected to carbon steel or stainless steel are presented in table 4.

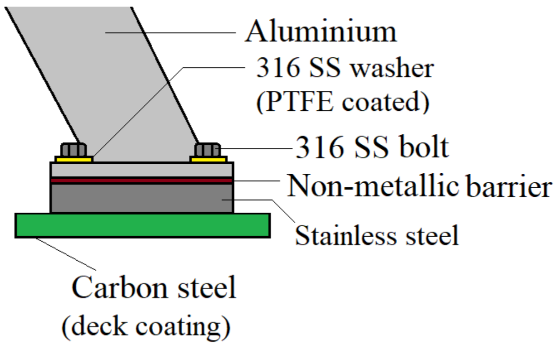
Table 4: Recommended measures for avoiding galvanic corrosion on ladders.

<table>
<tr><th>Ladder connection</th><th colspan="2">Recommended measures</th></tr>
<tr><td rowspan="4">
</td><td>1</td><td>A non-metallic barrier such as rubber or PTFE, preferably 3 - 4 mm thick, shall be used between aluminium and stainless steel or between aluminium and carbon steel.</td></tr>
<tr><td>2</td><td>Sealing compound shall be applied on the corners of connection in order to avoid the ingress of water.</td></tr>
<tr><td>3</td><td>Bolts details shall follow sections 6.5 and 6.6.</td></tr>
<tr><td>4</td><td>See also section 6.9 for PTFE details.</td></tr>
</table>

6.4 Stairs and access platforms

The recommended measures for avoiding galvanic corrosion on stairs and access platforms are presented in table 5.

Table 5: Recommended measures for avoiding galvanic corrosion on stair and access platforms.

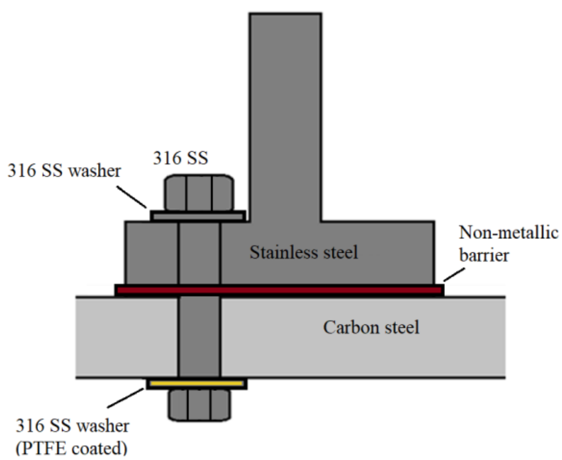
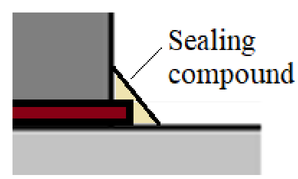
Stairs and access platforms connection	Recommended measures	
	1	A non-metallic barrier such as rubber or PTFE, preferably 3 – 4 mm thick, shall be used between aluminium and stainless steel.
	2	Painting shall be applied on the welded region between carbon steel and stainless steel. The paint shall be applied, if allowed, up to 50 mm from the welded part.
	3	Bolts details shall follow sections 6.5 and 6.6.
	4	See also section 6.9 for PTFE details.

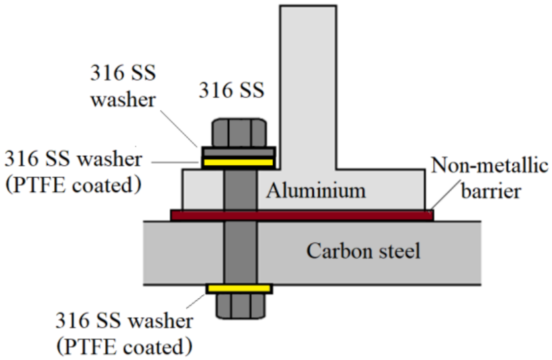
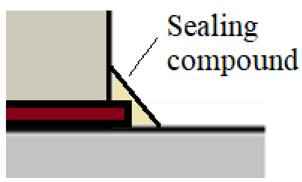
6.5 Horizontal bolted connections

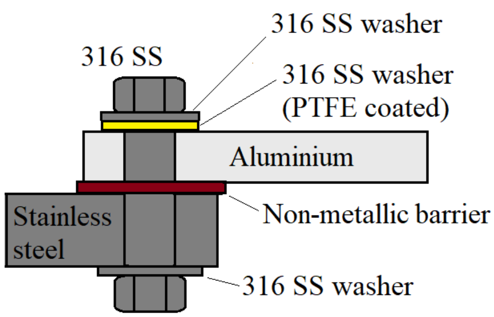
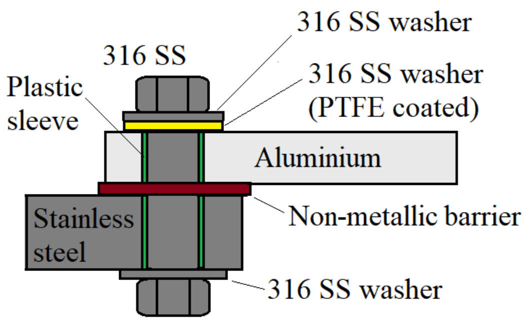
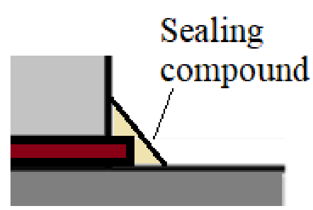
The recommended measures for different horizontal connections among aluminium, carbon and stainless steel are presented in table 6.

For all the following cases, stainless steel bolts shall be insulated from aluminium and carbon steel using PTFE coated washers sealed with Sealing compound.

Table 6: Recommended measures to avoid galvanic corrosion on horizontal bolted connections.

No.	Connection Type	Recommended measures	
1.	Stainless steel and carbon steel  	1.1	A non-metallic barrier such as rubber or PTFE, preferably 3 – 4 mm thick, shall be used between stainless steel and carbon steel. Carbon steel shall be fully painted.
		1.2	The contact surfaces including bolts, nuts, washers, rivets shall be cleaned and shall be free from any debris.
		1.3	Sealing compound shall be applied in bolt holes. Sealing compound shall be applied on the corners where two metals are connected as shown below in order to avoid water ingress. 
		1.4	Any holes, gaps or crevices where electrolytes can get trapped in shall be avoided during the design phase.

		1.5	See also section 6.9 for PTFE details.
2.	Aluminium and carbon steel  	2.1	A non-metallic barrier such as rubber or PTFE, preferably 3 – 4 mm thick, shall be used between aluminium and carbon steel. Carbon steel shall be fully painted. In case metallic shims are used instead of insulating material, Sealing compound shall be used on the surfaces of attached shims and edges in order to avoid water ingress. The metallic shim shall not extrude.
		2.2	The contact surfaces including bolts, nuts, washers, rivets shall be cleaned and shall be free from any debris.
		2.3	Sealing compound shall be applied in bolt hole. Sealing compound shall be applied on the corners where two metals are connected in order to avoid water ingress. 
		2.4	Any holes, gaps or crevices where electrolytes can get trapped in shall be avoided during the design phase.

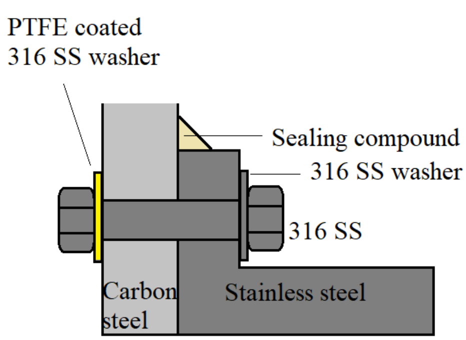
		2.5	See also section 6.9 for PTFE details.
3.	Aluminium and stainless steel  	3.1	A non-metallic barrier such as rubber or PTFE, preferably 3 – 4 mm thick, shall be used between aluminium and stainless steel.
		3.2	The contact surfaces including bolts, nuts, washers, rivets shall be cleaned and shall be free from any debris.
	Alternative solution with a plastic sleeve:  	3.3	Sealing compound shall be applied in bolt hole. Sealing compound shall be applied on the corners where two metals are connected. 
		3.4	Any holes, gaps or crevices where electrolytes can get trapped in shall be avoided during the design phase.
		3.5	See also section 6.9 for PTFE details.

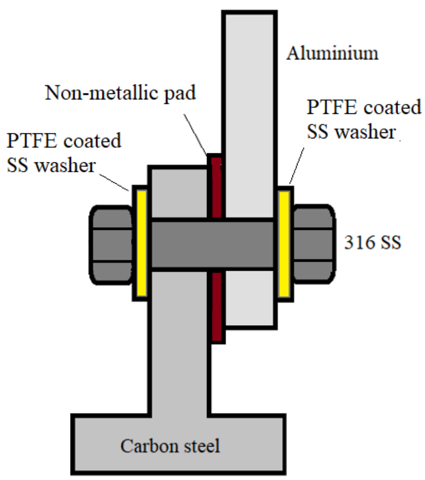
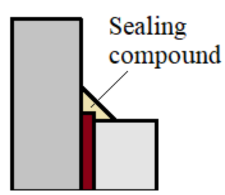
6.6 Vertical bolted connections

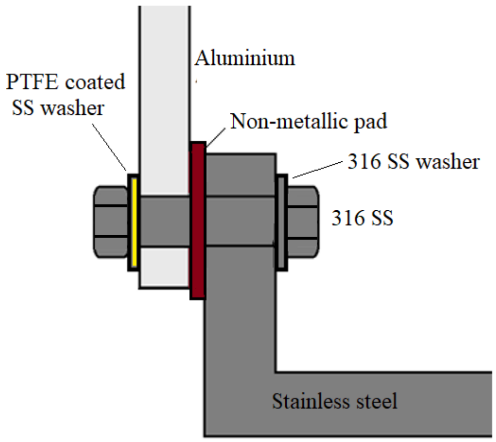
The recommended measures for different vertical connections among aluminium, carbon and stainless steel are proposed in table 7.

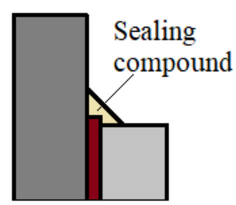
For all the following cases, stainless steel bolts shall be insulated from aluminium and carbon steel using PTFE coated washers sealed with Sealing compound.

Table 7: Recommended measures to avoid galvanic corrosion on horizontal bolted connections.

No.	Connection Type	Recommended measures	
1.	Carbon steel and stainless steel 	1.1	Carbon steel shall be fully painted.
		1.2	The contact surfaces including bolts, nuts, washers, rivets shall be cleaned and free from any debris.
		1.3	Sealing compound shall be applied in bolt hole. Sealing compound shall be applied on connection point between carbon steel and stainless steel.
		1.4	Any holes, gaps or crevices where electrolytes can get trapped in shall be avoided during the design phase.

		1.5	See also section 6.9 for PTFE details.
2.	Aluminium and carbon steel  	2.1	A non-metallic barrier such as rubber or PTFE, preferably 3 – 4 mm thick, shall be used between aluminium and carbon steel.
		2.2	The contact surfaces including bolts, nuts, washers, rivets shall be cleaned and shall be free from any debris.
		2.3	Sealing compound on bolt hole shall be applied. Sealing compound shall also be applied on the corners (top and bottom) where two metallic connections are made. 
		2.4	Avoid any structures where electrolyte can get trapped in during the design phase.

<table>
<tr>
<td rowspan="4">3.</td>
<td rowspan="4">Aluminium and stainless steel

</td>
<td>3.1</td>
<td>A non-metallic barrier such as rubber or PTFE, preferably 3 – 4 mm thick, shall be used between aluminium and stainless steel.</td>
</tr>
<tr>
<td>3.2</td>
<td>The contact surfaces including bolts, nuts, washers, rivets shall be cleaned and shall be free from any debris.</td>
</tr>
<tr>
<td>3.3</td>
<td>Sealing compound shall be applied in the bolt hole.

Sealing compound shall also be applied on the corners (top and bottom) where two metallic connections are made.

</td>
</tr>
<tr>
<td>3.4</td>
<td>Avoid any structures where electrolyte can get trapped in during the design phase.</td>
</tr>
</table>

6.7 Gratings

Galvanized carbon steel grating, with design lifetime > 20 years, shall be separated from the underlying structure by a non-metallic barrier such as PTFE tape, in order to reduce the loss of Zn. The aluminium grating, irrespective of design lifetime, shall be separated from the underlying structure by a non-metallic barrier such as PTFE tape. The tape shall extrude minimum 5 mm on edges as shown in Figure 23. However, if grating material is same as the underlying structure (for instance both are either aluminium or stainless steel), there is no need to add non-metallic barrier between them.

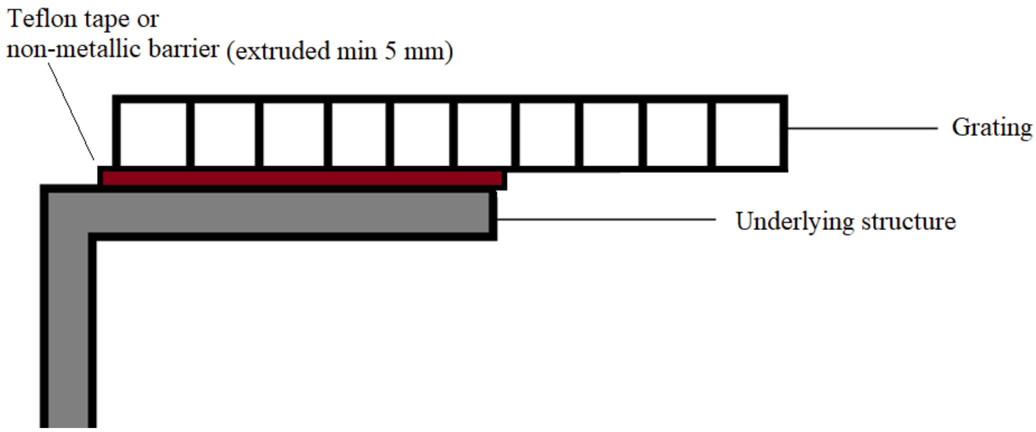


Figure 23: Schematic of gratings.

The grating fastener type can be HILTI Type S-BT GR or equivalent, which is screwed into the steel plate/RHS profile. All fastener components shall be of 316 SS. PTFE tape shall be applied on the point of contact of fastener on galvanized carbon steel or aluminium in case there is no paint layer/deck coating. Sealing compound shall be applied between stainless steel fastener and HDG carbon steel base for cases where PTFE tape can not be used.

The schematic of grating fastener (S-BT-GR) is presented in figure 24 and 25.

Figure 24: S-BT GR Threaded screw-in stud (stainless steel, metric thread) for grating fastenings on steel and aluminium in highly corrosive environments.

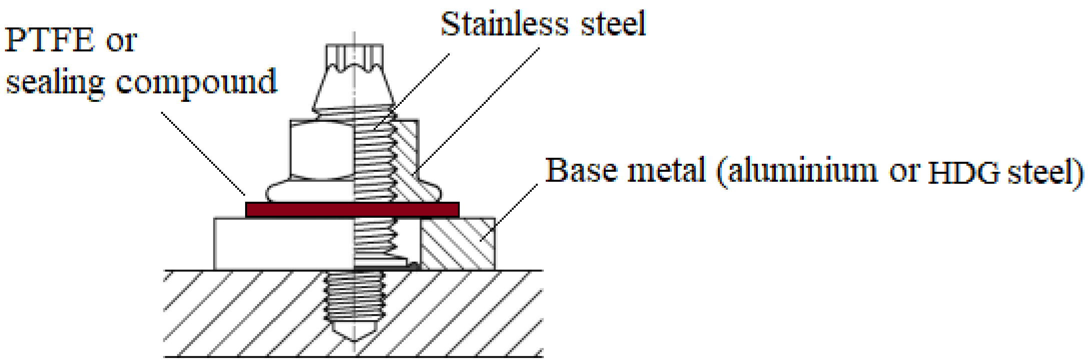


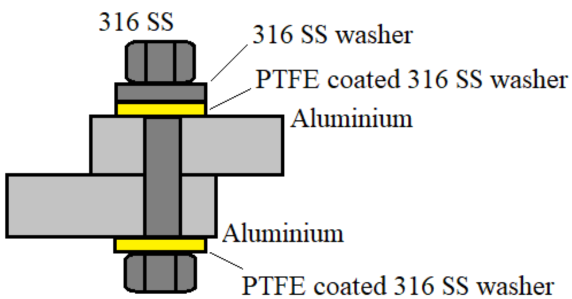
Figure 25: Section of HILTI Type S-BT-GR fastener (10).

6.8 Helideck Clips

Figure 26 shows the typical helideck clip. The recommended measures to avoid galvanic corrosion on helicopter clips are presented in table 8.

Figure 26: Helideck clips

Table 8: Recommended measures to avoid galvanic corrosion on helideck clips.

Helideck clips	Recommended measures	
	1	316 SS bolts shall be separated from aluminium using 316 SS washer and PTFE coated 316 SS washer on the upper horizontal surface where thicker water film can exist, and only one washer (PTFE coated 316 SS) can be used on vertical or horizontal surface facing downwards.
	2	Sealing compound shall be applied in the bolt hole. Sealing compound shall also be applied on the corners (top and bottom) where two metallic connections are made.
	3	Bolts details shall follow sections 6.5 and 6.6.
	4	See also section 6.9 for PTFE details.

6.9 PTFE coated items

For life time less than 20 years, one layer of PTFE is considered sufficiently, and for lifetime in excess of 20 years, two layer of PTFE coating is needed on structural items. For washers, one layer is to be specified regardless of life time. Figure 27 shows a 316 SS washed coated with PTFE.

Prior to appliance of coat, surfaces must be cleaned and blasted to 6-12 µm roughness. Xylan 1070 is applied to a thickness of 10 – 20 µm. Baking shall be at 220 – 245 ºC for minimum 15 minutes. For adhesion testing an adhesive tape shall be used, and no bare areas shall be seen after tape removal. The coating shall be reported, based on a procedure approved before the work starts.

For two layer, the second layer shall in total give a thickness of 20 – 38 µm. The hardening of the first layer, shall be relaxed to 120 ºC – 180 ºC.

For washers, when PTFE can be suspected to be seriously damaged during torqueing, two washers with PTFE coating can be used, or alternatively the second washer closest to nut or head, can be of 316 SS without PTFE coat.

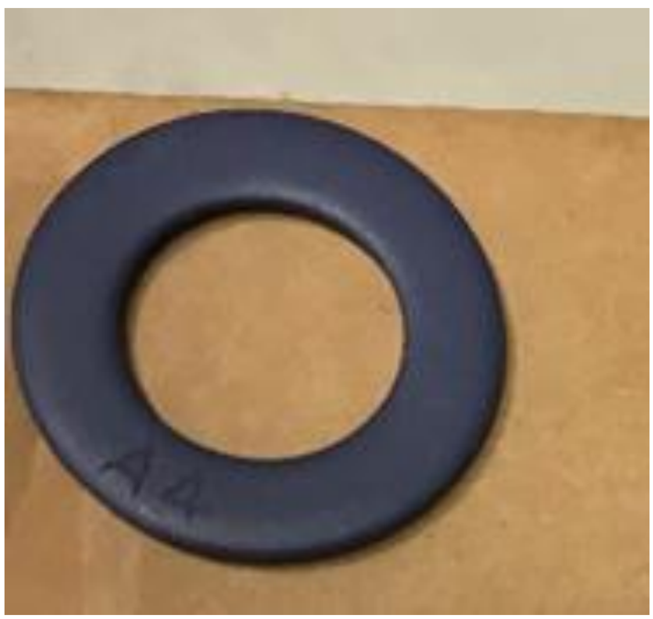


Figure 27: 316 SS washer with 10 – 15 µm, PTFE, type Xylan 1070 Blue.

References

1. Dr. Ing. Bjørn Aase, Hvorfor ryker så manger bolter? Presented at Konstruksjonsdagen, PTIL, Aug. 30, 2016, Stavanger, Norway.
2. M. A. Langøy, R. H. Hinderaker, T. L. Andersen, Safe Operations of Bolted Connections in the Oil and Gas Industries, Proceedings of the 38th International Conference on Ocean, Offshore & Arctic Engineering, Jun. 9 – 14, 2019, Glasgow, Scotland, UK.
3. NORSOK M-001 Material Selections.
4. H. P. Hack, Metals Handbook, Vol. 13, Corrosion, 9th ed., ASM, Metals Park, OH.
5. P. A. Schweitzer, Fundamentals of Metallic Corrosion, Corrosion Engineering Handbook, CRC Press, London, UK, 2006.
6. K. Trethewey, J. Chamberlain, Corrosion for Science and Engineering, Longman, Essex, UK, 2001.
7. ISO 3506-1:2020 Fasteners — Mechanical properties of corrosion-resistant stainless steel fasteners — Part 1: Bolts, screws and studs with specified grades and property classes.
8. ISO 7090 – Plain washers, Form B.
9. NORSOK M-102:2015 Structural Aluminium Fabrication.
10. Hilti S-BT Screw-in Threaded Studs Specification, July 2016.
11. NORSOK M-501 Surface Preparations and Protective Coatings.