

# The effect of wear and corrosion of steel components on the integrity of mooring systems for floating offshore installations

## Mooring Integrity Joint Industry Project Phase 2

Prepared by the **Joint Industry Project Steering Committee** for the Health and Safety Executive

**RR1096**

Research Report

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**Mooring integrity for floating offshore installations is an important safety issue for the offshore oil and gas industry. This report is one outcome from Phase 2 of the Joint Industry Project on Mooring Integrity. This work ran from 2008 to 2012 and had 35 industry participants. It followed the Phase 1 work described in HSE Research Report RR444 (2006). The Phase 2 work compiled research on good practice and an overview is given in HSE Research Report RR1090 (2017).**

**This report considers how the wear and corrosion of steel components in offshore mooring is affected by material properties, design and operation. The report focusses on chains and connecting components such as shackles, as well as considering components that mooring lines are in contact with, such as fairleads. The report identifies the main material properties of interest: hardness; surface properties; chemical composition; micro-structure and inclusions. It describes requirements in standards for specifications for materials. Corrosion aspects covered are: mechanisms and reactions; vulnerability of components; methods for protection of steel exposed in seawater. Wear aspects covered are: principles; the influence of material properties, friction and the seawater environment; considerations for different components. It identifies synergistic effects of wear and corrosion in the seawater environment that may result in higher wear rates.**

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## Mooring Integrity Joint Industry Project Phase 2

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# 1 PREFACE

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## **2 INTRODUCTION**

### **2.1 PURPOSE**

The purpose of this report / activity is to provide additional insight and guidelines into issues relating to wear and corrosion of mooring systems components and to identify how these degradation modes are affected by material properties, design and operation. The aim is to attempt to identify specific guidelines relating to material selection and design. Issues and topics that require further investigation and testing shall be identified. Such testing is outside the scope of this CTR.

Section 3 of the report deals with available information relating to properties and chemical composition of the relevant steels and how material issues are addressed in standards and guidelines. Corrosion and wear issues relating to properties and selection of materials are dealt with in Sections 4 and 5 respectively.

### **2.2 DEFINITIONS**

SHE            Standard Hydrogen Electrode.

HAZ           Heat Affected Zone.

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### **3 ISSUES RELATING TO MATERIAL COMPATIBILITY**

#### **3.1 PROPERTIES OF MATERIAL IN MOORING COMPONENTS**

Mooring system components are described in Section 14 of Phase 1 of the Mooring Integrity JIP [Ref 1] final report.

Considering wear and corrosion issues in mooring systems there are four different types (or groups) of components:

1. Synthetic fibre ropes where corrosion is not an issue - although other degradation mechanisms can occur, this is not covered in this report.
2. Steel wire ropes that are protected through galvanization of the individual wires or through integration of anode materials in other ways. This means that corrosion of steel wire ropes will be limited as long as the galvanising material remains. Polymer coating on steel wire ropes will also help to protect against corrosion.

A significant requirement is that the wire rope with end sockets are normally electrically isolated from neighbouring chain or other steel components that have significant areas of bare steel. Without electrical isolation the galvanic protection capacity may be consumed over a shorter time than intended since other steel surfaces will impose a drain. (The principle of electrical isolation should also be implemented for any steel components in a mooring system that has anodes attached for cathodic protection of the said component)

3. Chain and various connecting components such as shackles and tri-plates made from low alloy steel. These components are normally not protected against corrosion through coating or anodes. However, the top part of chains can be protected to some degree by anodes or impressed current protection from the vessel or the turret. It is the electrical resistance along the chain that reduces the effectiveness of the cathodic protection. The contact resistance between neighbouring links will probably contribute significantly to the overall resistance. These types of effects are not always taken into account in the design of cathodic protection systems.
4. In addition to components forming elements in the mooring line itself it is necessary to consider components that the mooring line will be in contact with such as fairleads, hawse pipes, trumpets and others.

This report covers steel components in mooring systems with focus on chain and interconnecting components. These components are specified in terms of the required steel grade normally ranging from R3 to R5. These grades are defined in terms of mechanical properties such as tensile strength and toughness. Minimum values for strength and impact energy are defined for the different grades in Table 3-1.

**Table 3-1 - Specification of the Required Mechanical Properties for Different Steel Grades for Chain**

		R5	R4S	R4		R3S		R3		API ORQ	
Quality Assurance ISO 9000		Required	Required	Required		Required		Required		Required	
Ultimate Strength Mpa min		1000	960	860		770		690		641	
Yield Strength Mpa min		760	700	580		490		410		-	
Reduction of Area % min		50	50	50		50		50		40	
Elongation % min		12	12	12		15		17		17	
Design Temperature °C		-20	-20	-20	(0)	-20	(0)	-20	(0)	-20	(0)
Impact Joules	B	58	56	50	(70)	45	(65)	40	(65)	40	(65)
(Average of three min)	W	42	40	36	(50)	33	(53)	30	(53)	30	(53)

The steel used in mooring system components fall under the definition of Low Alloy Steels that would broadly be defined as steel containing 1 – 5% of deliberately added alloying elements by weight. Table 3-2 presents indicative chemical composition of supplied R4 grade chain from 3 different manufacturers.

**Table 3-2 - Chemical Composition of Steel in Supplied Chain from Three Different Manufacturers**

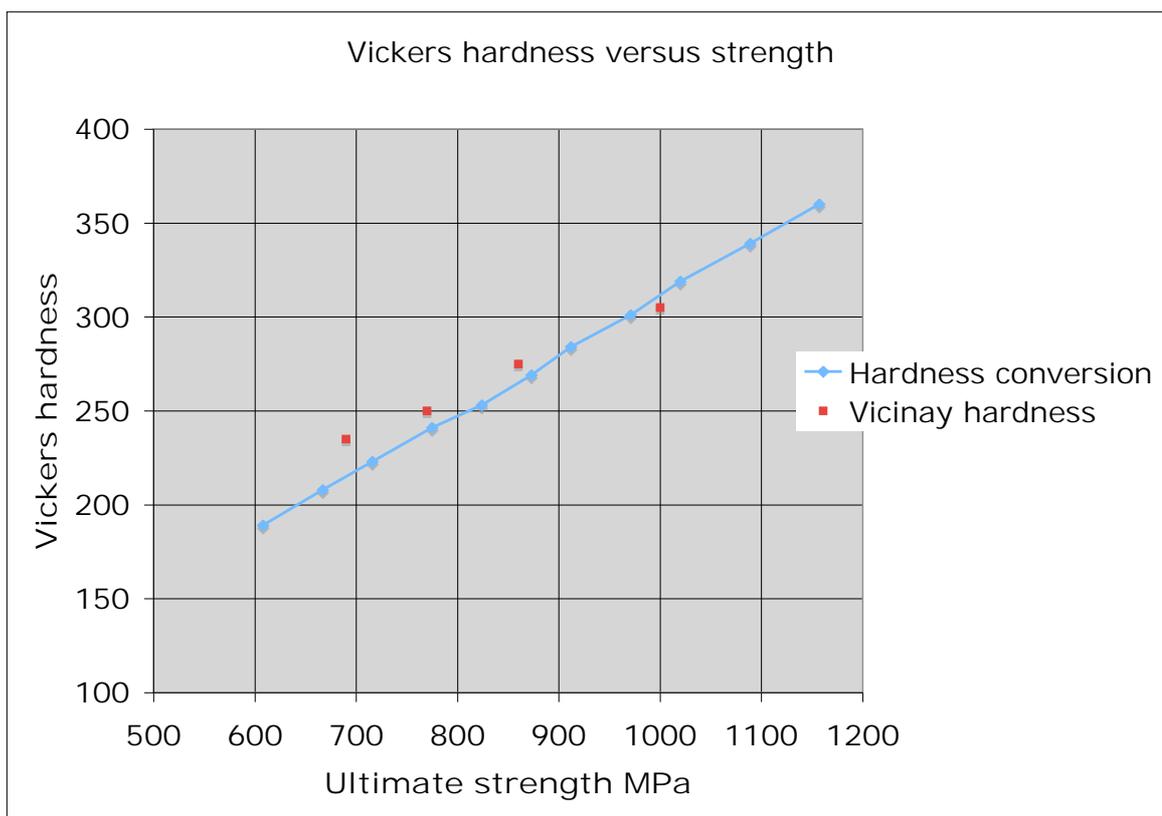
Manufacturer	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Sn	Al
1	0.22	0.31	1.26	0.007	0.015	1.19	0.23	0.74	0.14	0.01	0.21
2	0.211	0.274	1.05	0.015	0.008	1.1	0.25	0.56	0.25	0.014	0.032
3	0.23	0.22	1.49	0.012	0.006	0.95	0.41	0.81	0.06	0.03	0.28

Heat treatment is an essential element in achieving the required microstructure and homogeneity. Requirements for chemical composition and heat treatment as defined in relevant standards are described and discussed in Section 3.3.

For the degradation processes addressed in this report, the main material properties of interest will be:

- Hardness
- Surface properties, such as roughness and oxides
- Chemical composition
- Micro structure and inclusions

The hardness of steel tends to be proportional to the ultimate strength of the steel. Comparisons have been made of the measured hardness values from Vicinay in table 3-5 in [Ref 1] and an available conversion table on the Web ([www.steelstrip.co.uk](http://www.steelstrip.co.uk)) where hardness is related to strength. This can be seen in Figure 3-1 where hardness from the mentioned conversion table is compared to the data from Vicinay. This shows reasonable agreement and demonstrates proportionality.



**Figure 3-1 - Vickers Hardness versus Ultimate Strength (the red squares represent the hardness of grades R3, R3S, R4 and R5 according to data from Vicinay)**

### 3.2 CONSIDERATIONS REGARDING QUALITY OF RELEVANT STEEL

The best possible resistance to corrosion for steels under consideration in this report will be achieved through good homogeneity and fine grain structure. The possible development of phase changes in connection with welding or inadequate heat treatment will probably affect the corrosion resistance more than variations in chemical compositions for low alloy steel. Optimum procedures and comprehensive quality control are the best means to avoid potential material related problems.

If severe corrosion on mooring system components is experienced it should also be evaluated in the light of possible out of specification material properties.

It is worth noting that most steel structures and components used in the offshore industry today are protected against corrosion induced by the marine environment by the use of coatings and/or cathodic protection. This means that the mainly unprotected steel as found in chain and mooring components are special cases in the marine offshore industry. Focus on corrosion issues within the rest of the offshore industry will to a large extent be on corrosion protection or issues relating to corrosion induced by oil and gas environments. A significant part of our knowledge about the corrosion of steel in the seawater environment is from earlier phases within the marine and offshore industry before adequate protection was developed. Most of the steels used in those phases would be simpler and lower grade steels than those used in mooring systems today.

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### 3.3 SPECIFICATION OF MATERIALS IN RELEVANT STANDARDS

#### 3.3.1 Background

To better understand potential material compatibility issues it is worth providing a brief review of requirements defined in some of the relevant standards.

#### 3.3.2 Relevant Standards

DNV-OS-E302 – OFFSHORE MOORING CHAIN – October 2008 [Ref 2]

Under general requirements it is stated:

*The steels shall be killed (completely deoxidised) and fine grain treated. The austenite grain size shall be 5 or finer in accordance with ASTM E112 (5 corresponds to 256 grains per mm<sup>2</sup> surface). The fine grain size shall be deemed to be fulfilled if the steels contain Al, Nb, V or Ti, either singly or in any combination... (with minimum levels as defined in the standard).*

It is also stated:

*The level of inclusions shall be quantified and assessed to be sure inclusion levels are acceptable for the final product.*

Regarding chemical composition the following is defined:

*Specification of chemical composition shall be agreed between the manufacturer and purchaser. Steel grades R4, R4S and R5 shall contain a minimum of 0.20% molybdenum.*

The following heat treatment requirements are defined for mooring chains:

*Grade R3 and R3S shall be supplied as normalised, normalised and tempered, or quenched and tempered condition. Grade R4, R4S and R5 shall be supplied in the quenched and tempered condition. Tempering temperature shall not be less than 570°C and cooling after tempering shall be in water.*

The overall requirements on chemical composition are in principle that Mo content should be higher than 0.20% for Grades R4 and higher and that there are certain minimum requirements for alloying elements that contribute to grain size control (Al, Nb, V or Ti). Apart from this the chemical composition shall be agreed between the manufacturer and the purchaser. The heat treatment is essential for the microstructure and material properties. The requirements provide some specific definitions of the heat treatment, but several details will be up to the manufacturer.

API 2F – SPECIFICATION OF MOORING CHAIN [Ref 3]

The API 2F covers the ORQ grade which is fairly close to the R3 grade. In this specification the chemical composition is defined in terms of minimum contents and there are requirements for fine grain structure according to the following statements:

*All material shall be of fine grain quality. The chemical composition shall be determined at the steel mill on samples taken from the each ladle of each heat and shall comply with the composition shown in Table (See table 3.3).*

**Table 3-3 - Requirements for Chemical Composition as Defined in API 2F**

Element	Percent minimum	Percent maximum
Carbon, C	0.33	
Silicon, Si	0.20	0.35
Manganese, Mn	1.90	
Phosphorus, P	0.04	
Sulphur, S	0.04	
Nitrogen, N	0.015	
Chromium, Cr	0.25	
Copper, Cu	0.35	
Columbium, Cb (Niobium, Nb) <sup>3</sup>	0.05	
Nickel, Ni	0.40	
Vanadium, V <sup>3</sup>	0.10	
Aluminium, Al <sup>3</sup>	0.065	
Molybdenum, Mo	0.08	
<sup>3</sup> To obtain fine grain steel at least one of these fine grain refining elements in sufficient amount(s) must be present to meet the fine grain practice.		

For heat treatment the following is stated:

*The chain shall be normalised, normalised and tempered or quenched and tempered to produce a fine grain structure throughout the link's weld and fusion zone.*

### 3.3.3 Discussions

The main requirements for the steel components in mooring systems are the defined mechanical properties in terms of strength and toughness properties. This is achieved through the chemical composition and heat treatment. It may be worth noting that to obtain a particular type of property for the steel, different alloying elements can be used. Although some alloying elements can have two functions it is possible to achieve the required mechanical properties through ranges of chemical compositions. It is reasonable to assume that this is one of the reasons why, for example, DNV-OS-E320 is not rigidly prescriptive on chemical composition.

It should also be noted that no requirements have been found in the standards for surface hardness and roughness.

---

## 4 CORROSION ISSUES

### 4.1 GENERAL PRINCIPLES OF CORROSION

#### 4.1.1 Basic Mechanisms and Reactions

Corrosion of a metal (like steel) is an electrochemical process where metallic atoms are oxidized, normally ending up as oxides or salts. For normal corrosion of steel some iron atoms oxidize into positive ions ( $\text{Fe}^{2+}$ ) that go into solution when contacting water where they normally react with other ions and molecules to form oxides and salts. The locations on the metal surface where the metal ions are oxidized, represent anodic sites while the surplus electrons are left in the metal. For the overall corrosion process, there must be a complementary cathodic reaction (reduction) at cathodic sites, where surplus electrons leave the metal through a cathodic reaction, see Figure 4-1.

**Figure 4-1 Schematic Presentation of the Mechanisms and Reactions for Corrosion of Iron is missing/not available but standard texts on corrosion may be consulted.**

The anode reaction is:

Oxidation of Iron             $\text{Fe (metal)} \rightarrow \text{Fe}^{2+}(\text{in solution}) + 2\text{e}^- (\text{in metal})$

The two most important cathode reactions are:

Reduction of oxygen:     $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$

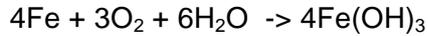
Reduction of hydrogen:  $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$

Reduction of hydrogen results in generation of gaseous  $\text{H}_2$  and will only be significant at lower pH values (higher concentrations of  $\text{H}^+$  ions) than in normal seawater. Reduction of hydrogen can also be enhanced by application of cathodic over-protection and be the source of hydrogen embrittlement of susceptible steels.

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The reduction of oxygen is considered the dominant cathodic reaction in the corrosion process of steel in sea water.

The  $\text{Fe}^{2+}$  ions in the water can react in different ways to form various oxides or hydroxides. The overall reaction to form ferric hydroxide can be written [Ref 5]



In corrosion products from steel in seawater Iron oxide-hydroxide  $\text{FeOOH}$  is normally found in various structures (e.g. goethite and lepidocrocite). It can also exist in hydrated forms such as monohydrate  $\text{FeOOH}\cdot\text{H}_2\text{O}$  which can be written  $\text{Fe}(\text{OH})_3$ .

Another common corrosion product is lepidocrocite (gamma  $\text{FeO}\cdot\text{OH}$ ), which has a yellow to orange colour [Ref 4].

It is also reported that magnetite ( $\text{Fe}_3\text{O}_4$ ) can form under certain conditions such as high concentrations of  $\text{Fe}^{+}$  or in low oxygen concentration. The magnetite is black and slightly magnetic and cathodic with respect to steel. As can be seen from Figure 4-2 apparently “black” coloured chain does occur and hence it would be desirable to test if such chain is slightly magnetic.



**Figure 4-2 - Example of “Black” Coloured Chain on the Back Deck of and Anchor Handling Tug**

It is important to note that the type of corrosion products that will form depend on the conditions close to the surface in terms of pH and concentrations of relevant species.

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#### 4.1.2 The Driving Force for Corrosion

The basic requirement for a corrosion reaction to take place is that it results in a lower “energy state”. The different electrode reactions involved in corrosion processes are characterised by an electrical potential (reduction potential) relative to a defined standard potential and therefore also in relation to each other. An anode reaction has to have a lower potential than the corresponding cathode reaction for corrosion to take place. Different metals exhibit different electrical potentials for the anode reaction. It is useful to recall that noble metals are resistant to corrosion and oxidation in moist air unlike most base metals. Platinum is an example of a noble metal – see Figure 4-4.

A less “noble” metal may thus be used as a sacrificial anode when in electrical contact with another metal object. For adequate protection all surfaces of the protected material should be driven electrically to become cathodic thus avoiding any anodic reaction. Based on the same principles of forcing a material to become fully cathodic corrosion can be prevented by impressing an adequate electrical potential (and a corresponding electrical current) relative to a standard potential.

The effective reduction potential for electrode reactions will to varying degrees depend on the composition and flow of the electrolyte (surrounding sea water), temperature, pH and surface properties. The tendency to corrode will depend on many factors and cannot be deduced directly from the reduction potentials.

Corrosion involves transfer of electrical charge between the metal and the electrolyte. At anodes positive charge will be transferred to the electrolyte while negative charge in the form of electrons will be transferred at the cathode. To ensure charge neutrality for a metal object the total anodic current  $I_a$  (charge per second) must equal the total cathodic current  $I_c$ .

When complementary cathodic and anodic reactions take place on a corroding metal the effective potential of the metal will typically end up between the equilibrium potentials of the anodic and cathodic reactions. The effective potential (out of equilibrium for both reactions) will be at the value where  $I_a = I_c$ .

### 4.1.3 Corrosion Tendency Diagrams

To understand corrosion issues of steel in sea water it is worth considering the Pourbaix diagram in Figure 4-3 [Ref 5]. This indicates which combinations of potential (of the steel) and pH (of the water) where corrosion will take place and where corrosion will be impossible or inhibited.

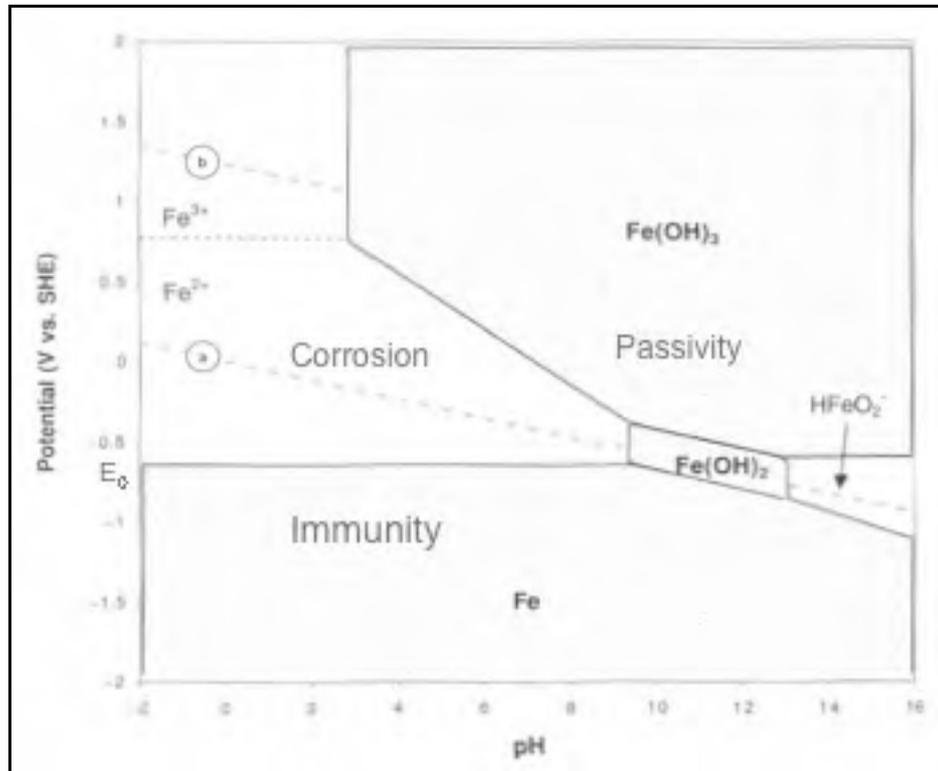


Figure 4-3 The Pourbaix Diagram for Steel at 25C. From [Ref 5]

The horizontal line at  $E_0 = -0.6$  corresponds to the potential value that is neutral for the anode reaction of Fe going into solution as  $Fe^{2+}$ . On this line the reaction  $Fe(\text{solid}) \rightarrow Fe^{2+}(\text{solution}) + 2e^-$  is neutralised by the reverse reaction:  $Fe^{2+}(\text{solution}) + 2e^- \rightarrow Fe(\text{solid})$ . Below this line the reverse reaction will become stronger than the dissolution reaction for iron and the steel becomes immune to corrosion. The line is horizontal out to around a  $pH=9$  and then starts to fall off with increasing  $pH$ . A significant region of the diagram indicates passivity. In this region any corrosion process will result in the formation of oxide or hydroxide films that will strongly limit the corrosion through the creation of a barrier for the transport of  $Fe^{2+}$  ions from the steel to the water. These films will have a direct bonding to the steel surface and will significantly reduce the rate of the anode reaction while the cathodic reaction can take place. The oxides are results of reactions taking place right on the surface and must be considered as an integral part of the steel surface.

---

#### 4.1.4 Corrosiveness and Natural Limitations

In the regions in the Pourbaix diagram where corrosion takes place there will be a finite rate of dissolution of iron through the anodic reaction. The corrosion will typically be of a general nature. Anodic and cathodic sites will change location in a fairly random pattern. The rate of corrosion in this region will depend on parameters such as:

- Composition of the electrolyte (sea water) affecting among other things
  - The dissolution activity for iron
  - Possible precipitation of Calcium carbonate and Magnesium hydroxides as protective layers on the steel surfaces
  - Electrical conductivity
  - The effects of chlorides on passivating films and possibly on pitting
- Limitations associated with the cathodic reaction. For oxygen reduction this will be:
  - Concentration of oxygen in the water
  - Flow speed for the water
  - Temperature
  - Salt deposits
  - The nature and thickness of corrosion deposits
- Oxides and surface deposits on the steels when installed
- Biofilms and marine growth

The  $E_o$  level in the Pourbaix diagram would represent the hypothetical equilibrium potential if no cathodic reactions could take place. However, cathodic reactions will take place and the dominant cathodic reaction for steel in sea water is oxygen reduction. Since the anodic and cathodic reactions are taking place close to each other on the steel surface the actual “common” potential for the steel will end up at a level between their respective equilibrium potentials. It is the deviation of the common potential from the respective equilibrium potentials that will be the driving force for the reactions. The common potential will be at a level where the total anodic current is equal to the cathodic current to ensure charge neutrality. There are methods to determine the potential through measurements and theoretical evaluation under controlled conditions.

Fresh seawater has a pH around 7.8-8.3 (see map of sea water pH variations in [Ref 7]). Considering the Pourbaix diagram the area for “free” corrosion stretches up to around pH=9 for a potential in the region of -0.6 -> -0.4V. The actual corrosion potential will be higher than -0.6 and can possibly be above -0.4V possibly taking the potential towards the passive region for the relevant pH levels. It should also be noted that oxygen reduction (cathodic reaction) on the steel surface will produce OH<sup>-</sup> ions driving the environment next to the surface in the alkaline direction thus increasing the pH. Thus possibly driving the reaction into the passive region of the diagram.

The transition between passive and active regions in the Pourbaix diagram is not sharp and for regions close to the transition there may be a mixture of passive and active regions on the steel surface. It is also assumed that in these regions the hydroxide films will be vulnerable and can locally be damaged by chemical reactions. Cathodic reactions can take place in passive locations as well as in active locations on the surface. Since the anodic reactions are limited to active areas the actual potentials and local corrosion rate will be affected. The result can be mixed regions with a combination of general and localised (pitting like) corrosion.

---

It is worth noting that deposits (other than closely bonded oxides resulting in passivation) on the steel surface can also strongly affect the corrosion rate. The reason is assumed to be that deposits represent an additional diffusion barrier for oxygen, but will also to some degree affect the transport of ions. The deposits can be corrosion products or salts. Calcium carbonate  $\text{CaCO}_3$  is known to significantly reduce the corrosion rate in sea water under conditions that are relevant for mooring systems. It is well known that calcium carbonate salts precipitate on the steel surface due to the increase in pH due to the oxygen reduction. It is also known that biofilms can drive the electrochemical potential in the noble direction due to effects on the oxygen availability.

Tests have shown that without any deposits, in air saturated slow-flowing sea water steel will corrode at a rate of 0.6mm/year and in flowing water several times this value. While typical corrosion rates in natural sea water allowing salt and corrosion product to deposit it is in the region of 0.1 -> 0.2 mm/year. However, there are anomalies that have no straight forward explanations.

In the context of natural environments for mooring components it is important to be aware of the influence of water flow on the conditions on steel surfaces affecting corrosion. Water flow will normally enhance the availability of oxygen on the steel surface through the renewal of "fresh oxygenated" water close to the surface. Water flow can also damage or remove protective deposits and thus affect the availability of oxygen or transport of ions. On the other hand several surfaces on mooring components can be shielded from the water flow and thus experience a more restricted availability of oxygen.

#### **4.1.5 Galvanic Effects**

Combining metals with different galvanic potentials can lead to preferential corrosion of the least noble material. The galvanic potential for a range of metals in seawater is presented in Figure 4-4. Zinc is at around -1V while platinum is at around +0.25. Low Alloy Steel range from -0.63V to -0.57V (a range of 0.06V) while mild steel range from -0.71V to -0.59V (a range of 0.12V). The relevance to corrosion is: if two metals with different galvanic potentials are electrically connected while in the same electrolyte, there will in principle be a tendency for the metal with the lowest or most negative potential (ie less noble) to corrode preferentially to the other metal. The degree of preferential corrosion will depend on the difference between the galvanic potentials but also influenced by several other parameters such as the cathodic efficiency of the most noble metal, the temperature, properties of the electrolyte and relative area effects. Typical galvanic corrosion is illustrated in the drawing in Figure 4-5 [Ref 6] where the least noble metal corrodes strongly close to the contact interface.

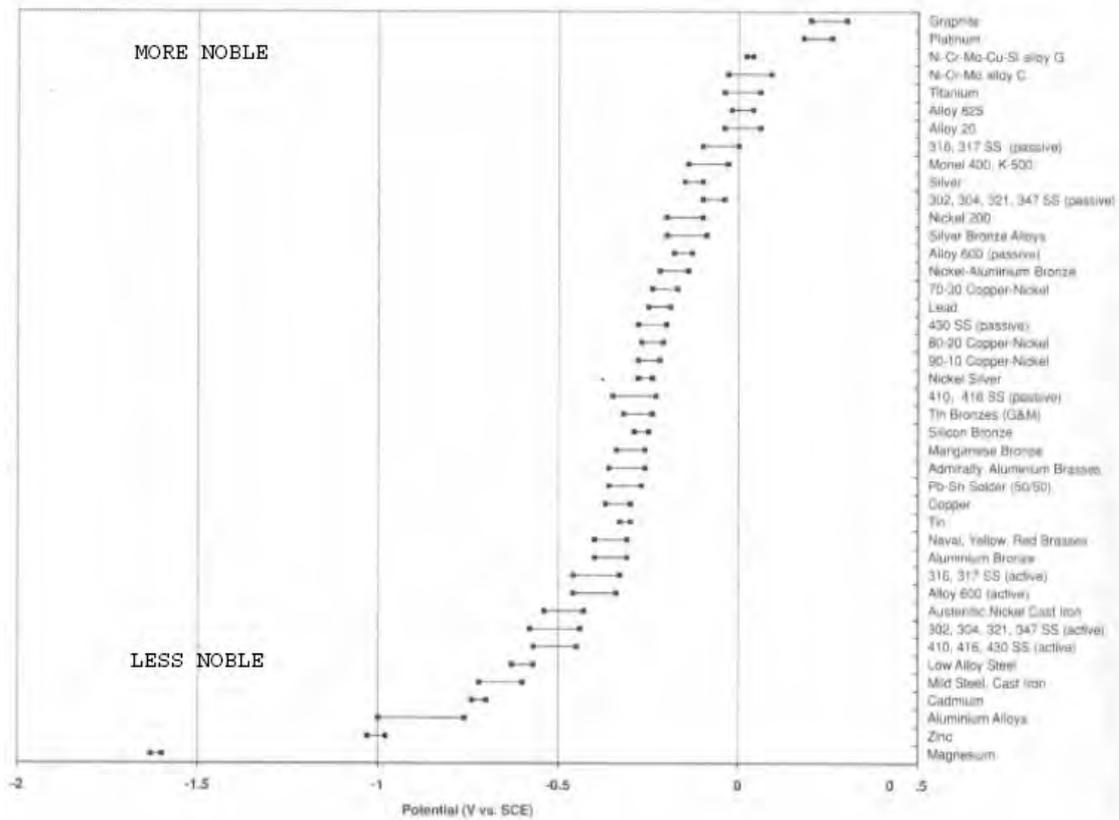


Figure 4-4 The Galvanic Series for a Selection of Metals in Slow Moving Sea Water. From [Ref 5]

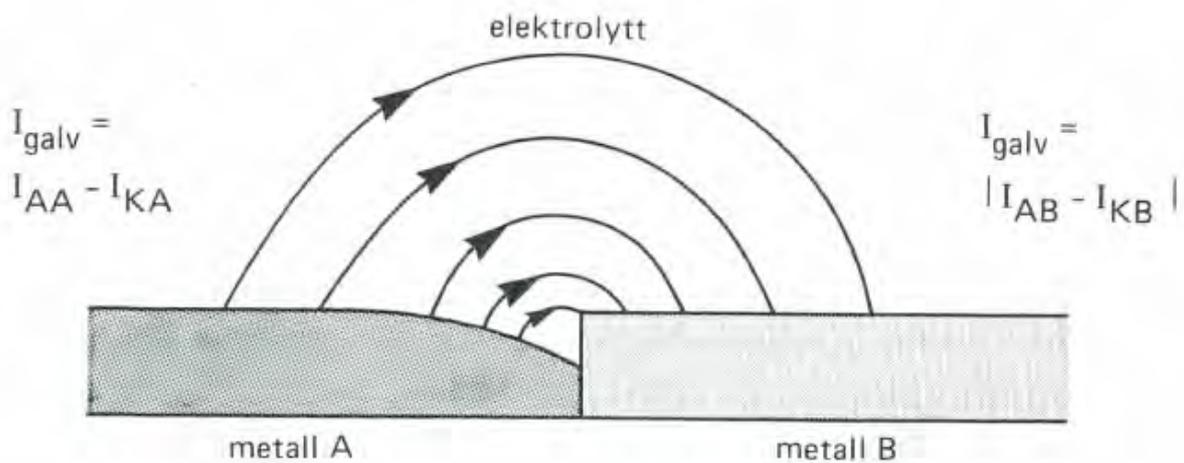


Figure 4-5 Schematic Presentation of Galvanic Corrosion of Metal A in Contact with Nobler Metal B. From [Ref 6]

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Characteristic corrosion patterns from galvanic effects is

- significant corrosion of the least noble metal
- virtually no attack on the most noble metal.

If the surface area of the most anodic material is very small compared to the most cathodic material it is possible to see significant corrosion of the least noble metal even if the difference in galvanic potential is low (say 100mV). However if the surface areas are similar or if the anodic surface area is larger than that of the cathodic material there will be limited corrosion effects if the difference in galvanic potentials is small. Any effects will normally show up on the least noble material close to the contact line. Good practice in this respect is to ensure to use identical materials throughout a system and if that is not feasible then use material of a more noble quality in components with the smallest exposed area.

#### 4.1.6 **Pitting or Localised Corrosion**

When anodic reactions are allowed to persist in the same position on a steel surface over long time the corrosion attack will be local and pit like. There can be several reasons for localised corrosion attack. Stainless steels are corrosion resistant because robust oxide films protect the surface ensuring that the material is in the passive region in the Pourbaix diagram. Some of the stainless steels will under certain conditions be prone to pitting conditions. This comes about in locations where the oxide film is damaged creating small anodic areas promoting high corrosion rates. The chemistry in pits can become acidic and prevent oxide films from reforming thus perpetuating the pitting corrosion.

On low alloy steels possible passivating films are far from as robust as on stainless steels. As discussed in the previous section one can foresee a mixed corrosion regime with a combination of anodic and passive regions. The reasons for this can be vulnerable passivation films that can be damaged by chemistry or through mechanical interaction. Local acidity created by bacterial activity can also damage salt films and drive the conditions away out of the passive condition thus promote anodic activity.

From the manufacturing of chains there will be oxide films on the surface. This may protect against corrosion. However, if such films are damaged locally, pitting corrosion can develop. If the oxides are brittle they can crack during high stress conditions and thus create locations for pitting corrosion.

It should also be noted that if there are small areas with lower oxygen concentration on a steel surface in between areas with higher concentration (oxygen cells) the low oxygen locations will be anodic. The reactions will go in the direction which restores equilibrium for the oxygen distribution. This sort of conditions can develop under uneven biofilms and marine growth. If they persist pitting like corrosion can be a result. Variations in renewal of oxygen due to water flow can also result in a stronger tendency to corrosion in regions where the renewal of oxygenated water is lowest.

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## 4.2 CORROSION VULNERABILITY FOR MOORING SYSTEM COMPONENTS

### 4.2.1 The Sea Water Environment

Typical composition of seawater is presented in Table [Ref 7].

Table 4-1 - Typical Composition of Sea Water in Open Sea. From [Ref 7]

Chemical Ion	Valence	Concentration ppm, mg/kg	Part of Salinity %	Molecular Weight	mmol/kg
Chloride Cl	-1	19345	55.03	35.5	546
Sodium Na	1	10752	30.59	23.0	468
Sulfate SO <sub>4</sub>	-2	2701	7.68	96.1	28.1
Magnesium Mg	2	1295	3.68	24.3	53.3
Calcium Ca	2	416	1.18	40.1	10.4
Potassium K	1	390	1.11	39.1	9.97
Bicarbonate CO <sub>3</sub>	-1	145	0.41	61.0	2.34
Bromide Br	-1	66	0.19	79.9	0.83
Borate BO <sub>3</sub>	-3	27	0.08	58.8	0.46
Strontium Sr	2	13	0.04	87.6	0.091
Fluoride F	-1	1	0.003	19.0	0.068

The composition of sea water adds up to a salinity of 3.5%. The salinity varies between regions depending on inflow of fresh water and evaporation. Salinity vary between 3.2% and 3.8% in relevant areas while the relative concentration of the different chemical ions stay more or less the same.

Oxygen is an important constituent in seawater with respect to corrosion. In the ocean surface the dissolved oxygen is around 7ppm by weight at 25°C. This represents the equilibrium solution of oxygen for the partial pressure of oxygen in air. The solution of oxygen in seawater is proportional to the partial pressure of oxygen in the atmosphere and depends on the salinity and temperature. The solubility goes down with increasing temperature and increasing salinity. At 5°C the solubility of oxygen is 45% higher than at 25°C.

It is important to note that the concentration of oxygen starts to drop with depth below typically 50-75m and at 800m it will typically have dropped to less than 20% of the concentration at the surface. It stays at that level at deeper depths. There will, however, be large differences from region to region on how the oxygen concentration varies with depth.

The pH of seawater ranges from 7.9 to 8.2 for relevant regions.

The biology of seawater is another property and feature that is important for corrosion. This will vary between regions and be influenced by temperature. Biological activities are responsible for the variation of oxygen concentration with water depth.

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Properties of sea water which influence corrosion are as follows:

- Oxygen concentration is critical to the corrosion process as it takes part in the principal cathodic reaction.
- The salinity determines the electrical conductivity of the sea water.
- Chlorides can react with and damage passivating oxide films and thus promote pitting corrosion and also promote general corrosion.
- The pH is important for the corrosion processes and the value around 8 is partly responsible for the fairly limiting corrosion rate of steel in seawater.
- The temperature can influence the corrosion quite strongly since temperature determines the activity level. There are reports of tests where the corrosion rate increased by a factor of 1.5 to 2 for a temperature increase of 10°C in the temperature regions of interest.
- Calcium ions will react with bicarbonate and precipitate as calcium carbonate and to varying degrees establish salt deposits/films on the steel surface if the pH increases above the prevailing level. The pH is known to increase close to a steel surface as a result of the cathodic oxygen reaction. In a similar way Magnesium Hydroxide may precipitate if the pH goes above defined levels. These salt deposits (calcareous deposits) are believed to strongly limit corrosion rates.
- The flow of water induced by current and wave action can influence corrosion in different ways. The availability of oxygen on a steel surface will be enhanced by the flow of water. High speed water flow can damage biofilms, marine growth and corrosion deposits thus influence the corrosion mechanisms.
- Biofilms, bacteria and marine growth resulting from the seawater environment can influence corrosion of steel significantly. The availability of oxygen can be modified and some bacteria can modify the local environment in such away as to induce excessive corrosion.

#### **4.2.2 Corrosion Mechanisms and Material Properties**

Corrosion of low alloy steel, as used in mooring components, can be divided into the following categories:

- Oxygen driven corrosion of homogeneous steel surfaces
- Galvanic corrosion caused by different galvanic potentials of steel materials (Oxygen reduction will be the dominant cathodic reaction)
- Microbiologically Influenced Corrosion (MIC). There are several candidate mechanisms but corrosion induced by Sulphate Reducing Bacteria (SRB) is believed to represent the most serious threat.
- Stray current is a possible corrosion mechanism that could be a result of faulty electrical equipment (or connection) or possibly from unfortunate designs of impressed current protection systems on a floating production system.

Inherent corrosion vulnerability of relevant steels is to a large degree depending on the homogeneity of the material. This would mean fine structure for grains and inclusions and homogeneous chemical composition and phase structure. On a surface with a high degree of homogeneity there will be short distances between anodic and cathodic sites and their locations are less likely to persist in the same spot. Precipitation of oxides and salts will be homogeneous thus ensuring a more even protection.

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Assuming good homogeneity theory and practical experience indicate that there are no noticeable differences in the inherent corrosion properties over the variability of chemical composition that can be typically be found in steels relevant for mooring systems.

The requirement to achieve adequate homogeneity is that the material itself and the components are manufactured and heat-treated according to appropriate and well defined procedures. Testing and analyses are required to demonstrate that requirements are met. Comprehensive verification of homogeneities would involve measurements of the variations of chemical composition, microstructure, crystal structure and inclusions. Grain size distribution is considered as a key microstructure property for controlling the quality and homogeneity. The analysis should be done according to ASTM E 112 standard quantifying the numbers and area distribution of grains on a polished surface under a metallurgical microscope.

Differences in structure and other compositional inhomogeneities will enhance the vulnerability to corrosion partly because of even small differences in galvanic potentials.

Attention should also be given to the surface condition of steel components from manufacturing. Oxides can have a profound effect on corrosion. If oxide films are continuous with good adherence they can reduce the corrosion rate. However, Oxides tend to be brittle and can crack easily thus exposing bare steel directly to the environment. The oxides such as Magnetite and Haematite are cathodic compared to steel thus more noble and will therefore promote corrosion if small areas of steel are exposed while large areas are covered by these oxides. Thus oxides can contribute to pitting corrosion. To avoid these effects potentially harmful oxide types should be removed.

#### **4.2.3 Galvanic Corrosion Effects**

Chain links shall in principle consist of uniform and homogeneous steel material including welds. This should ensure that there are no inherent galvanic corrosion effects in terms of the material. However, there are two regions where galvanic effects can come into play:

- The inter-grip area where wear tend to expose fresh steel surfaces
- The welds where conditions during welding can induce changes that are not adequately corrected for through heat treatment

#### **4.2.4 Inter-Grip Area**

Considering the corrosion behaviour of the inter-grip area it is worth noting a couple of relevant effects relating to the effective galvanic potential.

##### The Effects of Biofilms

Measurements have been reported in the literature [Ref 6] on differences in the galvanic potential in seawater conditions with and without biofilms. Some materials are strongly affected with significant increase in galvanic potential with biofilms (0.5V for some stainless steels). For Carbon steels and Low alloy steels there is an increase of around 0.1V in the effective galvanic potential caused by biofilms. This is referred to as enoblement.

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### The Effect of Surface Deposits from the Corrosion Process

Tests have been carried out to measure the change in the galvanic potential for metals where surface deposits are removed continuously to expose bare metal [Ref 6]. From tests in a Sodium Chloride solution it was shown that the galvanic potential dropped by about 0.1V compared to the situation where surface deposits from the corrosion process are allowed to stay. It is also known from other sources that fresh non-corroded steel will be more anodic (lower potential) than corroded steel of the same type. This can be seen when an old component, in say a mooring system, is exchanged with a new one, there will initially be a higher corrosion rate on the new component until corrosion products build up.

The relevance of these effects relate to the inter-grip region between chain links. Wear can expose bare steel surfaces through the removal of corrosion deposits and destruction of biofilms. Thus the effective galvanic potential becomes lower than other parts of the chain link surface. Thus the corrosion will tend to be promoted in these locations enhancing loss of material beyond what would be expected from conditions on other parts of the chain link. The corrosion effect would be expected to be influenced by the long term pattern for the extent of wear. Wear over a larger area may be better than a small wear area since larger anodic area may result in a smaller rate of corrosion per surface area.

#### **4.2.5 Flash Butt Welds on Chain Links**

It is expected that the procedures for flash welding are designed to avoid any changes in the material so as to ensure adequate strength characteristics. The subsequent heat treatment is expected to restore the required structure and homogeneity. However, there are several reports of selective corrosion in welds and heat effected zones (HAZ) on chains. Figure 3.5 shows a corroded weld from a chain link. This comes from a M.Sc. dissertation in 2003 from Pontificia Universidade Catolica do Rio de Janeiro [Ref 8]. The dissertation is in Portuguese with an abstract in English which together with pictures and tables has been the basis for this evaluation.



**Figure 4-6 - Examples of HAZ Corrosion on a Chain Link, from a M.Sc. Dissertation in 2003 from Pontificia Universidade Catolica do Rio de Janeiro [Ref 8]**

The chain is assumed to have been in service for a number of years and the steel grade was ORQ defined by API-2F [Ref 3]. This is different from grades used today but the investigation demonstrates possible effects that may be of relevance for today's chain grades. The corrosion in the HAZ was found on some links but not all. Material samples were taken out of welds & HAZ both with and without corrosion.

The galvanic potentials (using a high impedance voltmeter) for the samples were measured against a standard cell (silver / silver chloride) when submerged in a sea water solution. It was found that material in the corroded HAZs were anodic compared to the surrounding steel, while this was not so for material from non corroded welds. The material was also analysed in terms of structure and chemical composition. The results from the analysis of chemical composition are presented in Table 4-2 below.

**Table 4-2 - Concentration (% by weight) of Alloying Elements of Material from Weld Region Compared to API 2F Requirements. From [Ref 8]**

Source	C	Mo	Ni	Mn	Cr	Si	Al	P	S
Material with corrosion	0.311	<0.007	0.01	1.6	0.035	0.21	<0.010	0.027	0.011
Material without corrosion	0.319	<0.007	0.061	1.5	0.083	0.21	0.018	0.011	0.006
Minimum values from API -2F	0.33	0.08	0.4	1.9	0.25	0.2	0.065	0.04	0.04

Interesting observations from this data are the differences in concentration of Ni and Cr between the material with corrosion and the material without corrosion. It is claimed in the report that particles of an additional structural phase containing Ni and Cr found in the HAZ of the corroded chain was the cause of the anodic behaviour. The additional structural phase was identified through X-ray diffraction suggesting a crystal structure deviating from that found in the bulk of the material. This also resulted in excessive hardness of the material. It was also claimed that the cause was related to inadequate heat treatment after welding.

There have also been suggestions in the literature that flash welding can result in diffusion of certain alloying elements resulting in-homogeneities that may not necessarily be fully restored by heat treatment.

There are also other citations in the literature of selective or galvanic corrosion of material in the heat affected zone (HAZ). The causes have been described as either local phase changes by heat from welding, diffusion of certain alloying element due to temperature gradients or formation of inclusions such as MnS or certain carbides. Adequate heat treatment can restore the microstructure and appropriate welding procedures and the chemical composition should minimise the probability of weld / HAZ corrosion. The weld and HAZ represent a very small area compared to the rest of a chain link thus enhancing the risk of galvanic corrosion if the material ends up galvanic compared to the bulk material. There are reports [Ref 9] indicating that Carbon-manganese steels are more prone to HAZ corrosion relating to additional hardening caused by the welding temperature cycle.

It is possible to test for galvanic corrosion by taking out material samples and measure the galvanic potentials.. The galvanic potential of a sample can be measured against a standard cell such as a silver / silver chloride half cell. This can be used to identify any potential galvanic issues.. A parameter of interest will also be the corrosion exchange current  $i_0$ , which is the rate of loss of metal ions from a sample since this is proportional to the corrosion rate. For a freely corroding metal object there will be charge neutrality since the anodic dissolution is compensated by loss of electrons through the cathodic reaction. The  $i_0$  can, however, be determined by measuring the net electrical current as function of applied electrical potential. Extrapolations of the current for both positive and negative potentials enable estimation of  $i_0$ . The  $i_0$  will depend on the local condition on the and close to

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the surface thus its value measured in laboratory conditions is primary for comparison of materials..

#### 4.2.6 **Material Selection for Contacting Components**

An important factor for galvanic corrosion is the relative areas of noble (cathodic) versus less noble (anodic) materials. The worst configurations for galvanic corrosion are where the area of the anodic material is small compared to the cathodic area. The anodic reaction can become intense in a limited region to match the cathodic reaction over a large area. In general it is **essential to use material of the same quality or more noble alloys for small component such as shackle bolts, nuts, locking pins and smaller bolts**.

Galvanic corrosion can also take place where chains are contacting other components such as on fairleads, hawse pipes etc. The best way to minimise corrosion is to use materials with identical corrosion potentials and polarization curves. One should also make sure that the areas of exposed steel on contacting components should be large compared to the contact area for both components. If one of the contacting components is coated localised damage to the coating may lead to excessive corrosion, especially if the coated component is the most anodic one.

#### 4.2.7 **Microbiological Influences on Corrosion (MIC)**

Microbiologically influenced corrosion is covered in a separate study reported separately within the Mooring Integrity JIP [Ref 10].

It is worth noting that the relatively low corrosion rate for steel in seawater is at least partly due to calcareous deposits and the formation of oxides. Both the formation and maintenance of these protective features rely on a high pH close to the steel surface. If bacterial activity results in local acidification the stability of protective deposits may be threatened. Thus bacterial activity may interfere with natural corrosion protection mechanisms. While on the other hand biofilms contribute to ennoblement thus possibly enhancing corrosion resistance. The reason for bringing attention to these effects and mechanisms is to show that corrosion of steel in the seawater environment is the result of the combination and interaction of a number of mechanisms and environmental features.

#### 4.2.8 **Stray Current Corrosion**

Stray current corrosion normally refers to situations where un-intended electrical current or potentials are induced into a structure or a pipeline. The mechanism is known from onshore buried pipelines where a pipeline happens to be in the path of the return current from electric railway (where the rails are used to return current to the power source). Some of the current will end up in the ground, in particular if a parallel pipeline provides a fairly low resistance path. In the locations where the current leaves the pipeline, corrosion will take place through the loss of metal ions. On ships stray current corrosion can take place if welding is carried out with inappropriate grounding resulting in return current finding a path through the hull and seawater thus causing corrosion in the locations where the current transfer from steel to sea water. Typically one will find damage in locations where coating is missing allowing a low resistance path.

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It is interesting to note that the corrosion pattern associated with stray current corrosion on a copper water pipe (see Figure 4-6) is fairly similar to the normal corrosion pattern seen on mooring chain and shackles, see for example Figure 4-8 and Figure 4-7.



Figure 4-7 Example of stray current corrosion on a copper water pipe (ref. <http://metallurgist.com/html/Definitions/StrayCurrentCorrosion.htm>)



Figure 4-8 - Typical Corrosion Pattern on a chain after a Long Deployment



**Figure 4-9 - Example of the Corrosion Pattern on a Shackle Body After a Long Deployment**

On a FPSO stray current sources could be faults in electrical equipment where grounding arrangements lead to return current going unintentionally through the water. In locations where the current leaves (in the direction from positive to negative polarity) steel surfaces loss of material will take place through dissolution of metal ions.

Stray current corrosion can be induced from faulty equipment and should be avoided through appropriate design and maintenance of equipment. It is not inconceivable that parts of mooring systems can be affected by stray current corrosion, but it will require faulty equipment or unfortunate arrangements of Impressed Current Cathodic Protection (ICCP) systems where the return current goes via a chain. The latter would also require that the section of chain under question is partly isolated electrically from the turret or the floater. The actual arrangements have to be evaluated to identify dangers of stray current corrosion.

Another hypothetical situation could be a mooring chain passing next to some electrical equipment on the sea floor. If there was a fault in isolation and/or the return path for the current back to the floater, the smallest resistance path might be for some of the current to go via parts the chain or steel ropes. Close to the floater the current path may include jumping to the appropriate structure on the floater via a short distance of seawater. Depending on polarity the current could transfer through the release of metal ions to the water thus creating corrosion.

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Another possible cause of stray current corrosion on an FPSO could be a faulty ICCP system where the polarity is reversed. A well functioning ICCP system makes the protected steel adequately negative compared to a reference electrode. This means that the protected steel becomes cathodic and the exchange of electrical charge is via electrons consumed through oxygen reduction on the surface. This protection may reach some way down the mooring chains depending on electrical resistance primarily in metal to metal contact points. The further one moves down the chain the smaller the protection potential due to the resistance. If a fault should develop in the ICCP system the potential could be reversed (and this is known to have happened). Then the intended anode electrode would become cathodic and the protected steel would become anodic and metal ions will start to go into solution creating corrosion. What one would see is the most severe corrosion on bare steel closest to the return electrode and reducing in magnitude further away. To the extent that cathodic protection of a turret can reach down a mooring chain (with a diminishing degree with distance) the same will be true for stray current corrosion. This means that this kind of stray current corrosion on a mooring chain would be associated with probably more severe corrosion on other submerged uncoated steel components.

If stray current corrosion is suspected the first action should be to search for possible faults in electrical systems. Modern ICCP systems should be equipped with monitoring and logging facilities, which should be reviewed to identify any faults, such as regularly tripping out.

#### **4.2.9 Other Corrosion Mechanisms**

Stress corrosion cracking (SCC) is normally associated with highly loaded steel components with tendencies to inter-granular corrosion. The presence of high stresses can accelerate this. There are limited references to SCC on the steel grades used in mooring components.

Hydrogen induced stress cracking (HISC) is normally considered as an issue for very high strength steel – typically with yield strengths above 1000MPa. The conditions creating HISC will require high concentrations of atomic hydrogen that can diffuse into the steel. Hydrogen can be produced on steel surfaces that are cathodically protected with too high a potential resulting in hydrogen generation. Other conditions that can produce increased hydrogen generation is SRB producing H<sub>2</sub>S that partly dissociate to H<sup>+</sup> and HS<sup>-</sup>. Some of the H<sup>+</sup> ions will be reduced to atomic hydrogen.

#### **4.2.10 Protection against Corrosion**

The main methods for protection against corrosion on steel exposed in seawater are:

- Use of anticorrosive coating
- Cathodic protection using:
  - Anodes
  - Anodic surface treatment such as galvanisation
  - Impressed Current Cathodic Protection (ICCP)

Within mooring systems it is normal to integrate protection against corrosion of steel wire ropes through galvanisation of the individual anode wires. Anodes will also normally be installed to protect the end-sockets.

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Anode protection is also used to some extent on individual components such as on mid-water buoyancy arrangements.

ICCP or anodes on the floater may partly protect the upper parts of a mooring chain. The degree of protection will depend on the actual imposed electrical potential for a link. The electrical current flowing for protection has to overcome resistance in its path. Thus the potential will change governed by the electrical resistance and the current flowing. There will be an electrical contact resistance between links as well as some resistance along the links themselves thus the protection potential will effectively drop along the chain out from the floater. There will probably be significant variations in how the upper parts of chain is protected depending on several factors such as:

- Type and location of cathodic protection source
- Electrical contact from the floater to the chain
- Contact area and roughness of surfaces in the chain link inter-grip
- Tension in the mooring system
- Etc.

It is important to note that Cathodic Protection (CP) will not protect components above sea level. The highest vulnerability to corrosion will be in the splash zone where chains can be wetted by seawater regularly while spending most of the time exposed to air while the surface is fully wetted with water. This is relevant to external turrets and spread moored FPSOs.

When galvanised wire ropes connect directly to a section of chain that is not protected it is essential that the wire rope socket is electrically isolated from the chain section. The reason for this is that any bare steel surfaces within reasonable proximity (governed by the electrical resistance) will drain current from the galvanisation on the wire rope. The current will result in dissolution of the anode material that eventually can leave the wire rope unprotected. The same need for electrical isolation is required for other components that are protected with anodes within a mooring rope system.

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## 5 WEAR

### 5.1 PRINCIPLES

#### 5.1.1 General

Whenever two components in contact move in relation to each other, wear is a potential issue. In a mooring system wear can be a problem for the following component interactions:

- In the inter-grip between chain links or chain link and shackles
- The contact area between a shackle bolt and the inside surface of the hole the bolt connects through
- Locations where chains are in contact with hawse pipes / trumpets, fairleads, etc.
- Fairlead bearings (not addressed in this report)
- Turret bearings (not addressed in this report)

Wear will in principle be governed by:

- Properties of the interacting materials and surface properties
- Loads and pattern of relative movement of the contacting surfaces
- Properties and conditions of the environment such as:
  - Lubrication to reduce or prevent wear
  - Corrosive or oxidative influences

Wear is a part of the field of tribology which is the science of interacting surfaces addressing issues relating to the prediction and optimisation of wear and friction according to requirements. Reference is made to: "Practical Method for Calculating Mooring Chain Wear for Floating Offshore Installations, Mooring Integrity Joint Industry Project Phase 2" for further definition and discussions of the topic [Ref 11].

Interaction between sliding metal surfaces, as found in mooring systems, will generally be characterised as adhesive wear and possibly surface fatigue wear. In a reactive environment such as seawater it is also necessary to consider corrosive wear.

Abrasive wear may also have to be considered for a couple of reasons:

- If the steel under consideration include very hard particles such as large carbide inclusions.
- Adhesive wear can result in the formation of hard wear particles that can be trapped between the surfaces and act abrasively.

Wear can be considered to consist of the following phases:

- Primary or early stage or run-in period, where the rate of change can be high.
- Secondary or mid-age process where a steady rate of aging process is maintained. Most of the useful or working life of the component is comprised in this stage.
- Tertiary or old-age stage, where a high rate of aging leads to rapid failure.

Tribology covers a wide area including all types of surface damage, interacting materials and methods to achieve the optimum wear and friction properties. The issues addressed in this report are limited to the interaction of surfaces of steels that are relevant for mooring systems. It is important to be aware that tribology is a very complex field depending on a wide range of parameters. The knowledge and insight developed through testing tend to be valid only for specific objects and conditions. Generalised prediction models tend to include fudge factors that have to be calibrated for specific applications and conditions [Ref 12 and Ref 13].

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### **5.1.2 Influence from Material Surface Properties**

Properties of the materials under consideration represent key factors in the susceptibility to wear. It is worth noticing that considering adhesive wear pure iron will be more susceptible to wear than steel. The reason for this is the relative heterogeneity of steel due to the presence of alloying elements, inclusions and micro structures is believed to limit the number of asperities with strong adhesive interaction.

### **5.1.3 Hardness**

In general wear resistance increases with increasing hardness but there are examples of deviations from this rule. In terms of mooring systems this means that higher grade steel should exhibit better wear resistance than lower grade. The hardness tends to follow the ultimate strength as shown in Figure 3-1. General wear models include the hardness as a proportionality factor for the predicted wear volume.

Examples of deviations from the general rule are:

- A steel with a significant concentration of carbides (such as chrome carbides) can have a significantly higher abrasion power than a steel with low carbide content. Comparing the two, the former will appear wear resistant but can at the same time induce significant wear damage on other materials.
- During oil & gas drilling operations there is a desire to minimise the wear induced by the drill string on the inside of casings. One solution that has been established is to produce a very hard and smooth surface on critical parts of the drill string. The thinking behind this is to reduce adhesive forces and thus reduce the effective friction. Dissimilar materials can have very low adhesive interaction.

### **5.1.4 Roughness**

Roughness is a surface property that will affect wear. Very rough surfaces sliding against each other can lead to excessive wear and eventual seizure. While on the other hand very smooth surfaces can result in stronger adhesive forces, which can lead to significant surface damage. Thus there will probably be optimum surface roughnesses depending on the loads and the environment. It has been reported that most worn surfaces where lubrication is effective, tend to exhibit a favourable random roughness profile with respect to surface interaction (quasi-planar plateaux separated by randomly spaced narrow grooves) [Ref 12].

One would expect that if two different surfaces with different hardnesses are interacting:

- If the hardest material has the highest roughness the wear will be strongly preferential.
- If the hardest material has the lowest roughness there will probably be limited wear on the hardest surface and lower wear on the softest material compared to the previous case.

### **5.1.5 Friction and Minimisation of Wear**

Another property that is very relevant for wear is friction which will be given by the types of interacting materials, their roughnesses, hardnesses and lubrication. The lower the specific friction the less wear damage one would expect to see. The lubrication capability and reactivity of the environment would be expected to play an important role.

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In principle minimisation of wear will be achieved through limitations of adhesive forces, avoidance of abrasive effects and keeping friction low to minimise surface fatigue mechanisms. Contacting surfaces from identical, very pure and homogenous materials with smooth surfaces will generally exhibit the highest adhesive forces.

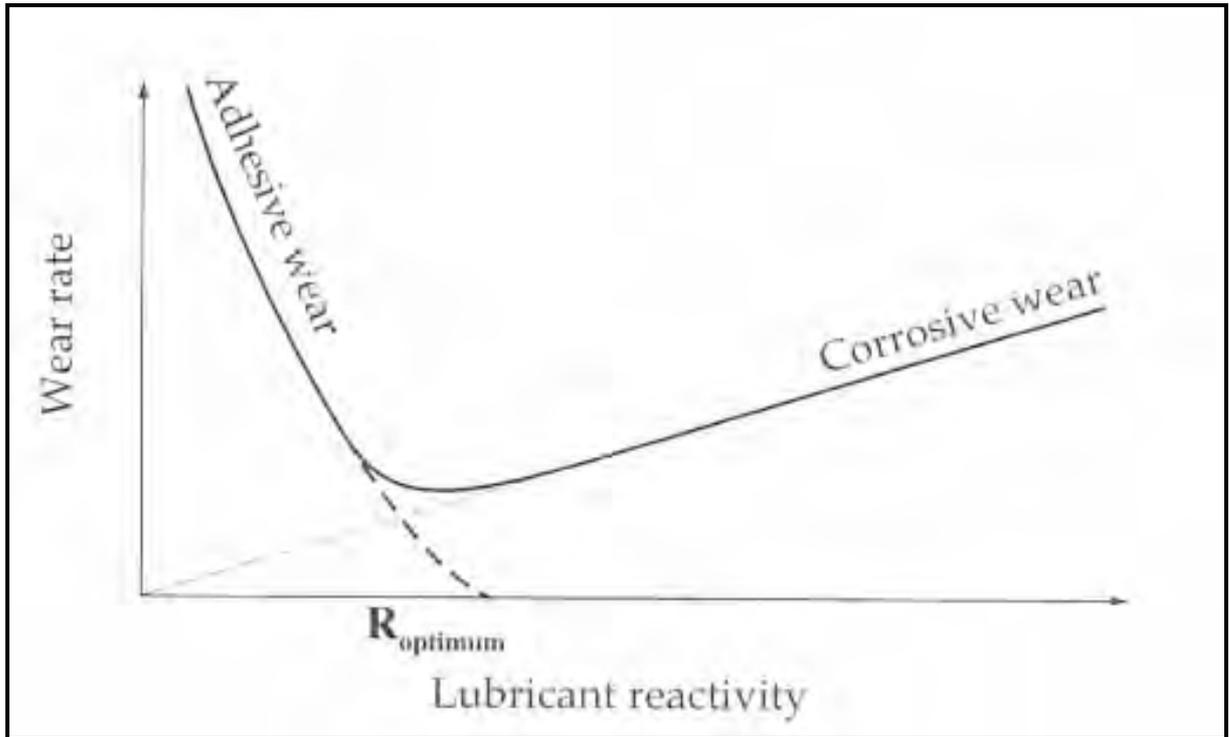
- When components made of identical materials are in contact there will be an optimum roughness that should be sought.
- When the materials are different or can be made different, it is beneficial to ensure an enhanced hardness on one of the contacting surfaces. It is essential that the hardest surface is as smooth as possible. The other surface should be rougher. This will achieve lower adhesion due to differences in materials and that the asperities of the hard material are much smaller than the softer material thus creating less damage.

### **5.1.6 Effects of the Sea Water Environment**

Properties of the environment and how it reacts with wear surfaces can have a strong influence on wear performance. Lubrication is an important element in tribology and will in many applications enable a reduction of wear to virtually zero. Water is unfortunately not a particularly effective lubricant and in addition seawater reacts with the steel surfaces.

When we consider two steel surfaces sliding against each other one can foresee a number of scenarios:

- The deposits are removed from the surfaces exposing bare steel to the seawater thus increasing the corrosion rate. Thus there will be metal to metal wear combined with an increased corrosion rate.
- If the deposits are removed from the steel surfaces then:
  - The removed particles can be trapped if there is a close fit between the surfaces. These particles would be expected to affect the wear process probably by enhancing the wear.
  - The removed particles are allowed to escape due to limited contact regions and the magnitude of the relative motion. This will leave a cleaner condition with adhesive wear and increased corrosion rate.
- The surface deposits remain intact while surfaces slide against each other. This can contribute to limit the wear and with limited excessive corrosion.
- The deposits are only locally damaged or partially removed leading to the localised corrosion that can result in pitting.



**Figure 5-1 Schematic Presentation of how Adhesive Wear can vary with the Reactivity (say corrosiveness) of the Lubricant. From [Ref 12]**

Figure 5-1 a diagram from reference [Ref 12] shows schematically how the wear rate for adhesive wear can vary with the reactivity (say corrosiveness) of the lubricant. The following is a statement from the reference:

*“The transition between sufficient corrosion to generate protective films and adhesive wear is present in most systems. The transition is dependent on load since as the load is increased, more asperities from opposing surfaces make contact at any given moment so that the average time between successive contacts for any single asperity is reduced”*

One would also expect that the relative sliding speed of contacting surfaces will affect the conditions for minimum wear.

No reported investigations have been found to document effects of salt and oxide deposits on the wear resistance for steel in seawater. In mooring systems there will be a wide range of contact pressures, areas of contact and movement pattern so it is quite possible that the corrosiveness of the seawater in some cases can be beneficial while in other cases or locations it can be damaging. This should form a part of investigation to determine and quantify the parameters affecting wear of low alloy steel in contact with each other in seawater.

It may also be worth asking whether biological material also can influence the wear properties of steel in seawater. A good lubrication should normally have a good affinity to the surfaces it protects and it is a question whether biological material will exhibit these properties for relevant conditions.

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### 5.1.7 The Complexities of Wear

A. Borruto et al. [Ref 14] report in their paper wear testing, in air, of a low alloy steel with two different hardnesses (Vickers 385 and 285) obtained through different heat treatments as well as different roughnesses. They also compared 3 different cleaning solvents applied every time they measured weight loss. These solvents are commonly used in tribology tests. Comparisons were made between “soft” against “soft” surfaces and hard against hard surfaces. The results show that in general there is lowest wear with the hardest material. However, for the most volatile cleaning solvent the drop in wear was in the order of 10% for the lowest roughness while the drop was 60% for the highest roughness. While for the 2 other solvents the corresponding reduction in wear were 20% and 17%. Comparing the effects of initial roughness on the hardest material showed that with the most volatile fluid the wear increased by 100% when going from the highest to the lowest roughness. While for the tests using the two other solvents gave a reduction of 20% when going from the highest to the lowest roughness. On the material with the lowest hardness there was a small reduction in wear (10% or less) in going from high to low roughness. The authors have retrospectively a range of plausible explanations for the observed effects covering lubrication of remaining solvents, differences in strain hardening and transition from adhesive to partly abrasive wear.

The reason for including this description is to illustrate the complexities and unpredictability for the wear processes even in very clean and well defined test arrangements. The wear in connection with mooring system will include different relative contact motions and will be affected by a range of different parameters. So the lesson to take is to be cautious in defining guidelines for material selection relating to wear without carrying out specific testing.

## 5.2 DISCUSSIONS OF WEAR IN MOORING SYSTEM COMPONENTS

### 5.2.1 Link to Link or Link to Shackle Inter-grip

Link to link and link to shackle inter-grip normally represent the largest surface areas exposed to wear on a mooring system. The components are made from low alloy steel specified according to the required grade and it is expected that the surface hardness reflects the ultimate strength of the steel. The composition of the steel is defined by the manufacturer under the requirements defined by the chosen standard. Heat treatment should lead to a fine grain structure.

Proof loading will result in some plastic deformation in the inter-grip area, such as the so called “Witness Mark” (see Figure 5-2) which can sometimes be seen on chain. This can result in further hardening of the material (strain hardening).



**Figure 5-2 - Example of a Fairly Pronounced Witness Mark Showing the Chain Has Been Tensioned**

The surface roughness is to a large extent defined by the properties of the steel bar and the forming process. The optimum roughness with respect to minimisation of wear will depend on the contact pressure and will probably be influenced by the seawater.

The interaction of chain links in the inter-grip zone is defined in [Ref 11] and consists of a combination of rolling and sliding events.

The contact pressures and rolling and sliding distances will vary significantly and will change with the degree of wear. Through the summer season there will be calm periods with very limited interaction, while during high sea states the relative motion will be significantly larger.

Wear will be strongly influenced by corrosion, since the interaction is expected to influence and possibly remove salt and oxide deposits. Thus the wear process may result in a higher loss of material than wear and corrosion would add up to independently. It is also possible that corrosion and salt deposits can reduce wear under certain load and relative motion patterns.

If it turns out that a generalised wear model is not able to adequately predict material loss through wear it may be worth initiating a test program to quantify the effects of the combination of corrosion and wear over a range of relevant conditions. This should result in procedures that could enable operators to predict chain wear more precisely as function of design and operating conditions.

If it is possible to influence the roughness in the inter-grip zone it may be valuable to investigate the optimum roughness for wear for typical operating conditions.

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Within this study there have been no investigation into the possible application of friction reducing substances on chain links. For surface treatment to be effective there has to be adequate affinity to the steel surface to sustain the conditions. Experience to date, although limited, is that special hardened coatings tend to eventually peel off. More feedback from the mooring community on this issue.

### **5.2.2 Bolt to Inside of Bolt-Hole**

The contact between shackle bolts and the inside of the load transferring bolt hole represents normally a close fit with a relatively large contact area. The purpose of such connections is to transfer load and allow rotation with a low friction to minimise wear. If wear can lead to too much loss of material the design and material selection should ensure preferential wear on the component that can be replaced most easily. Normally this would mean the bolt.

The bolt will normally be the component that can most easily be modified in terms of material hardness and roughness. Rather than reducing the hardness on one component it might be better to increase it compared to the nominal values if contacting surfaces have similar hardnesses. Thus it would make sense to ensure enhanced hardness of the bolt surface combined with a high degree of smoothness. To minimise friction it may be worth considering using a different material with low adhesive interaction with steel. Such solutions will not ensure preferential wear but may ensure the best overall wear resistance.

The hardness of the bolt surface can be achieved through:

- Heat treatment
- Surface modification through introduction of alloying elements in the surface
- Deposition of a hard material on the surface such as Wolfram Carbide or ceramics. (Wolfram Carbide was deposited on contacting parts of drill string components to reduce friction and wear on the casing during drilling)
- Use a different steel material in the bolt that can be surface hardened

Designers should seek information from manufacturers supplying low friction bearings for use in sea water.

One could also consider the deposition of a softer material on the bolt surface as for instance a suitable Copper alloy. This can also result in low adhesive forces and reduced friction. It is, however, essential to ensure that galvanic or other corrosion issues are avoided. This should be verified through testing.

For the conditions on mooring systems it has not been possible to identify directly relevant existing industry experience that can provide direct guidelines for the material selection and material treatment. To solve wear issues for other applications than mooring systems it has been necessary to develop solutions through specific testing.

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Generalised statements in textbooks suggest that to ensure preferential wear the hardness should differ by 30-50%. This will depend on the material under question and there are no well-defined general rules. However, it is worth noting that the difference in hardness between R4 and R5 is around 10% while R3 has a hardness that is proximately 23% lower than R5 grade, see Figure 3-1. This suggests that the hardness differences required for preferential wear cannot be achieved by a suitable combination of standard grades for mooring chains. If better solutions to reduce wear for mooring system components are required for long term deployments, we believe that it is necessary to carry out a testing and optimisation program. This might consist of the following:

- Determine inherent wear properties within the same grade and between grades
- Determine optimum surface roughness as a function of contact pressure
- Investigate the effect of artificial and real seawater (including biology)
- Investigate possible methods to increase the hardness
- Select and test methods to increase hardness and optimise roughness – absolute and relative.

It is important to engage the chain and connector manufacturers as part of this process. Unfortunately this may prove to be difficult to achieve since inevitably there are commercial implications for whoever can develop an improved design of low wear chain, connector or fairlead.

### **5.2.3 Chain to Hawse Pipe/Trumpet**

There are examples of high rates of local loss of material in locations of chain links where they have been in contact with hawse pipes and vice versa. It is possible that at points of contact there may be irregular welds or sharp edges that can create localised high friction. This can cause high wear rates. Possible repeated and irregular removal of surface salt and corrosion deposits may result in exposure of bare metal that will be slightly anodic compared to surfaces that are not affected by wear. Thus synergistic enhancement of loss of material through wear and corrosion may take place.

The first step to limit the risk of excessive loss of material for these interactions is to minimise friction through design that avoid surfaces and edges with high roughness and irregularities. One should ensure well rounded surfaces with an optimum roughness at contact points. The optimum roughness will depend on hardness, types of materials involved and contact pressures.

It may also be worth considering possibilities of using materials with a higher surface hardness in the contact area on the hawse pipe.

To enable optimum long term solutions it may be necessary to investigate, test and develop specific procedures.

- Investigate field cases in terms of selected materials, designs, fabrication, as installed conditions and experience during field operation.
- Define and carry out testing on relevant materials and components under controlled conditions.
- Develop more specific guidelines for relevant components based on physical testing.

Given that wear has been seen in this area on a number of FPSOs, from different turret providers, it is recommended that further investigation and testing should be carried out on this topic.

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## 6 SUMMARY

This JIP sub-report is the result of evaluation of material compatibility and degradation issues for steel parts of mooring systems on permanently moored floating installations. The assessment has focussed on chain and connecting components such as shackle and tri-plates as well as vessel fixed equipments that are in metallic contact with mooring chain. Possible material issues related to steel wire ropes, such as fretting, are not addressed.

### 6.1 MATERIAL PROPERTIES

Steel components in a mooring system are made from low alloy steel with typically less than 5% alloying elements with a minimum yield strengths of 700 MPa and 760 MPa for the R4 and R5 grades respectively. The primary requirements for the different grades are defined in terms of mechanical properties and toughness.

Relevant industry standards for mooring chains specify requirements for acceptable types of heat treatments and grain size. Certain alloying elements such as Molybdenum should exceed defined minimum values. Apart from this the chemical composition should be agreed between manufacturer and purchaser.

The main material compatibility and degradation issues considered are corrosion and wear. The susceptibility to fatigue is not considered, but it is essential to be aware that excessive corrosion or wear can lead to the initiation of fatigue cracks under cyclic loading.

The corrosion and wear properties will be influenced by the chemical composition, microstructure, hardness and surface condition in terms of roughness and oxides. For the relevant steel qualities hardness tend to be proportional to the strength of the steel. The hardness of the R4 grade has a Vicker's hardness around 275 while the equivalent for R5 is around 305.

### 6.2 CORROSION

Low alloy steels exposed to seawater environment will corrode through dissolution (oxidation) of iron as the anodic reaction and reduction of oxygen as the cathodic reaction. Models predict general corrosion where anodic and cathodic sites move around on the surface while in reality there will be a combination of general and pitting corrosion. A high degree of homogeneity of the steel (on the surface) will be the best inherent material property to minimise corrosion. However, conditions on the surface and close to the surface will strongly influence the corrosion behaviour. Availability of oxygen (enhanced by flowing water) and temperature are important factors. It has been reported in the literature that a 10 degrees increase in temperature could increase the corrosion rate by a factor between 1.5 and 2.

Formation of calcareous deposits on the steel surface is considered to be one of the strongest features to limit the corrosion rate. Deposits of corrosion products (such a iron hydroxides) will also contribute to limiting corrosion rates. Bare steel surfaces are more anodic (more prone to corrosion) than surfaces covered with deposits and bio-films. Thus damages to surface deposits can lead to enhanced corrosion and possibly tendencies to pitting corrosion.

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Relative motion of contacting steel surfaces in the link to link inter-grip area in chains will lead to damage of surface deposits and exposure of bare steel surfaces. This will make the inter-grip areas more vulnerable to corrosion and the same also apply in similar ways to other contact areas with relative motion. The location where the chain is in contact with the hawse pipe is an example.

There are reported cases of excessive corrosion in the weld region (HAZ) on chain links. One reported investigation has demonstrated that the likely cause was related to the formation of a structural (micro-structural) steel phase that was more anodic than the base material. This may have been caused by inadequate heat treatment resulting in significant in-homogeneities in the steel. This points to the importance of ensuring good material homogeneity.

Galvanic corrosion can take place when materials with different galvanic potentials are electrically connected. Low alloy steels with similar composition and microstructure will exhibit similar galvanic potentials in the same environment ensuring that galvanic corrosion is unlikely. If there is a need to combine components with different galvanic potentials it is important that the smallest component is made from a more noble material. If the smallest component is less noble excessive corrosion can take place on the smallest component.

Non-intentional electrical current that pass through parts of a mooring line may causes stray current corrosion. Sources of current could be faulty electrical equipment or impressed current cathodic protection systems with poor design. In locations where the electrical currents leave a steel component excessive dissolution of metal ions will take place. Stray current corrosion should be avoided through appropriate design and adequate maintenance.

Cathodic protection is normally not implemented on mooring chains and connecting components. However cathodic protection systems on the floater will reach some way down the chain. The reach will depend on the electrical resistance between chain links and the level of protection will go down with distance from where the chain is electrically connected to the floater. It has been estimated that CP will loose any noticeable effect 20 – 40 links out from the floater the chain is connected to.

It is important to note that wire ropes that are protected through galvanisation should be electrically isolated from steel components they are connected to. This is to avoid that the galvanisation is consumed through cathodic protection of other steel components rather than protect the wire rope itself. This principle of electrical isolation must also be applied for components that are protected with attached anodes to avoid non-intentional anode consumption.

### **6.3 WEAR**

Mooring system components are susceptible to wear on contacting surfaces such as the inter grip between chain links, shackle bolt and at locations where chains are in contact with hawse pipes and fairleads. The degree of wear will depend on properties of the surfaces such as roughness and hardness, the environment, contact forces and the movement pattern.

The corrosive nature of seawater may lead to synergistic wear rates that are higher than the sum of wear and corrosion as independent processes. Wear can remove protective deposits enhancing the rate of corrosion and corrosion may increase surface roughness. There will be significant variability due to variations in contact forces, movement patterns and environmental conditions.

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The first and simplest step to minimise wear is to reduce friction by ensuring that contacting surfaces are reasonably smooth without any sharp edges or proud weld deposits in contact locations.

Another solution to reduce wear is to increase the hardness on one of the contacting surfaces (for instance in shackle bolts). The increase should be significant (minimum 30%) and the hardest surface should have the lowest roughness. The differences in hardnesses for standard steel grades for mooring system components are too small to achieve the required hardness differences. Special surface treatments or deposits should be considered such as Wolfram Carbide or ceramics but it is important that they do not peel off. The use of a different material than steel on the harder surface will also reduce the adhesive wear.

## **6.4 DEVELOPMENT NEEDS**

To enhance the design optimisation and service life prediction capabilities related to corrosion and wear of mooring components a range of experimental type investigations should be carried out. These should cover:

- The influence from surface conditions on the corrosion properties of chain links.
- Measure the variation in corrosion properties of materials from different batches and different manufacturers.
- Establish standardised methods for measuring galvanic properties of material samples taken from different location on chain links or other relevant components.
- Characterisation of combined wear and corrosion properties for a range of relevant configurations and conditions.
- Possible effects from stray current
- Solutions for cathodic protection
- Enhanced material selection and preparation to minimise wear.

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# The effect of wear and corrosion of steel components on the integrity of mooring systems for floating offshore installations

## Mooring Integrity Joint Industry Project Phase 2

Mooring integrity for floating offshore installations is an important safety issue for the offshore oil and gas industry. This report is one outcome from Phase 2 of the Joint Industry Project on Mooring Integrity. This work ran from 2008 to 2012 and had 35 industry participants. It followed the Phase 1 work described in HSE Research Report RR444 (2006). The Phase 2 work compiled research on good practice and an overview is given in HSE Research Report RR1090 (2017).

This report considers how the wear and corrosion of steel components in offshore mooring is affected by material properties, design and operation. The report focusses on chains and connecting components such as shackles, as well as considering components that mooring lines are in contact with, such as fairleads. The report identifies the main material properties of interest: hardness; surface properties; chemical composition; micro-structure and inclusions. It describes requirements in standards for specifications for materials. Corrosion aspects covered are: mechanisms and reactions; vulnerability of components; methods for protection of steel exposed in seawater. Wear aspects covered are: principles; the influence of material properties, friction and the seawater environment; considerations for different components. It identifies synergistic effects of wear and corrosion in the seawater environment that may result in higher wear rates.

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