# Hydrogen assisted cracking of jack-up installations

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# Document overview

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**Abstract:**

This study is based on available literature and practical service experiences with cracking in the lower leg and spudcan areas in jack-up offshore structures as response to increasing interest in causes, effects and prevention of hydrogen related cracking in high strength steel weldments. The aim is to map the causes, mechanisms and extent of hydrogen-induced cracks in high strength steels used in jack-up installations.

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# 1 Summary

Hydrogen cracks in jack-up rigs were first observed in the UK sector in 1988. The hydrogen-induced cracks were discovered in the welds between spudcans and chords, and also between chord and braces. Installations in the Norwegian sector have apparently (until quite recently) not suffered this kind of cracking. In 2022, Ptil was noticed of relatively long cracks observed in the legs on a jack-up. The cracks were located in the welds connecting the spudcan to the chords and were determined to be hydrogen cracks.

Common reasons for the failures observed in the 1980s and again in the more recently experienced cracking are attributable to combinations of fabrication related flaws and cracks which have progressed in subsequent service under influence of weld residual stresses and service loads and ingress of hydrogen into the steel due to cathodic protection. In this document the fabrication-related and service-related cracking are referred to as hydrogen assisted cold cracking (HACC) and Hydrogen induced stress cracking (HISC.)

The essential difference from then to now is that crack initiations in the 1980s were mainly in the base metal heat affected zone in contrast to present-day crack initiations which are more often in the weld metal. If good weld quality is not achieved during fabrication and if in-service hydrogen charging is not considered in design and in selection of materials, the risk of in-service cracking can increase and limit the integrity of the installation. By following the major classification rules, guidance notes and recommendations applicable to offshore jack-up installations to the letter it is possible to use high strength steels grades in the range 500 to 690 MPa (SMYS) without problems with cracking due to HACC and HISC in the lower leg and spudcan areas. The overall experience is that the underlying and decisive causes are more related to deficiencies in implementation of effective QA-QC routines during fabrication, rather than deficiencies in either the steel material, the welding consumables, the structural design or the environmental loads. It is further emphasised that none of the examined jack-up structures have experienced fast propagating brittle cracks or been close to a collapse. Nevertheless, if cracks are detected, it is essential to perform a redundancy analysis to ensure structural integrity until permanent mitigation by repair/re-strengthening/re-welding can be performed.

This study is based on available literature and up-to-date practical service experiences with cracking in the lower leg and spudcan areas in jack-up offshore structures as response to increasing interest expressed by Ptil.

The interrelation and sequential development of the observed cracks is described as follows:

1. The welding process provides a susceptible microstructure and residual stress thereby enabling micro fissuring and initiation of cracking by HACC due to hydrogen uptake during welding.
2. Hydrogen charging through bare steel surfaces due to in-service cathodic protection triggers further crack growth of preexisting cracks by HISC.
3. Structural stresses composed of weld residual stresses and environmental loads (wave, wind, sea current and gravity) drives the crack growth apace due to stress concentration around cracks effects. The effect may fade away as/if the crack grows out of the load zone or away from susceptible microstructures.

The main conclusions to be derived from the study are:

- Although cathodic protection contributed to cracking, the root cause is usually linked to the presence of undetected fabrication defects.
- Coating can prevent bulk hydrogen charging of the steel thereby reduce the damaging effect of hydrogen from cathodic protection.
- Laboratory tests show that 690 MPa structural steels can retain integrity under hydrogen charging.
- The 690 MPa structural steels can be used in critical parts only if good weld quality and detection of defects can be verified.
- NDT is essential in the fabrication phase. Current in-service UWILD inspections may not detect all indications.
- It will be reasonable to assume that offshore wind turbine installation vessels will encounter similar hydrogen assisted/induced cracking phenomena.

The above statements are applicable to all jack-up rigs as well as fixed structures in marine environment.

## 1.1 Abbreviations

| | |
|---|---|
| $\sigma$ | Stress |
| A | Crack length |
| Ag/AgCl | Reference electrode based on Silver/Silver chloride |
| AIDE | Adsorption-induced dislocation emission |
| CCT | Continuous cooling transformation |
| CE | Carbon equivalent |
| CP | Cathodic protection |
| CTOD | crack tip opening displacement |
| EH | Equilibrium potential for reduction of hydrogen |
| ET | Eddy current testing |
| GSHC | Galvanically induced stress corrosion |
| HACC | Hydrogen assisted (weld) cold cracking |
| HAFCG | Hydrogen accelerated fatigue crack growth |
| HAZ | heat affected zone |
| HB | Hydrogen blistering |
| HE | Hydrogen embrittlement |
| HEDE | Hydrogen-enhanced de-cohesion |
| HELP | Hydrogen-enhanced localized plasticity |
| HESIV | Hydrogen-enhanced strain-induced vacancy |
| HIC | Hydrogen induced cracking |
| HICC | Hydrogen-induced cold cracking |
| HISC | Hydrogen induced stress cracking |
| HSC | Hydrogen stress cracking |
| HSS | High Strength Steel |
| HV | Hardness Vickers |
| I | Current |
| ICCP | Impressed current cathodic protection |
| IR | Potential |
| K | stress intensity factor |
| $K_I$ | stress intensity factor (mode I, crack opening) |

| | |
|---|---|
| $K_{IC}$ | Critical stress intensity factor |
| $K_{SCC}$ | Stress intensity threshold factor for subcritical cracking |
| $K_{TH}$ | Stress intensity threshold factor |
| LEFM | Linear elastic fracture mechanics |
| PT | Penetrant testing |
| MT | Magnetic particle testing |
| MWL | Mean water level |
| N | Number of load cycles |
| NFE | Non-destructive examination |
| NDT | Non-destructive testing |
| PMI | Positive material identification |
| PSA | Petroleum Safety Authority |
| Ptil | Petroleumstilsynet (PSA in English) |
| PWHT | Post weld heat treatment |
| QA | Quality Assurance |
| QC | Quality Control |
| QT | Quenched and tempered |
| R | Resistance |
| $R_e$ | Yield stress |
| RA | Reduction of area |
| SCC | Stress corrosion cracking |
| SCE | Saturated calomel electrode |
| SEM | Scanning electron microscope |
| SHE | Standard hydrogen electrode |
| SOHIC | Stress-oriented hydrogen induced cracking |
| SMYS | Specified minimum yield strength |
| SSC | Sulphide stress cracking |
| SRB | Sulphate reducing bacteria |
| SSRT | Slow strain rate testing |
| SWC | Stepwise cracking |
| SZC | Soft zone cracking |

| | |
|---|---|
| t | Time |
| UT | Ultrasonic testing |
| UTS | Ultimate tensile strength |
| UWILD | Underwater inspection in lieu of dry-docking |
| VI | Visual inspection |
| WM | Weld metal |
| WPS | Welding procedure specification |
| WPQR | Welding procedure qualification records |

# 2 Introduction

## 2.1 Background

Jack-up rigs are a type of mobile platforms that consists of a buoyant hull fitted with a number of movable legs, capable of raising its hull above surface of the sea. The buoyant hull enables transportation of the unit and all attached machinery to a desired location. Once on the location, the hull is raised to the required elevation above the surface of the sea, supported by legs on the seabed. The legs may be designed to penetrate the seabed, fitted with spudcans (footings with enlarged sections) or attached to a bottom mat. Jack-up structures typically utilise high strength low alloy steels (690 MPa specified minimum yield strength) in chord and rack plate in the lower parts of the legs. The combination of high strength steel, welding residual stresses, applied service load and exposure to cathodic protection in seawater may lead to hydrogen assisted cracking as observed in previous incidents with crack development in the lower parts of the retractable leg structures. Hydrogen can affect the microstructural integrity of high strength steel causing cracking or embrittlement of the material. If hydrogen is introduced during welding, then a phenomenon referred to as hydrogen assisted cold cracking (HACC) can occur. The steel may also be exposed to hydrogen from electrochemical processes, such as corrosion or cathodic protection. This can then lead to another embrittling phenomenon referred to as hydrogen induced stress cracking (HISC) and if cyclic loads are involved hydrogen accelerated fatigue crack growth (HAFCG) can occur.

During the 1980s and through to 1990s, a series of cracking phenomena were encountered in submerged parts of jack-up rigs, both in the lower high strength steel section of the legs and inside the spudcans [1]. The investigations concluded that the cracking was fabrication related weld cold cracking, subsequently followed by crack growth due to hydrogen assisted cracking (in current terminology HACC and HISC).

Over the years, improvements in steel and weld consumable manufacturing have succeeded in decreasing the susceptibility of welded structures to hydrogen cracking.  By also improving structural design that ensure lower stress levels, it has now become routine to use higher strength steels in offshore structures. However, in a hectic construction phase, sometimes in combination with challenging climatic conditions, it can be difficult to follow the recommendations in every detail and occasional cases of hydrogen related cracking occur from time to time.

## 2.2 Scope of work

The aim is to describe the causes, mechanisms and extent of hydrogen-induced cracks in high strength steels used in jack-up installations. The study is based on a literature review and lessons learnt from past events. The intended outcomes are to provide a better understanding of (a) the mechanisms of hydrogen cracking (b) the extent of such cracks, as well as (c) the measures that can be applied to avoid the problem.

The sources utilised in conducting the work will be:

- Available literature and previous studies on jack-up rig incidents
- FORCE Technology experience with failure analysis, welding and NDT through the past 40 years
- Replies to Ptil notification sent to rig owners of an incident with request to inspect relevant positions of their jack-up rigs in service

The current report presents the results from the work conducted from June until the end of 2023 by key personnel from FORCE Technology Norway and Denmark. The main contributors are Marianne Videm, Ditte Bilgrav Bangsgaard, Rian Holdstock, Jeppe Havstrup, Harry Otteskov and Mads Holm.

## 2.3 Objectives

The objective of the study is to supply answers to the following:

- Evaluate the conditions contributing to hydrogen cracking, initiation and growth
- Assess the magnitude of the factors and their mutual influence on the susceptibility to hydrogen cracks, including the importance of residual stresses and material properties
- Evaluate sources of hydrogen
- Define the mechanisms for hydrogen cracking, in particular the influence on mechanisms relevant for jack-up installations
- Determine if hydrogen cracking is only a problem in high-strength steel
- Establish measures to prevent hydrogen cracking, such as limitations for cathodic protection (CP)
- Describe the causes and magnitude of tensile stresses that can cause hydrogen cracking

To meet these objectives, the work has been organised in the following subtasks:

- Existing knowledge
- Hydrogen failure mechanisms
- Hydrogen sources
- Material interactions
- Fracture and crack growth
- Design, fabrication and operation
- Detection and testing
- Industry experience

## 2.4 Limitations and assumptions

The first limitation is that the work will focus on jack-up legs, and hence leaves out materials and structures that are located on other parts of the asset. The first assumption is then that the cracking mechanisms will be generic and can therefore be applicable to many other areas and assets, such as offshore wind turbine installation vessels as well as emerging offshore Power-to-X installations.

The second limitation is that industry stakeholders are not fully represented in this work. An extension is proposed in Section 11, to increase industry involvement and dissemination. The second assumption is that the problem of hydrogen cracking has not been eliminated and continuous improvements can still be made.

## 2.5 The jack-up design

Offshore jack-up installations include drilling rigs, accommodation rigs, wind turbine installation vessels typically used in water depths up to 120 meters. They consist of a buoyant hull (or deck) with moveable legs that can be raised or lowered. During operation, the legs of the jack-up platform are lowered to the seabed, and the hull is raised above the water level to provide a stable work environment. The hull carries the work equipment, cranes, workshop, material depot and accommodation facilities. The weight of the platform and the downward pressure from the legs firmly embed the platform into the sea floor, providing additional stability. The legs of a jack-up platform are constructed from high strength steel and are often designed for maximum strength to withstand operational and environmental loads. In some designs, a spudcan at the base of each leg helps to distribute the load over a larger seabed area. When the legs are raised, it can be towed to different locations [2]. Movable jack-up installations are classified as ships as they can be subject to drydock inspection and maintenance. If and when they are used as permanent installations these aspects can be more difficult and costly.

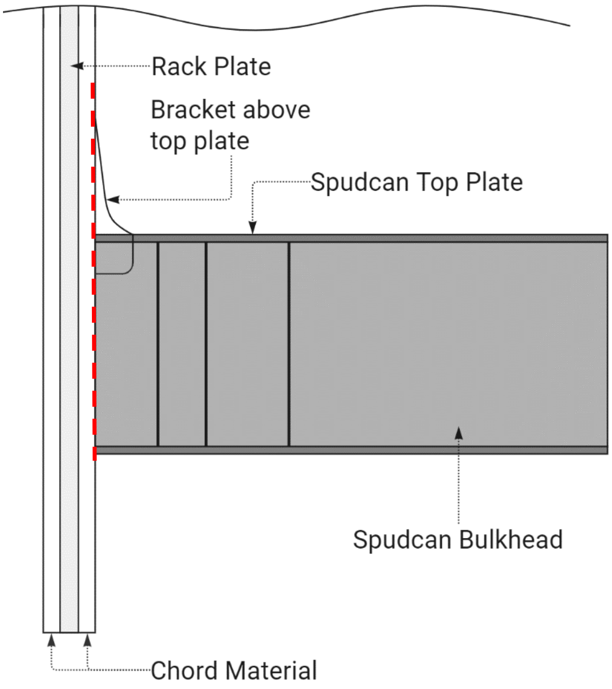


Figure 2-1 Structural details at the spudcan to leg transition. The red line shows positions where cracking has occurred.

The spudcan at the base of each leg provides a function of sliding and bearing resistance to the jack-up rig when deployed into the seabed. Structural details of the leg-to-spudcan position are shown in Figure 2-1 with indication of the knee bracket, chord and rack plate. A cross sectional view of a spudcan leg with the position of the welds between chord material, rack plate and spudcan bulkheads is shown in Figure 2-2. Typical dimensions of the rack plate are thicknesses up to 250 mm whereas the chord, spudcan bulkhead and knee bracket would typically be in thicknesses up to 120 mm, hence resulting in a significant size of the welds. Examples of crack appearance in high strength steel welds are shown in Figure 2-3.

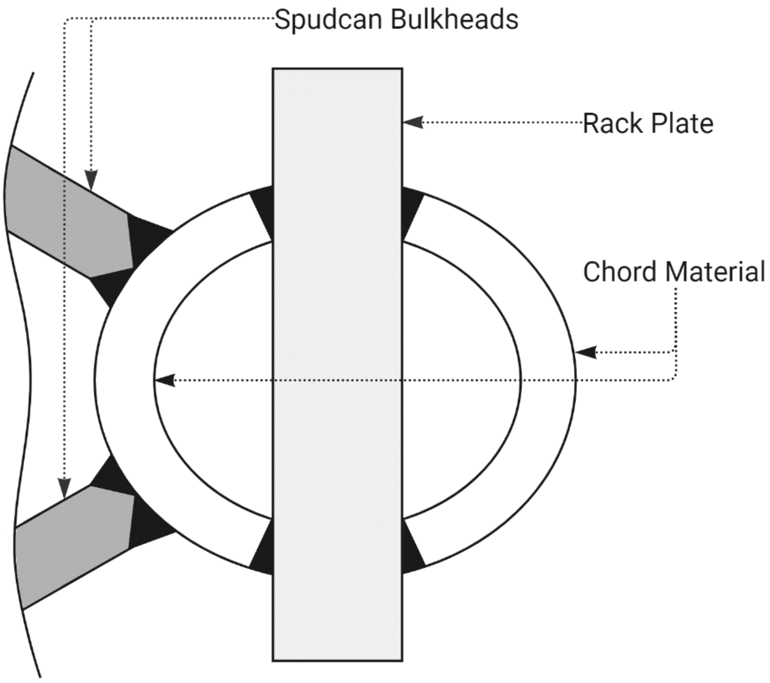


Figure 2-2 Top view through a jack-up leg showing the position of chord, rack and spudcan bulkheads.

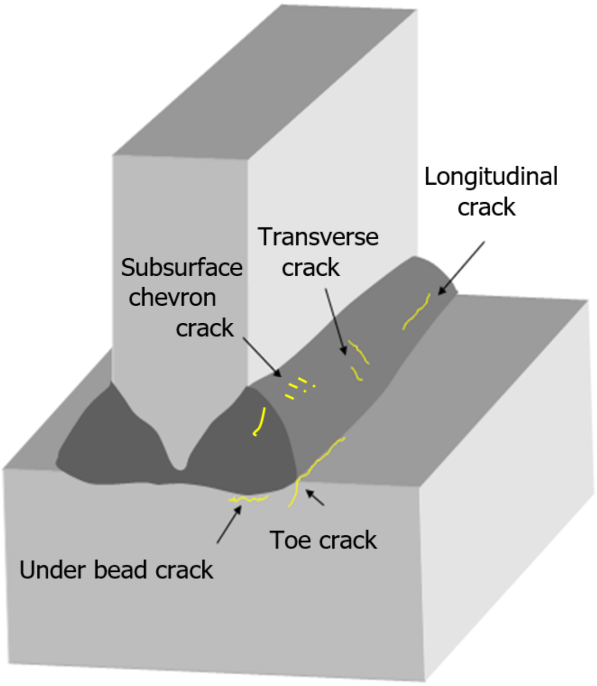


Figure 2-3 Different appearances of hydrogen assisted cracking in high strength steel.

# 3 Aspects of hydrogen cracking

This section summarises the practical aspects and experience related to occurrence and prevention of hydrogen related cracking. Further details on failure mechanisms, hydrogen sources and the influence of stress is given in the subsequent sections.

## 3.1 Overview

Evaluations of hydrogen cracking in jack-up rigs lower leg and spudcan areas identified the general root cause to be related to undetected and/or undocumented fabrication flaws in these areas. During operational conditions under the influence of service loads and cathodic protection, these fabrication flaws developed into surface breaking flaws. The sources of hydrogen are in general believed to be from:

- Welding
- Cathodic protection
- Corrosion

The complexity of the design, fabrication and operational conditions for offshore structures makes it difficult to eliminate the risk of hydrogen cracking completely, but experiences, technological advancements and the classification rules, guidance documents and recommendations generally allows managing the risk more efficiently. In addition to general education on and awareness of hydrogen cracking at all levels in design and production of structures in high strength steel, the main steps in eliminating hydrogen related cracking include:

- Use of steels that have a proven low susceptibility to hydrogen embrittlement
- Use of welding procedures qualified for asset design and operational conditions
- Use of NDT procedure qualified for asset design and operational conditions
- Ensure full traceability of fabrication and maintenance activities
- Use coatings that provide a physical barrier to corrosion and electrochemical reactions

### 3.1.1 Steels with intrinsically low susceptibility to hydrogen embrittlement

First of all, it is recommended to use material with intrinsically low susceptibility to hydrogen embrittlement for critical parts of the structure. Selection of steel grade for the legs and spudcans is a trade-off between strength properties and functional requirements with yield strength, impact toughness and weight being of high priority. To obtain the same capacity in a steel structure with use of lower strength grades, increased dimensions are needed, i.e. increased weight of the structure, but the benefit is that the risk of hydrogen related cracking is eliminated or subdued. Hydrogen embrittlement is of less concern for steel grades with SMYS < 500 MPa, but for SMYS > 500 MPa the increasing susceptibility to hydrogen embrittlement with increasing strength/hardness contributes to increase the risk of hydrogen cracking both during fabrication and during service. It should therefore be considered in the design phase whether lower strength rather than less weight can be prioritised for the critical parts. This will not prevent development of hydrogen assisted cracking as such, but it may reduce the susceptibility to HACC during fabrication and it will prevent the cracks to develop into catastrophically, fast propagating brittle HISC failures of highly stressed structures exposed to hydrogen in service. See Sections 3.7 and 6.1 for further details.

### 3.1.2 QA-QC during fabrication

Secondly, it is essential to define welding and NDT procedures and manage, monitor and document fabrication activities to avoid structures with weld defects leaving the construction yard. Full traceability of the asset is a prerequisite, and the attention must be directed towards:

- Deviations from WPS
- Modifications
- Repairs

The aim of the above is to avoid HACC and weld imperfections during fabrication by use of appropriate weld consumables adapted to the actual steel properties and implementation of optimum welding procedures. Deviation from the specified welding procedure influences the quality and increases the tendency to HACC. Therefore, effective welding supervision is of paramount importance to prevent or counteract deviations due to e.g. upsets in production, adverse weather condition, insufficient weather shielding, carelessness in consumable handling, temporary lack of temperature control, omission (deliberately or incidentally) of pre-heat and post weld heat treatment, whether during welding or in connection with weld repairs or weld corrections etc. NDT methods, procedures and acceptance criteria shall be established and implemented in the fabrication phase to detect defects, that may develop to cracks in service. This is elaborated in Sections 3.8, 6.2 and 10.1.

### 3.1.3 Durable barrier coatings and cathodic protection

Finally, avoidance or minimizing development of HISC is obtained by application of a coatings that stop hydrogen generated from cathodic protection to interact with bare, metallic steel surfaces, i.e. formation of atomic hydrogen and subsequent absorption into the steel. In-service HISC is triggered by hydrogen charging, also termed hydrogenation, of the steel from cathodic protection processes acting on bare, metallic steel surfaces. Hydrogenation is the process during which hydrogen is introduced into the metal. It can be prevented or subdued to acceptable levels by combined use of cathodic protection (at suitable potentials) and use of an impervious, durable coating that forms a barrier that keeps out charged ions and retards the penetration of water. See also Sections 3.10, 9.3 and 9.4.

## 3.2 Brief introduction to hydrogen embrittlement

Hydrogen embrittlement, is described as a loss of ductility in an otherwise ductile material due to joint activity of three variables:

- Absorbed hydrogen in the steel
- Susceptible microstructure
- Tensile stress/straining

The interplay between these three variables is schematically illustrated in Figure 3-1. A fourth variable is time for hydrogen to migrate into critical regions. The interaction of these variables can materialise into crack initiation and growth. The overlapped region can increase or decrease depending on the significance of the individual parameters. A vital remark in relation to the prevention of cracking is that elimination or suppression of one or more of the variables can preclude the embrittling effect. The actual mechanisms behind the destructive effect of hydrogen are still debated among scientists, and more information on hydrogen embrittlement mechanisms is presented in Section 4 and 8. For practical purposes it is sufficient to know that too much hydrogen, being present at too high stresses, and in a susceptible microstructure can result in a loss of structural continuity due to cracks, and in severe cases with large cracks loss of redundancy and hence loss of structural integrity.

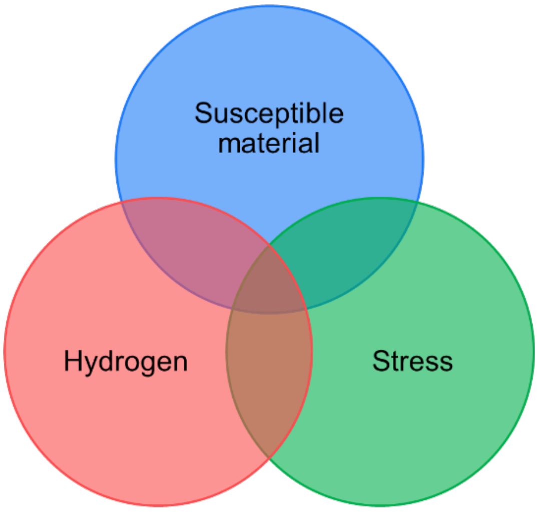


Figure 3-1- Factors involved in hydrogen embrittlement.

## 3.3 Experiences

In the 1980s through 1990s the jack-up industry experienced a series of high strength steel cracking phenomena in submerged parts of jack-up rigs lower leg and spudcan steel structures. Problems were encountered both inside the spudcan and along external welds joining the spudcan to the leg chords [2]. Investigations funded by HSE [3] and major classification societies [1] concluded that the cracking problems were related to imperfections and hydrogen cracking occurring in connection with welding. Cracks may have grown during service due to hydrogen absorption from cathodic protection, but there was a general lack of metallographic and fractographic examinations and supporting data from actual potential surveys to confirm this relationship. The main conclusion was, however, that good service could be expected once a sound weld was achieved during fabrication.

Remedial action consisted of local repair welding and there were no cases of sudden brittle crack propagation or catastrophically failures once the repairs were done. The inside spudcan issue comprised the effect of putrefied, anoxic seawater with sulphate reducing bacteria, cathodic protection at low potentials. Mitigation schemes specifying regular flushing with fresh seawater, addition of corrosion inhibitors, use of diode-controlled anodes to avoid low potentials and internal coating. The most successful mitigation strategi has proven to be removal of internal anodes and application of high-quality epoxy coating, as used on the outside of the spudcan.

Examinations of cracks detected in the period from early 2000 to 2023 on the bottom parts of the retractable legs of offshore jack-up installations operating in the North Sea and in the Middle East confirm that hydrogen was involved in the damage process. However, the underlying and decisive causes is mostly related to deficiencies in the implementation of effective QA-QC routines during fabrication, rather than deficiencies in either the steel, the welding consumables, the structural design or the environmental loads. In terms of the severity of the hydrogen cracks, there was no evidence of catastrophically, fast propagating brittle failure or fatigue crack growth in the examined cases.

Figure 3-2 to Figure 3-4 show the typical appearance of hydrogen induced cold cracks in weld metal. On a macroscopic level the cracks look like brittle cracks, but on a microscopic level micro-ductility is observed.

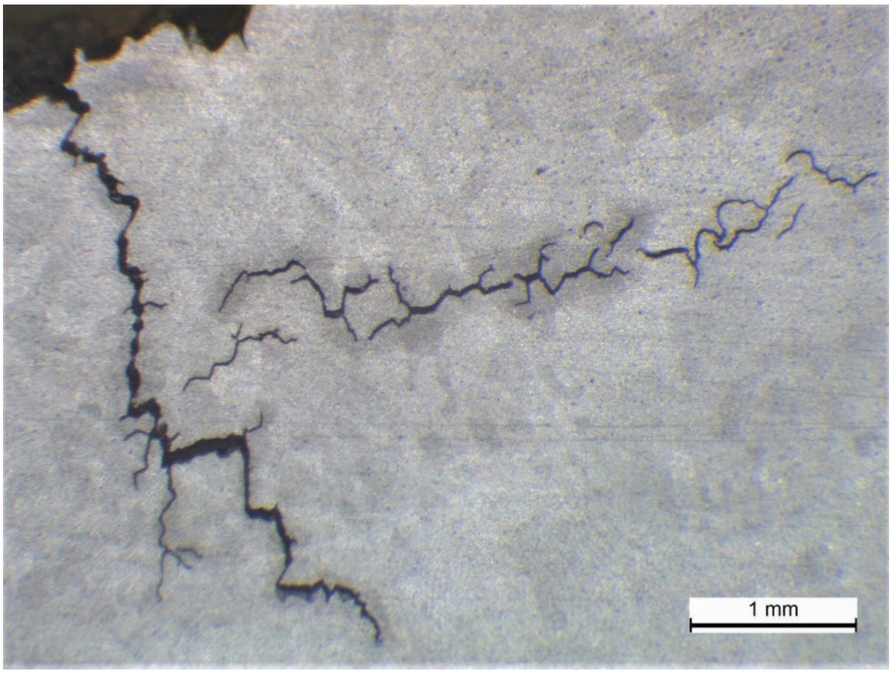


Figure 3-2 Typical appearance of hydrogen induced cracks in weld metal. The main indicators are changes in crack direction and also branching of the smaller cracks.

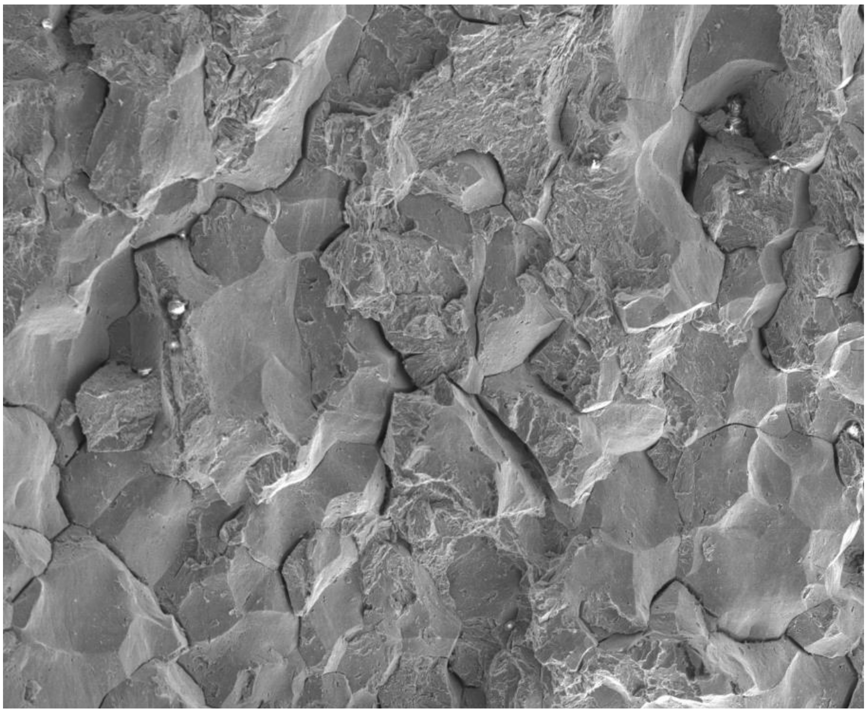


Figure 3-3 SEM image of crack propagation in 690 MPa base and weld material shows typical features of hydrogen assisted cracking with presence of micro-ductility.

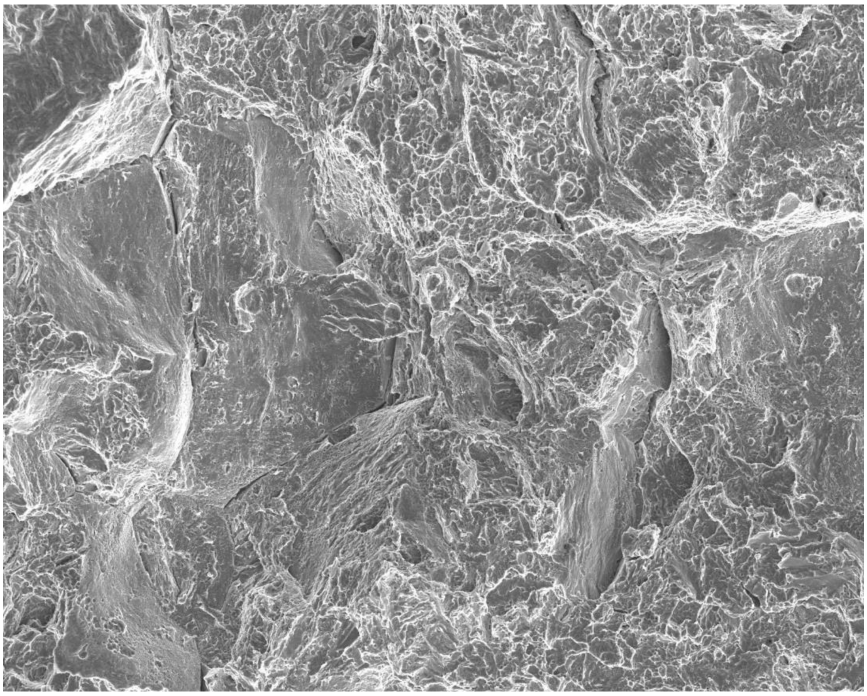


Figure 3-4 Closer SEM view of the observed micro-ductility confirming the crack propagating to occur at a slower pace than brittle instantaneous fracture.

The remedies used to reestablish the integrity of the hydrogen crack included removal of the defects by grinding or gouging, smooth grinding of the weld surface at a distance and performance of detailed UT to ensure and verify sound material, followed by a weld repair using suitable procedures and consumables. Preheating and post weld soaking was also applied. The repaired region was then re-examined by NDT and recoated to the original coating specification.

The crack positions, crack paths and crack surface appearances identified two interrelated, but time-wise divided crack scenarios:

- Fabrication-related cracking
- Service-related cracking

Fabrication related cracks are generally hydrogen assisted cold cracking (HACC) which are locally confined cracks developing within base metal heat affected zone, HAZ, and/or weld metal in connection with the fabrication welding. The hydrogen is absorbed in the weld pool during welding and is present inside the weld before thermal contraction and low temperature phase transformations take place during cooling. The cracks can be subsurface or surface breaking. Their orientation relative to the weld axes may be longitudinal, transverse or at an angle (chevron pattern) pending on direction of stresses and local microstructural features. Occasionally more traditional weld defects like micro fissures, hot cracks (solidification cracks), slag inclusions and lack of fusion may occur. Both hydrogen cold cracks and traditional weld defects may act as initiation sites for subsequent service-related crack development.

Service-related cracks are caused by hydrogen induced stress cracking (HISC) which develop when structural steel members with residual stresses and static loads are subjected to hydrogen charging through bare (uncoated) steel surfaces under cathodic protection. The experience is that HISC is rare in well-coated jack-up structures as the coating generally is an electron conductive barrier that prevents hydrogen charging. However, if previous weld defects or HACC develops into surface breaking defects this will allow cathodic protection to interact with bare steel in the cracks thereby triggering the onset of HISC. The protection potential in a local area in a fully coated structure is close to that of the sacrificial anodes, i.e., -1.05 V (Ag/AgCl), due to high conductivity and low IR drop in seawater. This will act as a point source capable of introducing locally high hydrogen concentrations at the crack tip as further explained in Sections 3.10, 5.2 and 9.4.

Structural parts that repeatedly penetrate the seabed or other areas where the applied coating can be damaged or removed by abrasion combined with deaerated water and presence of sulphate reducing bacteria in the sediments can aggravate the hydrogen uptake and provoke initiation of HISC.

HISC crack propagation is generally transverse to main stress direction but may deviate or branch. Even though HISC cracks in steel grades with SMYS $\leq$690 MPa may be benign in the sense that crack growth occurs by slowly progressing plasticity related hydrogen induced cracking, they will still be of concern and need to be addressed to mitigate the risk of failure. The interrelation and sequential development of the observed cracks is described as follows:

1. The welding process provides a susceptible microstructure and residual stress thereby enabling micro fissuring and initiation of cracking by HACC due to hydrogen uptake during welding.
2. Hydrogen charging through bare steel surfaces due to in-service cathodic protection triggers further crack growth of preexisting cracks by HISC.
3. Structural stresses composed of weld residual stresses, applied stresses and environmental loads (wave, wind, sea current, gravity) drives the crack growth due to stress concentration around cracks effects. The rate of cracking will reduce when the crack grows out of the load zone, or away from susceptible microstructures.

The factors involved in development of susceptible microstructures are treated in Section 6 while hydrogen sources and stresses are treated in Section 5 and 7, respectively.

## 3.4 Fabrication-related hydrogen cracking, HACC

Hydrogen assisted cold cracking (HACC), or just weld cold cracks, results from the combined action of trapped hydrogen, martensite formation and weld residual stresses. The weld cold cracks relate to internal hydrogen embrittlement due to hydrogen introduced in the welding process.  Hydrogen atoms becoming absorbed in the weld pool and can migrate through the heat affected zone (HAZ) and into the base metal, but also between weld beads which is why transverse hydrogen cracks typically are present rather close to the outer surface. The principal source of hydrogen during welding is thermal decomposition of moisture in the atmosphere and in the weld consumables, and decomposition of surface paint, oil and grease contaminated bevels contained in the flux. The amount of hydrogen generated is influenced by the electrode type. The susceptibility to hydrogen cracks increases during cooling as thermal contraction generates residual stresses along with formation of low temperature transformation microstructures like bainite and martensite. The combination of residual stresses and susceptible microstructures easily crack upon presence of hydrogen either in weld metal or in heat-affected zone (HAZ) of the base metal.

Over the years the steel manufacturers and weld consumable suppliers have succeeded in reducing the general susceptibility to hydrogen cold cracking when welding high strength steels, thereby enabling the use high strength steel strength classes 500 MPa to 690 MPa (SMYS) in offshore structures.

Despite these steel improvements it is still necessary to control the welding process to eliminate excessive hydrogen absorption during welding and use adequate preheating, heat input during welding, interpass temperature to ensure an acceptable thermal cycle followed by post weld soaking to ensure high quality welding and thereby suppress HACC. This is expounded in Section 6.2.

Regarding selection of safe welding parameters, attention is drawn to the fact that the high strength steel class labels, 500, 550 and 690 MPa merely states the specified minimum yield strength (SMYS) of each class in its delivery condition (referring to the lowest thickness range). The actual mechanical properties and carbon equivalent can vary considerably with plate thickness as elaborated in further detail in Section 6.1.

It is important to take the actual values of yield and hardness (ultimate strength) into consideration to get an overview of the materials HACC susceptibility. Additionally, the welding according to a qualified welding procedure is required. Both hardness and ductility of the welded structure (base metal, HAZ and weld metal) is essential. Anyhow, a maximum hardness of 330 HV is recommended with 350 HV as absolute upper limit [4].

## 3.5 Service-related hydrogen cracking, HISC

Hydrogen induced stress cracking (HISC) is characterised as crack propagation due to local hydrogen embrittlement caused by sufficient hydrogen concentration and stress concentration at the crack tip during the cracking process. HISC requires renewed hydrogenation of the steel during the cracking process. In marine jack-up structures the source of hydrogen is mainly the cathode reaction taking place on bare (metallic clean) steel surfaces, i.e. uncoated surfaces. The HISC susceptibility increases with strength/hardness of the steel. Generally loading above the yield stress is required, but nominally lower stresses suffices if local stress concentrations are involved, i.e. if the steel structure contains crack-like flaws in the form of HACC or weld defects.

The behaviour can be described and predicted by linear elastic fracture mechanics (LEFM) as illustrated in Figure 3-5. If the stress intensity factor, K, reaches or exceeds a critical, material intrinsic, value at the crack tip known as the critical stress intensity factor, also termed fracture toughness, $K_{IC}$, the crack becomes unstable, and the structure may fail catastrophically. If the steel contains or is charged with hydrogen the onset of crack growth takes place at a lower (subcritical) stress intensity known as $K_{TH}$. The crack propagation rate may initially rise but will stabilise at a more or less stable rate independent of the K-value. Cracking will continue only if the K value remains above the $K_{TH}$ and if the level of absorbed hydrogen is maintained ahead of the crack tip. As a result, the critical stress intensity level, $K_{IC}$, may never be reached in real structures:

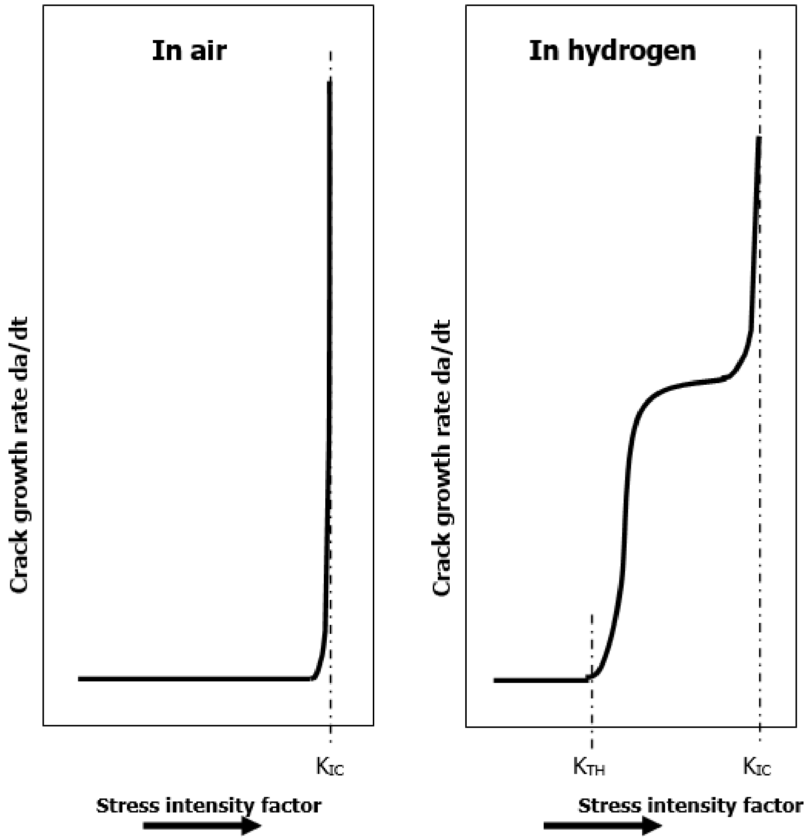


Figure 3-5 Schematic crack growth rate da/dt versus stress intensity factor. (a - crack length, t - time).

- Under constant displacement conditions as in case of stress redistribution due to load path redundancy, structural redundancy and/or internal redundancy the crack growth ceases as it runs out of pace.
- In constant load situations, the crack growth can continue as long as the hydrogenation is sufficient, but the propagation takes place in time dependent, re-occurring steps as hydrogen needs to assemble at the moving crack tip before cracking can continue and ultimately result in failure by ductile overload.

In contrast to a bare steel structure where cathodic protection leads to bulk hydrogen charging of the steel, hydrogen charging of coated structures is only possible through cracks breaking the surface and thereby exposing bare steel. Cracks in a coated steel structure are only point sources hydrogen charging. Hydrogen can diffuse into the bulk material surrounding the crack and thus diminish the concentration of hydrogen ahead of the crack tip. The remaining, adhering coating will still prevent cathodic reactions. More information on crack growth by HISC and the effect of a crack revealing bare steel on a coated structure is available in Section 4.1 and 8.

It is a general misconception that HISC necessarily will result in brittle, fast propagating, and catastrophic failure. The steel strength classes considered here are generally weldable and can behave ductile also when subjected to hydrogenation due to cathodic protection. The ductility/fracture toughness can locally be challenged by welding producing high hardness zones areas in the base metal and weld metal HAZ in combination with excessive hydrogen charging.

## 3.6 Prevention of hydrogen cracking

Experience has identified the main problem of hydrogen related cracking of coated marine structures to be growth of in-service HISC evolving from fabrication cracks or flaws (HACC and traditional weld defects) in the weld.

By following the major classification rules, guidance notes and recommendation applicable to offshore jack-up structures to the letter it is possible to use high strength steels grades in the range 500 to 690 MPa without running into problems with observed cracking due to HACC and HISC. However, in hectic, time-constrained construction phases often combined with challenging climatic conditions, upsets in production, deviations in welding procedure, un-authorised (foul) weld repairs etc. something can go amiss. The following advisory notes regarding prevention of HACC and HISC are highlighting some of the important steps in the selection of material, WPS and WPQR, weld supervision, NDT, coating and cathodic protection based on recent experiences.

The first principle is to select strength-wise appropriate materials and weld consumables to ensure that base material and deposited weld metal in nominal flawless condition has a low intrinsic susceptibility to hydrogen embrittlement It does not prevent development of hydrogen assisted cracking as such, but it may prevent developments of catastrophically, fast propagating brittle failures if and when surface breaking or subsurface defects are simultaneously affected by high stresses and hydrogenation.

Secondly, selection of materials, welding consumables, weld procedures and implementation of a QA-QC program and NDT must be appropriate to prevent surface breaking or subsurface HACC (and other weld flaws and imperfections) to remain un-detected in the critical structure elements where they may act as embryos for subsequent in-service HISC development.

Thirdly, application of a good barrier coating is required. The coating can exclude hydrogenation of the steel by the cathodic protection system which is otherwise required to prevent general corrosion and stress corrosion cracking of marine steel structures.

Special considerations should be aimed at the coating of lower parts of the spudcan, i.e. the spudcan bottom and protruding parts of the chord and rack structure which repeatable penetrate into the seabed. Coating may be damaged and removed by abrasion from sand and gravel thus exposing the weld zones to massive, bulk hydrogenation from the subsea CP system which can result in cracking, see Figure 3-6.

## 3.7 Material consideration

As mentioned above and elaborated in subsequent paragraphs, hydrogen charging can be prevented or subdued to acceptable levels by combining cathodic protection with use of impervious, durable and non-electron conductive barrier coatings. Improved design with integrated structural redundancy and lowering of stress levels and stress concentrations also adds to secure structure integrity during use. It is also possible to use fracture mechanics testing to define the crack development sensitivity of the steel in terms of defining maximum size of flaws permissible in the weld zone, however, it is difficult to set up accept criteria as this invariably prerequisites knowledge of position and possible sizes of defects, imperfections or cracks and the probability of detection of these flaws by the applied NDT. Anyway, the results obtained from such tests is by nature very conservative not least on account of the bulk hydrogenation in laboratory test specimens as compared to the single side and often very localised hydrogen uptake in real structures, i.e. coated surface with surface breaking cracks or in areas with coating deterioration.

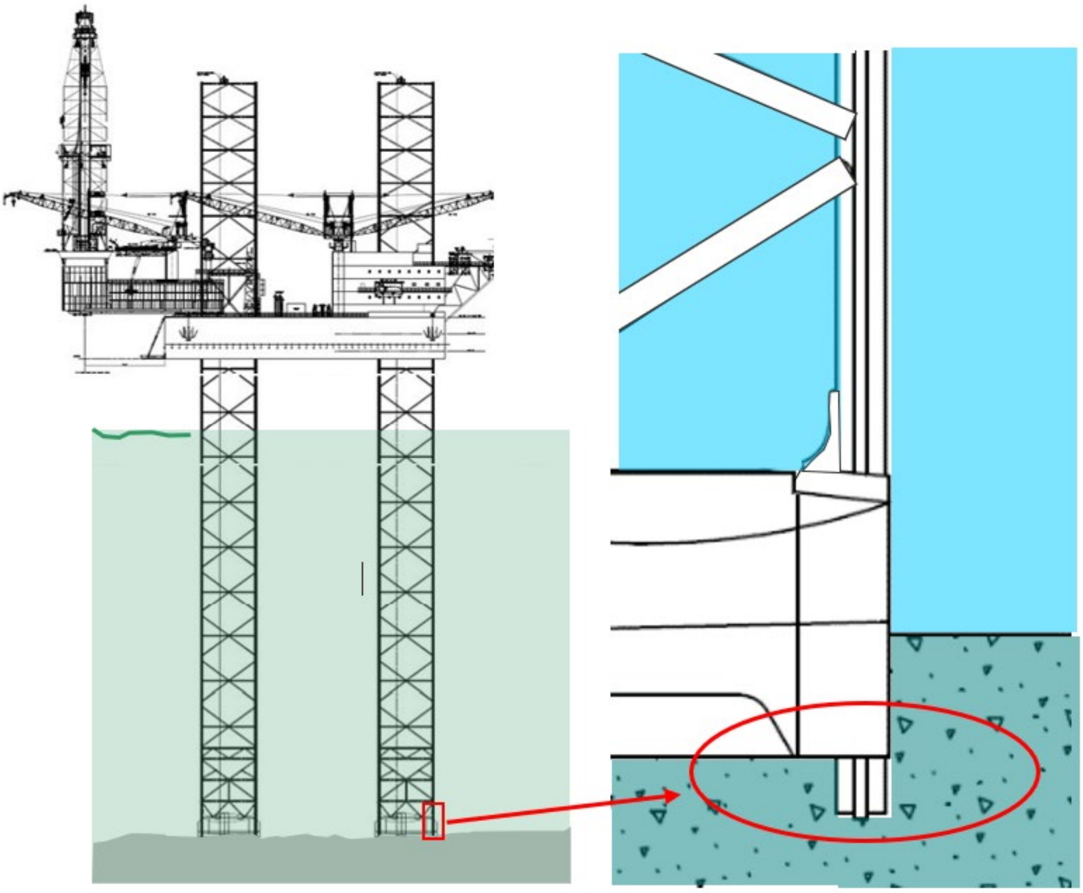


Figure 3-6 Illustration of abrasion exposed area in spudcan and lower leg structure. Abrasion of multilayered coating and corrosion of the bare steel poses a risk.

The risk of fabrication related HACC can be reduced by selecting materials for the critical parts in the leg and spudcan area with actual yield strength below 700 MPa and with hardness in the completed weld zones below 330 HV (350 HV as an absolute upper limit). The 350 HV limit is based on practical experience with high strength steels under cathodic protection in seawater [5] [4]. This indicates that steel with hardness below the limit are intrinsically resistant to HISC. Test results presented in Section 4.2 verify that quenched and tempered high strength low alloy steel with actual yield strength < 700 MPa can retain more than 90% of the fracture toughness compared to steels with yield strength below 500 MPa. Similarly, comparison of reduction of area (RA) when testing quenched and tempered fastener material comparable to 690 MPa steels in hydrogen and air (Figure 6-2) indicate that these steels can have high fracture toughness and low intrinsic susceptibility to hydrogen embrittlement. Accordingly, these materials have proven compatibility with subsea CP systems if hardness is maintained < 350 HV [5].

While material certificate data (mechanical properties, hardness, chemical composition) can indicate the usability of a given steel in subsea applications with CP, it is necessary to determine and document the CP compatibility. The intrinsic resistance towards hydrogen embrittlement of the base metal and the weldment can be performed by constant strain rate testing (at 8.3 x 10-6 mm/mm/s) in air and seawater at -1050 mV (Ag/AgCl) which is the potential of typical aluminium sacrificial anodes. As indicated in Section 6.1 $RA_H/ RA_{Air} > 0.90$ where $RA_H$ and $RA_{Air}$ are reduction of area at break in hydrogenated condition and in air, respectively, is suggested as an accept criterion.

The fabrication and inspection of offshore steel structures shall be in accordance with international standards, e.g. ISO 15614-1. These standards require qualification of welding procedures and welders. It is recommended that the welding procedure qualification (WPQ) includes weld metal longitudinal tensile tests and that filler materials be chosen to match the base material properties, according to the class rules and recommendation.

The welding procedure qualification records (WPQR) shall be made with project specific materials, selected to represent the highest hardness, highest carbon equivalent (CE) or highest yield ratio within each thickness group at the discretion of the classification society.

Materials selection as per above will help to reduce both the risk of HACC and HISC during service. Following the class rules on materials selection can result in flawless structures provided attention is paid to welds. Lack of compliance with welding procedures in the fabrication phase is typically what causes issues in a later stage, not the choice of material in itself, but selection of a higher strength material or materials with high carbon equivalents will increase the HACC and HISC susceptibility of the weld zone due to increased hardenability properties. Moreover, the added advantage of improved NDT and application of barrier coating indicate that also steels with an actual yield stress > 700 MPa can be used.

## 3.8 Welding supervision

The propensity for HACC increases if the welding parameters deviate from the welding procedure and setup used in the WPQR as described in Section 3-4 and 6-2. Deviations can result from non-standard fabrication activities, such as welding in adverse and uncomfortable environmental conditions, carelessness in consumable handling restarting welding after power outages and hasty welding due to schedule demands.

Sound and flawless welds are prerequisite of good management of the welding operations. This calls for planned and traceable fabrication activities, that also include training for the workforce in how to prevent hydrogen cracking. Formation of HACC or other weld imperfections are seldom an issue when the welding fulfils the requirements in qualified welding procedures. The problems arise when the procedure is not followed in every detail. Hence, supervision of the welding operations is essential to detect deviations and thereby obtain the desired quality.

The example in Figure 3-7 illustrates presence of numerous subsurface cracks after grinding in an area with irregular weld appearance. Cracks or crack-like indications like these are not compliant with the WPS acceptance criteria. Supervision during welding or visual inspection after welding can reveal deviations from the welding procedure, but the detection of type and extent of the cracking is possible only by smooth grinding the weld surface and detailed NDT.

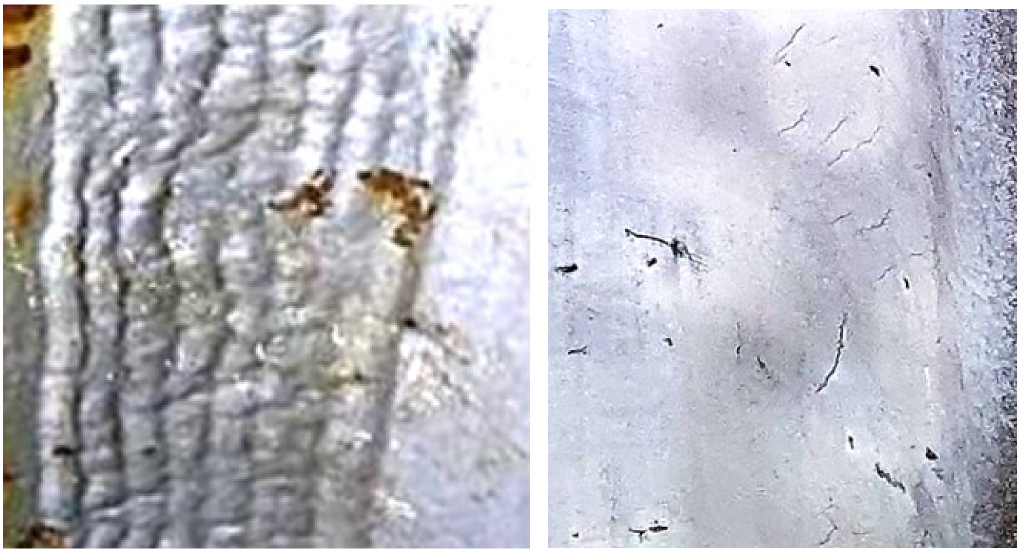


Figure 3-7 Left image shows irregular appearing weld zone in chord to rack weld examined after several year in service. Right image shows the same area after smooth grinding and magnetic particle testing.

Supervision of welding operations should therefore be considered the primary method to obtain the desired quality. This can be achieved by implementing rigid and strict welding supervision schemes to obtain the same quality level in practice as in the WPQR and hence reduce the extent of HACC to insignificant levels. The supervision shall include, but is not necessarily be limited to:

- Observations and logging of preheating time and temperature, weld heat input, interpass temperature and post weld soaking time and temperature, including repair welds, visual inspection of in-process and completed welds, included repair welds.
- The supervision shall be performed by class or independent 3rd party to confirm that the materials, procedures and workmanship are in conformance with the project specification and pertaining construction documents.
- If the implementation of an effective surveillance program is not feasible, e.g. due to part fabrication taking place at different places (or at subcontractors) at the same time etc, it is advised to smooth ground all critical welds to allow use of advanced UT. Sufficient time should be allocated for repair welding in the production programme.

Experience from site supervision usually does not reveal issues with the welding procedures. The shipyards producing offshore structures have qualified welding engineers employed, and thus evaluation of the welding procedures would most likely not provide add value. Welding supervision is however considered a primary method to verify that each sequence is in accordance with the welding procedures, ultimately to reduce the extent of HACC.

## 3.9 Non-destructive testing

Non-destructive testing (NDT) does not in itself improve the weld quality but merely provide documentation of the welded structure. Any weld defects determined by NDT shall be repaired and registration of weld defect repairs by position, extent and type shall be part of the NDT "as built" documentation. Thereby, the documentation shall verify areas of weld repairs during fabrication and verify that defects were not present prior to service.

Experience with structures made of thick plates indicates that the probability of crack detection in fabrication welds can be low [6]. One reason can be that the NDT procedures used during fabrication concentrates on detecting longitudinal defect indications while transverse indications and chevron cracking are surpassed due to the surface profiles of the weld cap layers. It is possible to increase the probability of detecting longitudinal, transverse and chevron cracks by smooth grinding of the weld surfaces followed by application of more detailed NDT, e.g. by the use of ultrasonic testing (UT). However, no standardised method and acceptance criteria exist as the size of the indications are difficult to evaluate.

The weld surface appearance as shown in Figure 3-8 is unsuitable for any kind of NDT. Further details on this matter are found in Section 10.The presence of such welds can be due to a lack of quality control, the omission of 3rd part surveillance, difficult welding conditions or lack of workmanship.

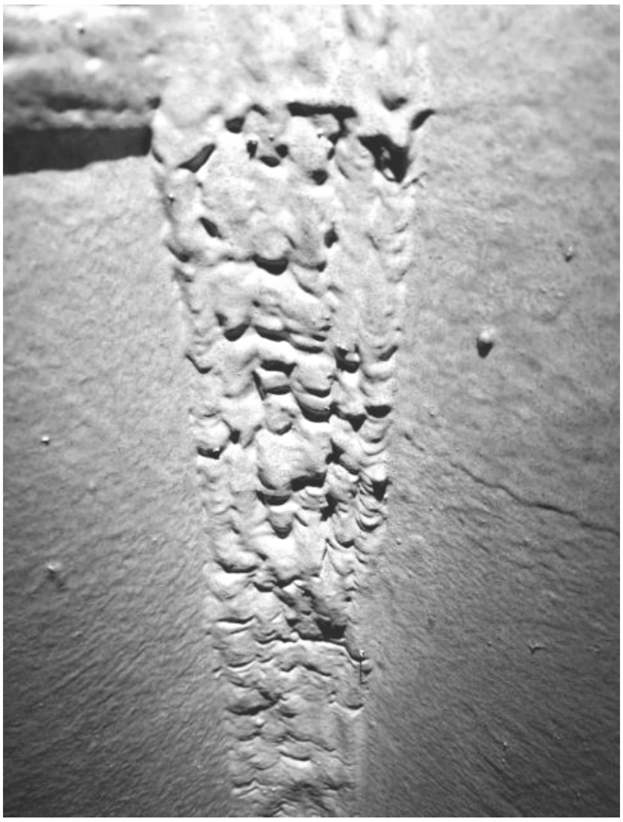


Figure 3-8 Example of poor weld quality.

## 3.10 Corrosion protection

Steel structures exposed to seawater is traditionally protected by a combination of barrier coatings (epoxy) to prevent access of seawater to the steel surface supplemented with cathodic protection to prevent corrosion at bare steel, i.e. coating defects or damage.

The purpose of coating is to create a barrier that keeps out charged ions and retards the penetration of water. The coating shall be compatible with cathodic protection. If not previously qualified, pre-qualification testing of the coating under applicable cathodic protection potential levels shall be performed to confirm resistance to cathodic disbonding of the coating at scratches and porosities.

According to NORSOK M-001 [7] applicable to fixed offshore installations, a coating system in accordance with NORSOK M-501 [8] coating system 7 shall be applied on carbon steel submerged in seawater. A coating system corresponding to system 7B is recommended for jack-up legs and spudcan areas which is exposed to seawater at ambient temperature. The coating system shall be prequalified according to the same or a similar standard.

Coatings deteriorate over time in service, but it is possible to obtain more than 15 years of service life by following the coating manufacturers advice on surface pre-treatment and cleanliness, number of coatings and dry film thickness. If the specification is not strictly followed more frequent coating refurbishment is required. The option of metallisation is described in Section 9.3.

The combination of coating and cathodic protection provides efficient corrosion protection of structures submerged in seawater. In general terms, cathodic protection (CP) consists of lowering the electrode potential of the steel to a sufficiently low potential where iron is thermodynamically stable by means of supply of electrons from an external source, i.e. by use of sacrificial anodes or impressed current systems.

The simplified Potential-pH diagram in Figure 3-9 identifies thermodynamically stable iron phases and the stability of hydrogen in water at chemical equilibrium. The lower dashed diagonal line represents for the reversible hydrogen electrode.  At potentials below this line hydrogen evolution will take place. Accordingly, immunity by cathodic protection is at any given pH only achieved at potentials below the reversible hydrogen electrode. Accordingly, hydrogen liberation is irreversibly connected to cathodic protection.

CP systems designed to comply with recommendations and codes applicable to offshore structures [7] [4] [8] require a potential below -0.8 V (Ag/AgCl) to prevent corrosion of structures in seawater. However, CP systems with sacrificial anodes produce more negative potentials, i.e. down to -1.05 V which is the output potential of the aluminium sacrificial anodes typically used. The penalty is that the liberation of hydrogen atoms at local bare steel surfaces increase exponentially, see Figure 5-4 in Section 5.2.

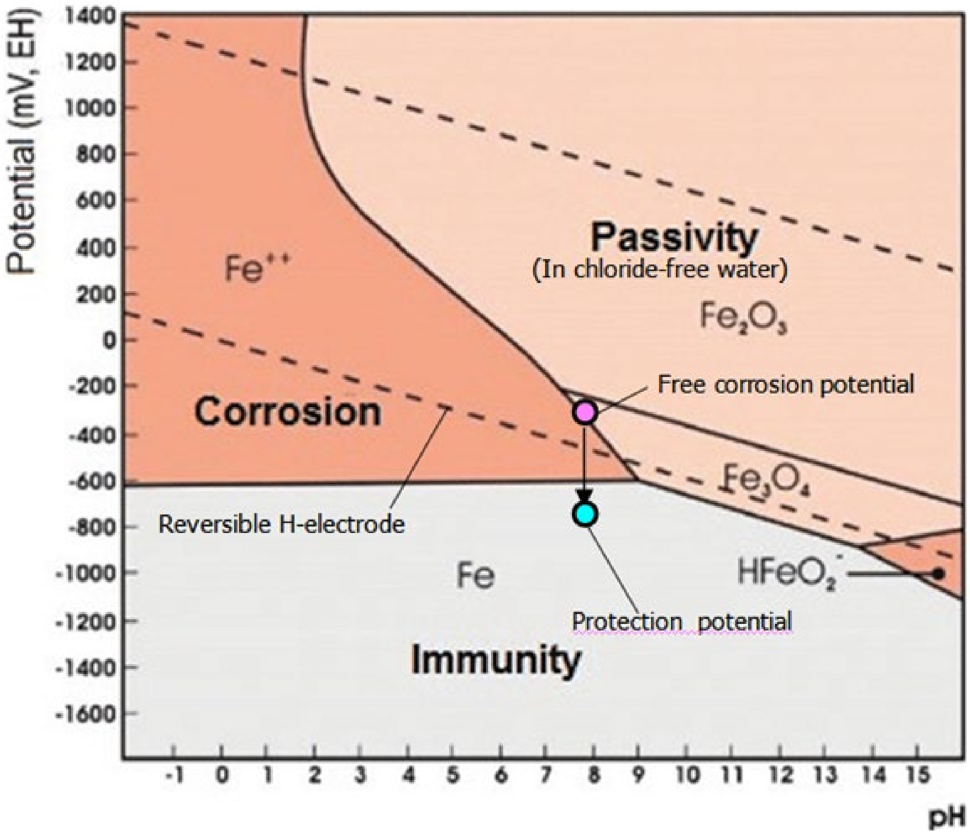


Figure 3-9 Illustration of corrosion protection area by cathodic protection as a function of pH and electrochemical potential.

# 4 Hydrogen embrittlement

Hydrogen embrittlement (HE) is a common term used for the embrittling effect caused by the presence of hydrogen in susceptible microstructures. It is a generic term, and different terms are used for the same mechanisms dependent on industry, environment, source of hydrogen, appearance of crack and role of stress [9]. $H_2S$ containing environments (sour service) are well known for several cracking mechanisms. ISO 15156-1 [9]describes several cracking mechanisms which are well-known in hydrocarbon service. Each cracking mechanisms can be influenced by factors such as microstructure, alloy composition, and environmental conditions. Understanding these mechanisms is important in selecting appropriate materials and defining effective mitigation strategies.

Although HE is a well-known problem, the damage mechanisms are complex, specifically because the loss of ductility can be influenced by factors that are not necessarily uniform, such as microstructure, alloy composition, and environmental conditions. Accordingly, several variables have to be considered, and these variables may change over time.

Definitions for different types of hydrogen damage within the hydrogen embrittlement umbrella are:

- Hydrogen accelerated fatigue crack growth (HAFCG)
  - Accelerated fatigue crack growth rate and reduced fatigue life in presence of hydrogen
- Hydrogen assisted cracking (HAC)
  - Also called hydrogen cracking (HC)
  - Has also been used for hydrogen assisted cold cracking (HACC) and delayed cracking
  - Cracking at or near room temperature
  - Occurs after the weld has cooled
  - Can affect base material and the weld
- Hydrogen induced cracking (HIC)
  - Also called hydrogen blistering
  - Creates internal voids or bubbles in the steel
  - No externally applied loading is required for cracking
  - Atomic hydrogen diffuses into the steel and recombines to form molecular hydrogen
  - Typical for steels with a high impurity level
- Hydrogen induced stress cracking (HISC)
  - The cracking results from presence of hydrogen in a metal and tensile stress
  - The hydrogen results from a cathode reaction in seawater, typically due to cathodic protection.
  - Hydrogen embrittlement in metals that are generally not sensitive to SSC
  - The hydrogen is galvanically induced, e.g. due to cathodic protection in seawater, but can occur due to acid corrosion on the metal surface
- Hydrogen stress cracking (HSC)/Galvanically induced stress corrosion (GHSC)
  - The cracking results from the presence of hydrogen in a metal and tensile stress
  - The hydrogen results from galvanic coupling (as a cathode) to a less noble material, or from the corrosion in acids like $H_2S$ and HCl

- Soft zone cracking (SZC)
  - A form of SSC that can occur when the steel contains local soft zones (zones with low-yield strength)
  - Soft zones can yield and accumulate plastic strain locally, increasing the SSC susceptibility.
  - Welds in carbon steel is most susceptible to formation of soft zones.

- Stepwise cracking (SWC)
  - Cracking that connects HIC cracks on adjacent planes in the steel

- Stress corrosion cracking (SCC)
  - A general term used to describe cracking involving localised corrosion (anodic process) and tensile stresses
  - Most prominent at elevated temperature in chloride containing environments
  - May also occur in $H_2S$ containing environments, influenced by tensile stresses, partial pressure of $H_2S$, pH and chlorides

- Stress-oriented hydrogen induced cracking (SOHIC)
  - Ladder-like array of cracks linking HIC cracks
  - SOHIC, SWC and SZC relates to SSC/HIC
  - Restricted to carbon steel plates and their weldments.

- Sulphide stress cracking (SSC)
  - Cracking involving corrosion in presence of $H_2S$ and tensile stress
  - Atomic hydrogen is produced by corrosion on the metal surface
  - Presence of sulphides and/or sulphur slows recombination of atomic hydrogen
  - High strength materials and hard weld zones are prone to SSC
  - Influenced by tensile stresses, partial pressure of $H_2S$ and pH
  - Most prominent at room temperature

Only hydrogen in the atomic state is able to enter the material and diffuse through the crystal lattice of the material. In the molecular state hydrogen is not able to penetrate the microstructure. Atomic hydrogen is generated at the cathode of a corrosion cell. By accepting electrons from the cathode hydrogen ions are reduced to atomic hydrogen. Most of the hydrogen atoms will recombine forming molecular hydrogen gas that is released from the surface where the cathodic reaction is taking place. A small fraction of the atomic hydrogen formed can diffuse into the material. The degree of loss of integrity depends on hardness, presence of inclusions, and microstructural features such as crystal structure, grain boundaries and dislocations.

The presence of hydrogen in the microstructure has an influence on the ductility of the material and its behaviour under applied stress. Figure 3-1 illustrates that simultaneous presence of a sufficiently high concentration of absorbed hydrogen, tensile stresses (applied and/or residual) and a susceptible microstructure can result in hydrogen induced damage. These three factors are mutually dependent in the sense that less hydrogen or lower stresses are required to cause damage in a more susceptible microstructure, and vice versa.

The material strength (i.e. tensile strength and/or hardness) has a first-order effect on HE susceptibility. As strength increases, steel becomes harder, less ductile, less tough, and more susceptible to HE.

Hydrogen embrittlement can affect most alloy families commonly used offshore such as high strength carbon and low alloy steels, along with ferritic, martensitic and duplex stainless steels, titanium and nickel-based alloys. Austenitic stainless steels, on the other hand, tend to be fairly resistant to hydrogen embrittlement due to the austenite phase being less susceptible to HE. Hydrogen embrittlement caused by hydrogen released by electrolysis of water during cathodic protection is one of the most common causes for material failure subsea. HISC has been responsible for a large number of major in-service failures of duplex stainless steels [10, 11]. DNV-RP-F112 [12] provide guidelines to avoid HISC failures of duplex stainless steel components for subsea equipment exposed to cathodic protection. Also low alloy steels [13] and nickel-based alloys can fail by this cracking mechanism. HISC of low alloy steels used for jack-up rigs is addressed in this report.

## 4.1 Damage mechanisms

Multiple phenomena such as hydrogen dissolution, hydrogen diffusion, hydrogen redistribution and hydrogen interactions with vacancies, dislocations, grain boundaries and other phase interfaces are involved in cracking process. Only hydrogen in the atomic state is capable of entering into steels and the damage mechanisms involve the following steps:

- Hydrogen is transported to the steel surface
- Hydrogen is attached to the steel surface (adsorption)
- Hydrogen enters the steel surface (absorption)
- Hydrogen diffuses within the steel driven by variations in hydrogen concentration, stress and temperature
- Hydrogen interferes with microstructural features causing crack initiation and growth

The following subsections provide a brief outline of the main theories developed to explain the damage mechanisms caused by hydrogen absorbed in high strength steels [14]. Note that some mechanisms work together, others oppose each other. As an example, two opposing mechanisms (ductile vs. brittle) are shown in Figure 4-1 and Figure 4-2.

### 4.1.1 Planar pressure theory

The planar pressure theory [15] proposes that molecular hydrogen within the steel creates very high pressures in voids, pores, and other defects where hydrogen can accumulate. The subsequent increase in pressure will then introduce internal stresses high enough to initiate internal hydrogen embrittlement.

### 4.1.2 Adsorption theory

This mechanism was proposed by Petch and Stables (1952) [16] who argued that hydrogen acts like an acid and lowers the free surface energy, which holds the atoms together. The hydrogen adsorbed onto the internal surfaces of cracks or voids decreases the surface energy and allows a crack to grow under a lower applied stress. Adsorption of hydrogen atoms at the crack tip leads to the weakening of interatomic bonds, which in turn facilitates dislocation injection from the crack tip. The crack subsequently grows by slip and the formation of microvoids.

### 4.1.3 Hydrogen enhanced decohesion

Bastein and Azou (1952) [17] proposed that the dislocations that move during plastic deformation carries hydrogen atoms along. When these dislocations pile up at structural defects the site becomes over-saturated by hydrogen. Also, Troiano (1962) [18] argued that hydrogen interacts with dislocation pile-ups in areas of tri-axial stress, thereby lowering the cohesive strength. The interaction of hydrogen with the dislocations ahead of the stress concentration is proposed to be sufficient to cause fracture if the concentration of hydrogen reaches a certain level.

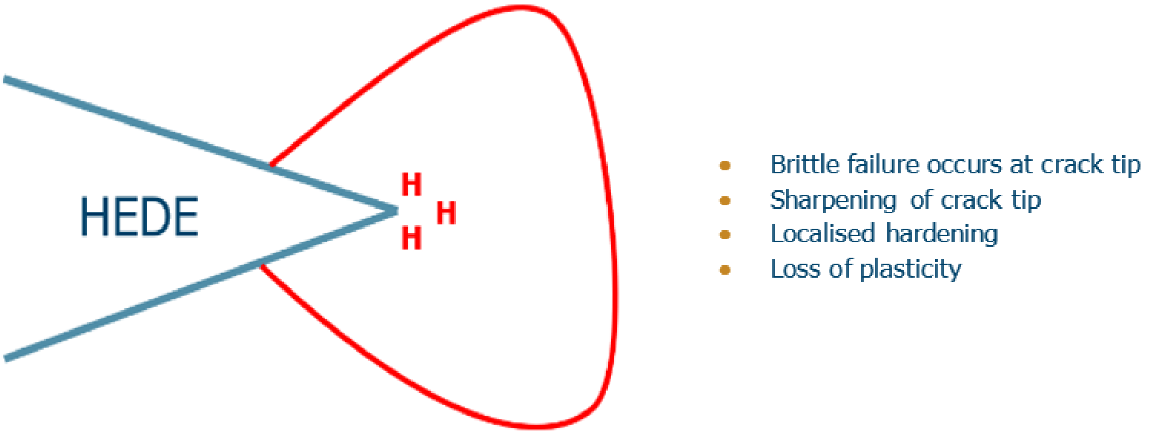


Figure 4-1 Schematic illustration of HEDE damage mechanism for brittle crack propagation.

Oriani (1972) [19] developed the initial theory further and proposed that hydrogen damage occurs when the tensile stress at the crack tip exceeds the local atomic cohesion strength, which has been lowered by the presence of hydrogen.

In the hydrogen enhanced decohesion (HEDE) theory, hydrogen accumulates at trapping sites, such as voids, cracks and interfaces, thereby reducing the bond strength. The damage occurs in regions located ahead of the crack tip where the tensile stresses are maximized. This theory requires that a critical hydrogen concentration is present for brittle fracture to occur and that dissolved hydrogen decreases the cohesion forces between atoms.

### 4.1.4 Hydride induced embrittlement

Brittle cleavage-like fracture associated with stress-induced hydride formation is one of the established hydrogen embrittlement mechanisms. Hydrogen accumulation is believed to promote a local formation of hydrides, assisting the generation of stacking faults and also causing a local stress concentration. Subsequently under increased stress, crack propagation take place by the successive cracking of the hydrides generating formation of several crack fronts.

The nucleation and growth of hydrides in the zone ahead of a crack has been observed by several researchers [20]. The investigations revealed that the hydrides first nucleated in the stress field associated with a crack. The crack then propagated, not by the growth of individual hydrides, but by the nucleation and growth of new hydrides in the stress field, demonstrating that the small hydrides coalesced to form larger hydrides. The metal hydrides are not only brittle and less dense than the metal matrix, but they also precipitate at dislocations, grain boundaries and other defects [21].

### 4.1.5 Microplasticity theory

Beachem (1972) [22] proposed that microplasticity controls what happens at the crack tip. This theory allows hydrogen ahead of the crack tip to contribute to microscopic plastic deformation of the microstructure, rather than an embrittlement process. The absorption of hydrogen is assumed to enhance the ease of dislocation motion and/or dislocation generation. The idea is that the distribution of hydrogen will be non-uniform and may accumulate in certain regions. During an applied stress, the flow stress in these regions (on a microscopic level) will be reduced, resulting in localised deformation which leads to a highly localised ductile failure, which by mistake is interpreted as a brittle fracture.

By this mechanism the hydrogen ahead of the crack tip assists in whatever microscopic deformation the microstructure allows for. Beachem reasons that intergranular, quasi cleavage and microvoid coalescence are all possible fracture modes, which can be associated with HACC. The actual fracture mode is dependent on the microstructure, crack tip stress intensity and the hydrogen concentration.

Other researchers have also experimentally validated the argument that several types of fracture mode can be involved in HACC [23] [24]. This model therefore unifies several theories, and the basic effect of hydrogen in the microstructure appears to point to facilitate dislocation motion or dislocation generation, or a combination of both. This postulation is supported by observations that atomic hydrogen decreases the friction under dislocation movement on the slip planes and therefore causes plastic deformation of the lattice. The crack formation mechanism is thought to occur by microvoid coalescence or simply a dislocation avalanche (Gedeon and Eagar, 1990) [25].

### 4.1.6 Adsorption induced localised slip model

Lynch (1988) [26] has proposed a localised plastic deformation mechanism but also supports the ejection of dislocations from the crack tip, thereby promoting the coalescence of cracks with voids ahead of an existing crack front. The overall result is a process involving plastic flow, similar to that proposed by Beachem (1972) and Birnbaum and Sofronis (1996), but plastic flow is governed by the ejection of dislocations at the crack tip. The adsorption of hydrogen atoms at the crack tip will result in weakening of the interatomic bonds, thereby facilitating dislocation ejection from a crack tip. The crack subsequently grows by slip and formation of microvoids. Lynch (1988) states that segregation of impurities, such as phosphorus, to prior austenite grain boundaries will increase the susceptibility to HACC by promoting intergranular fracture. The impurities can weaken interatomic bonds at the crack tip, facilitating decohesion or the creation/movement of dislocations. Lynch (1988), however, warns that the explanations for the observed microstructural effects on the susceptibility to HACC are speculative, as the microstructures and fracture paths are not characterised in sufficient detail. Moreover, is often difficult to compare the results from different researchers because different methods are to assess the susceptibility to HACC.

### 4.1.7 Hydrogen enhanced localised plasticity

The hydrogen enhanced localised plasticity (HELP) theory was developed by Beachem in 1972 and assumes that hydrogen facilitates dislocation movement and crack growth by slip and formation of microvoids. The model argues for a hydrogen induced localised ductile rupture process, which results in the traditional observations of macroscopic brittle behaviour. As with the decohesion model, the HELP model requires the accumulation of hydrogen in a stress field, i.e. in the vicinity of the crack tip or in the vicinity of a dislocation.

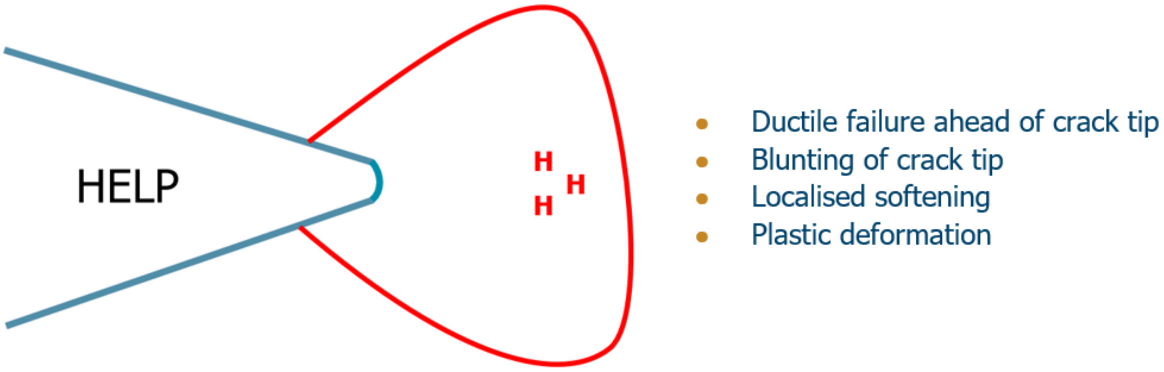


Figure 4-2 Schematic illustration of HELP damage mechanism for ductile crack propagation.

During the dislocation movement (induced by an external stress), the atomic hydrogen eases the dislocation movement by shielding against the stress fields between the dislocations as well around other imperfections. The shielding lowers the local yield stress, resulting in the dislocation movement occurring at low levels of shear stress. Hence, microcracks are formed by microvoid formation under the influence of shear stresses caused by the dislocation movement. The macroscopic ductility is therefore limited due to the onset of extensive localised plastic deformation, a viewpoint that may be counter intuitive. The basis for the HELP model has been adopted by many researchers, notably by Sofronis, Birnbaum and Lynch [26], [27] and [28].

## 4.2 Fracture toughness

The presence of hydrogen in the steel has only little influence on the material in terms of:

- Yield strength
- Ultimate tensile strength
- $\Delta K$ threshold for initiation of fatigue
- High cycle fatigue endurance limit
- Impact toughness

Hydrogen may, however, affect the fracture toughness, i.e. elongation and reduction of area at fracture. Figure 4-3 illustrates loss of ductility as the strain rate is lowered in presence of hydrogen, i.e. at a low rate of deformation of the material, the required time for diffusion of hydrogen and related embrittlement is available. As seen in Table 6-1 the strength level of X100 is comparable to that of 690 MPa steel.

To illustrate how hydrogen affects the properties of low alloy steels, relevant test data has been extracted from pipeline steels, which are very similar to those used in jack-up rigs, but much more data is available. The examples serve to illustrate how the properties of low alloy steels comparable to 690 MPa steels or higher strength steels are affected by the presence of hydrogen. For these steels, the embrittling process is strain rate sensitive, i.e. hydrogen needs time to diffuse and accumulate at specific trap sites, before it can cause damage. Slower strain rates therefore tend to give a greater embrittling effect at room temperature, or near room temperature conditions, when compared with higher stain rates.

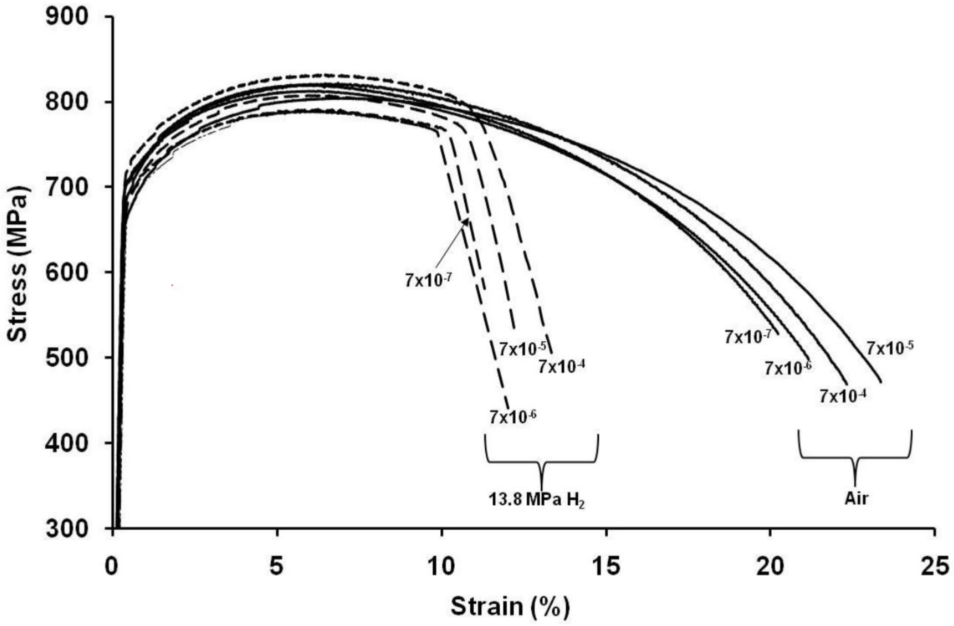


Figure 4-3 Effect of strain rate on tensile properties of X100 steel in hydrogen service. Hydrogen gas pressure in MPa stated at each curve [29].

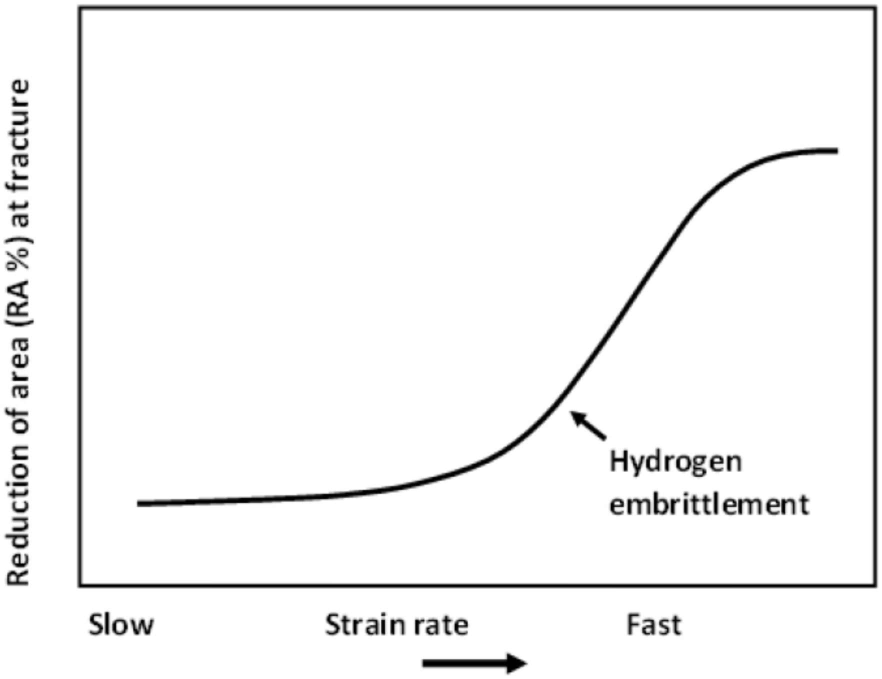


Figure 4-4 Schematic illustration of the effect of strain rate on fracture ductility in presence of hydrogen.

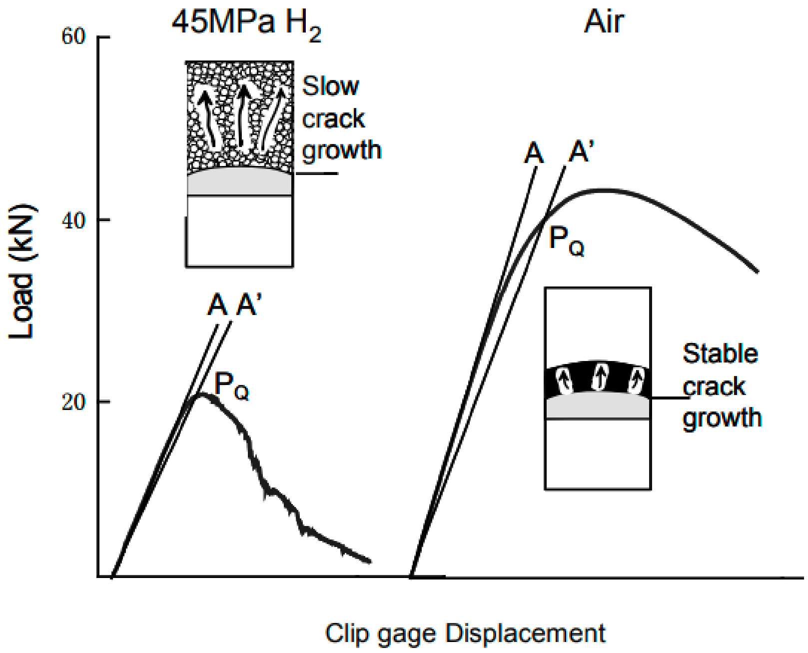


Figure 4-5 Effect of hydrogen on plane-strain fracture toughness of SCM435 [30].

The rate at which deformation of the material takes place, i.e. the strain rate, in impact testing is high. Accordingly, the hydrogen has no time to saturate the material ahead of the crack. On the other hand, slow strain rates favour loss of ductility as shown in Figure 4-4. This is something to be aware of when evaluating test results from testing in a hydrogen-containing environment.

Wada et al. [30] studied the plane strain fracture toughness of SCM435, a steel used for high strength bolts, but with comparable or higher strength than of 690 MPa low alloy steel used for the jack-up rigs. Crack growth initiates at a lower load when testing in hydrogen compared to testing in air, but no cleavage fracture was observed in any of the tested samples. Instead, the material failed by slow crack growth in presence of local hydrogen embrittlement at the crack tip. According to Wada et al. the cracking mechanism may appear brittle on a macroscopic level, but microscopic examination revealed a ductile and slow progressing fracture mode. The argument was that slow crack growth can be observed in CTOD tests and rising load fracture toughness tests of the base metal and in most cases also in the weld zone. The fact that the failure proceeds with slow crack growth is essential when assessing the structural redundancy of jack-ups with detected cracks.

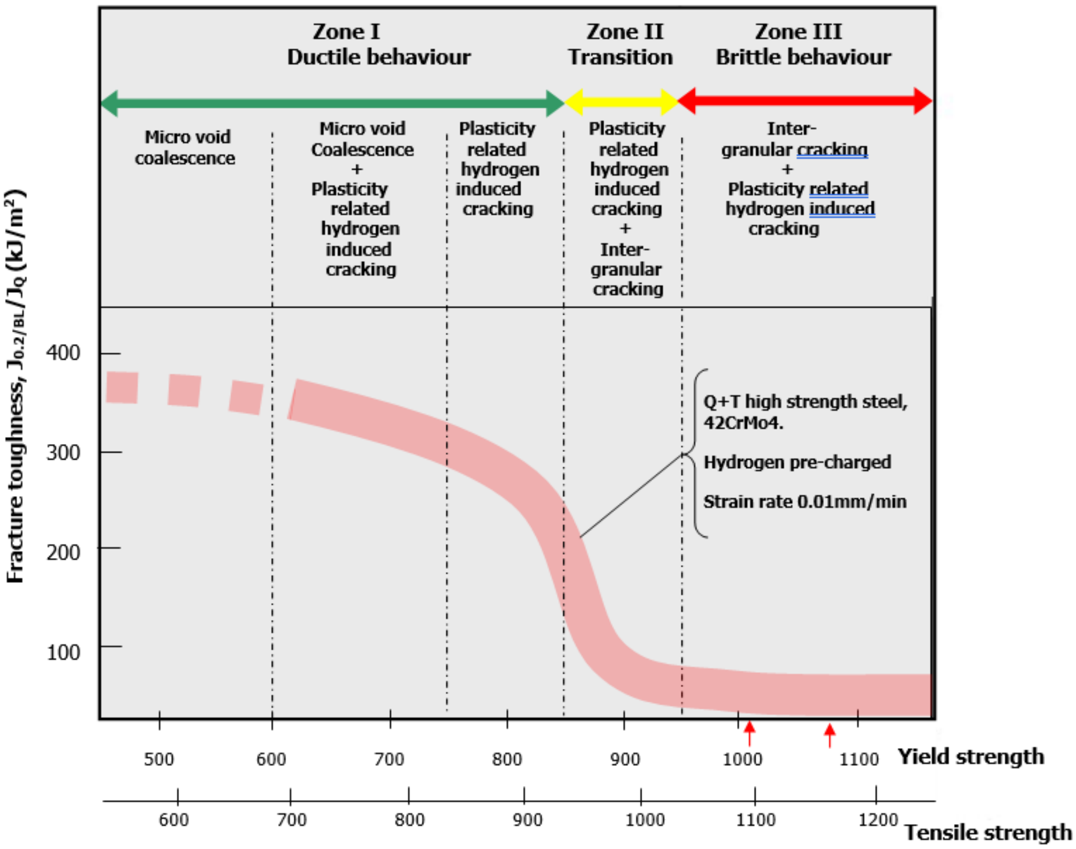
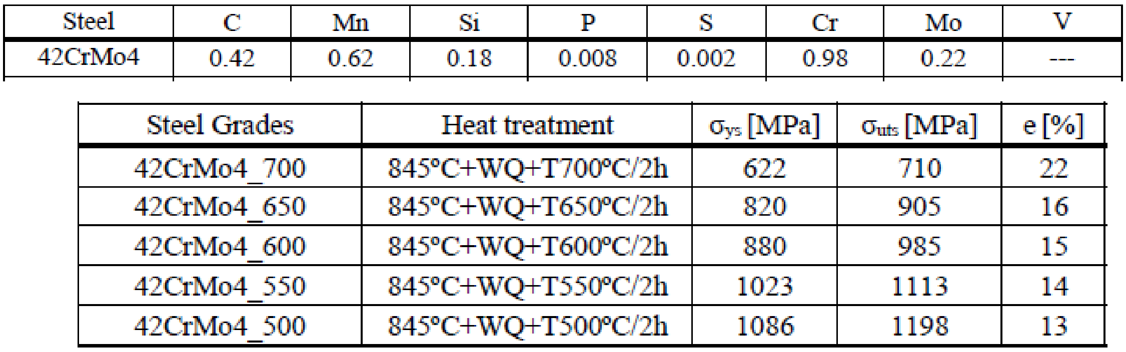


Figure 4-6 Relationship between fracture toughness in terms of the J integral and strength obtained by heat treatment of 42CrMo4 steel in presence of hydrogen [31].

Figure 4-6 shows the relationship between fracture toughness in terms of the J integral ($J_{0.2/BL}$) corresponding to strain energy release rate at crack extensions at 0.2 mm blunting line) and material strength. The material used was 42CrMo4 steel. This material is when quenched and tempered similar to the 690MPa low alloy steel used for jack-up installations. The material was heat treated at different temperatures to simulate steels with different strengths as shown in Figure 4-7. The heat-treated samples were subsequently hydrogenised by charging in 450 bar hydrogen gas, roughly corresponding to cathodic protection in seawater before fracture mechanics testing. Characterisation of the crack micro-mechanisms was obtained by post-test fractography. The test results, i.e. retaining of ductile behaviour in presence of hydrogen, demonstrated by a low reduction (<10%) of J-integral for steels with 500 and 700 MPa yield strength, confirm the experiences that ferritic/ferritic-pearlitic low alloy steels with actual yield strength below 700 MPa are compatible with subsea CP systems [5]. Actually, the tests performed show ductile behaviour with slow progressing cracking in the base metal at least up to 850 MPa. Beyond these limits there is a significant drop in toughness and transition in crack morphology towards intergranular cracking.



| Steel | C | Mn | Si | P | S | Cr | Mo | V |
|---|---|---|---|---|---|---|---|---|
| 42CrMo4 | 0.42 | 0.62 | 0.18 | 0.008 | 0.002 | 0.98 | 0.22 | --- |

| Steel Grades | Heat treatment | $\sigma_{ys}$ [MPa] | $\sigma_{uts}$ [MPa] | e [%] |
|---|---|---|---|---|
| 42CrMo4_700 | 845°C+WQ+T700°C/2h | 622 | 710 | 22 |
| 42CrMo4_650 | 845°C+WQ+T650°C/2h | 820 | 905 | 16 |
| 42CrMo4_600 | 845°C+WQ+T600°C/2h | 880 | 985 | 15 |
| 42CrMo4_550 | 845°C+WQ+T550°C/2h | 1023 | 1113 | 14 |
| 42CrMo4_500 | 845°C+WQ+T500°C/2h | 1086 | 1198 | 13 |

Figure 4-7 Chemical composition, heat treatment and obtained mechanical properties of 42CrMo4 steel.

## 4.3 Crack propagation

While the cracking phenomenon can arise in seemingly flawless and defect-free materials the presence of manufacturing defects (including weld cold cracks, HACC) and other non-coherent internal fissures may ease the crack initiation and growth. Small subsurface weld cracks originating from fabrication can remain undetected by NDT but be forced to break open to the surface during loading. Such cracks may subsequently grow by mechanisms like:

- Hydrogen accelerated fatigue crack growth
- Hydrogen induced stress cracking

The effect of hydrogen on crack growth is illustrated in Figure 4-8 which shows the combination of hydrogen assisted fatigue crack growth and hydrogen induced stress cracking behaviour versus $K_{max}$ for a given stress ratio R ($K_{min}$/ $K_{max}$). K is the stress intensity factor being proportional to s·a½ (s = stress, a = crack height). The growth rate is expressed by da/dN (crack growth per load cycle) for fatigue and da/dt (crack growth per time unit) for hydrogen induced stress cracking (HISC) versus $K_{max}$. N and t are linked by frequency, i.e. t = N· frequency. Fatigue cracking initiates when ΔK ($K_{max}$- $K_{min}$) exceeds the threshold value $\Delta K_{th}$ for fatigue. The growth rate is accelerated by the presence of hydrogen (red line) relative to test in air (blue line). When $K_{max}$ exceeds the threshold for subcritical crack in hydrogen, $K_{ISCC}$, the crack growth rate is further accelerated (dotted line) until reaching the plateau level for the hydrogen induced stress cracking mechanism and before approaching the $K_C$ for onset of unstable cracking.

Figure 4-9 shows the effect of hydrogen on fatigue crack growth rate of X100 steel. Once the delta $K_{th}$ is exceeded. Below the threshold value there is no influence of hydrogen.

Figure 4-10 illustrates schematically the relation between flaw (crack height) and endurance limit for initiation of fatigue, threshold for subcritical crack growth and for overload failure. At low stress and small flaws cracking will occur only under fluctuating stress conditions. At higher stress or larger flaws static stress cracking environment assisted subcritical crack growth (e.g. HISC) may dominate fatigue and dominate the cracking scenario until final overload failure takes over.

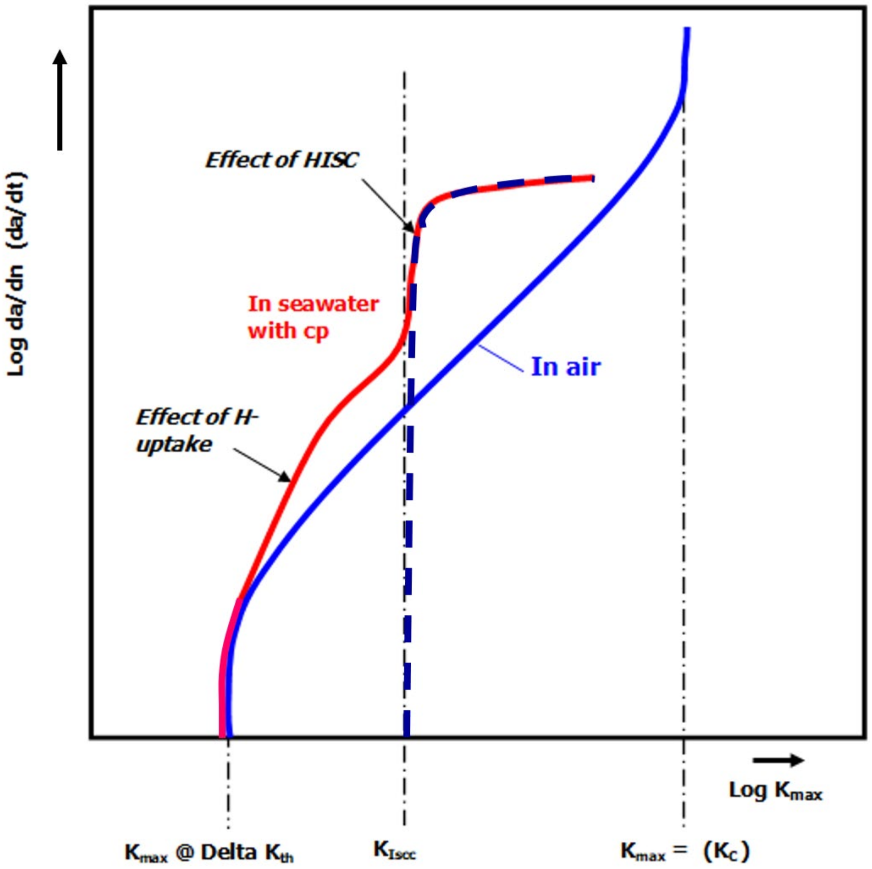


Figure 4-8 Schematic illustration of combined hydrogen assisted fatigue crack growth and hydrogen induced stress cracking behaviour versus $K_{max}$ for a given stress ratio.

At low fatigue loads, the growth rate of cracks in a jack-up rig will be quite low (e.g. < 0.00005 mm/cycle). During bad weather with high wind and wave events, the stress amplitude can be higher, but due to short duration, the overall influence on the total crack growth can be small.

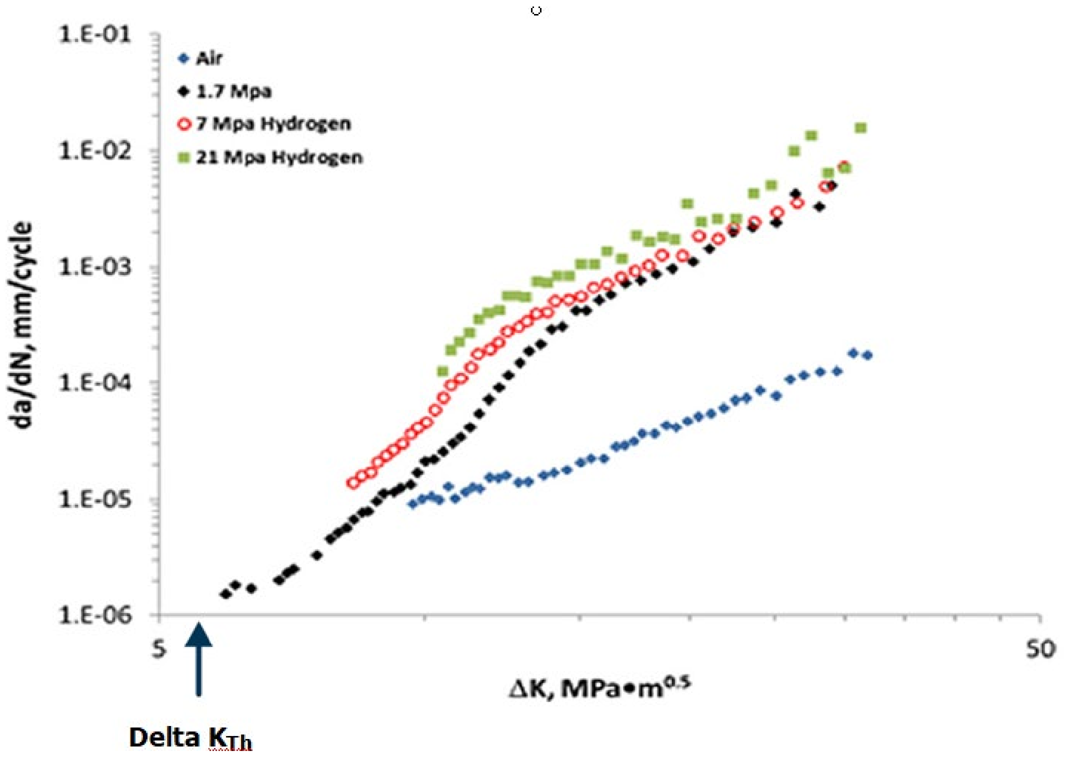


Figure 4-9 Fatigue crack growth of X100 steel in air and in hydrogen [32].

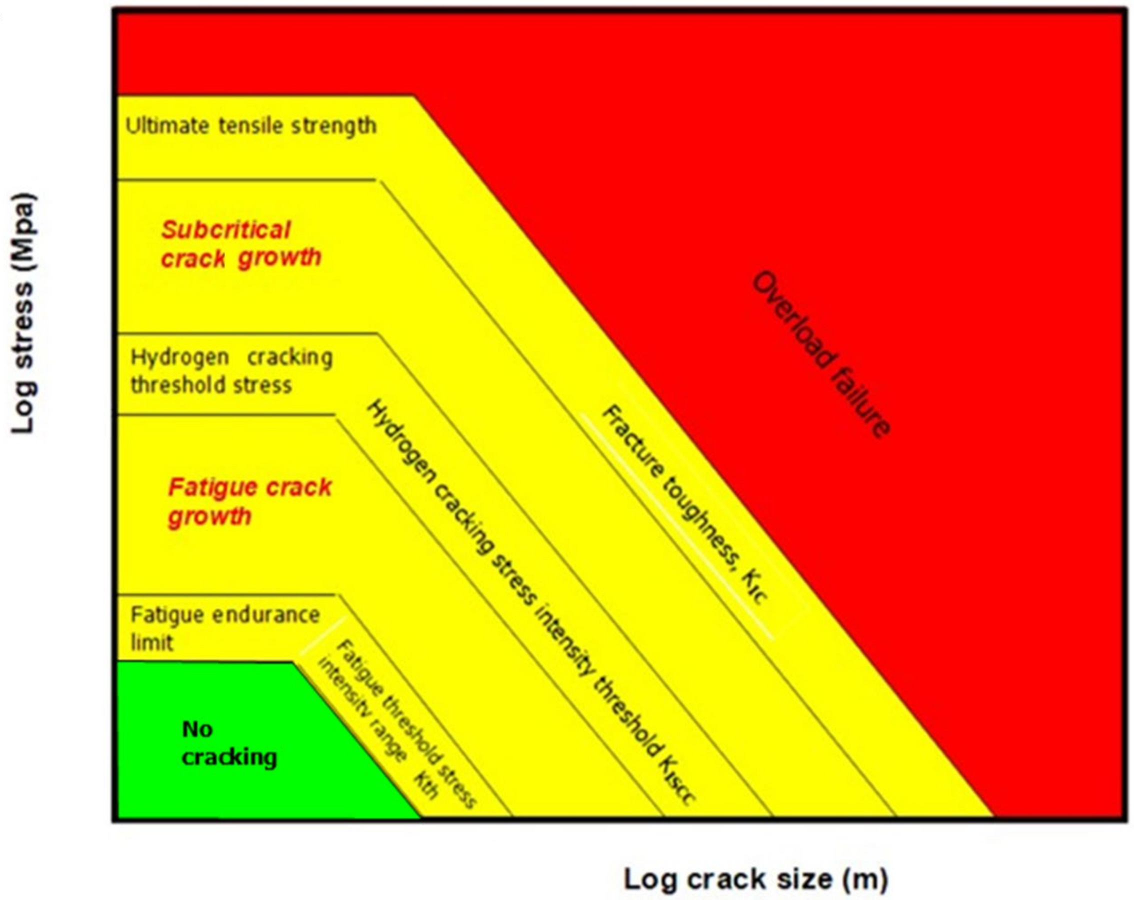


Figure 4-10 Failure stress versus flaw size with threshold for onset of fatigue crack initiation, initiation of subcritical cracks and final overload failure [33].

# 5 Hydrogen sources

Hydrogen may enter the steel structure prior to or in service. The main sources of hydrogen, relevant to jack-up structures are:

- Welding (prior to service)
- Cathodic protection

Also corrosion can cause stress corrosion cracking of high strength steels in seawater, but this is only the case in acidized environments (e.g. in presence of $H_2S$ or $CO_2$, in deep crevices or in putrefied water in closed compartments). In areas swept by aerated seawater the presence of oxygen will subdue the absorption of possible released hydrogen atoms at the steel surface.

## 5.1 Hydrogen from welding

The principal source of hydrogen during welding is moisture contained in the flux, i.e. the coating of electrodes, the flux in cored wires and the flux used in submerged arc welding. The amount of hydrogen generated is influenced by the electrode type. Basic electrodes normally generate less hydrogen than rutile and cellulosic electrodes.

It is important to note that there can be other significant sources of hydrogen, e.g. from the material, where processing or service history has left the steel with a significant level of hydrogen or moisture from the atmosphere. Hydrogen may also be derived from the surface of the material or the consumable. Sources of hydrogen will include:

- Oil, grease and dirt
- Rust
- Coatings
- Cleaning fluids

As described in Section 6.2 hydrogen cracking occurs when hydrogen atoms become trapped within the weld zone, causing cracks to form. Hydrogen cracking can occur in both the weld metal and the base material heat-affected zone (HAZ). The effect of hydrogen in the weldment is influenced by the hardenability and with high cooling rates, the risk of forming a hard, brittle microstructures in weld and HAZ.

The solubility of hydrogen in steel is strongly dependent on crystal structure, temperature and composition. Even more hydrogen is soluble in molten steel. Thus, if too much hydrogen is introduced into the liquid pool during welding, excess hydrogen will diffuse into the heat affected zone during cooling. Additionally, hydrogen is much more soluble in austenite than in ferrite and the solubility is reduced with reducing temperature when the liquid metal or high temperature HAZ is rapidly cooled down to room temperature under nonequilibrium conditions. This may result in hydrogen supersaturation in the low temperature transformation phases which in combination with contraction induced stresses can result in HACC before the excess hydrogen dissipates into the surrounding material.

To mitigate the risk of a hydrogen embrittlement from the welding process, the diffusible hydrogen can be baked out by applying temperature. Soaking of the weld upon weld completion by raising the temperature to around 200 °C for an extended period is widely used as a safeguard to avoid diffusible hydrogen in the structure during new-build or repair. This is also a well-known method applied to high-strength steel bolts during manufacturing to mitigate the risk of HE after installation, when stress is applied. As seen Figure 5-1 the hydrogen diffusivity as a function of temperature for ferritic materials displays a significant impact of heating above 150-200 °C.

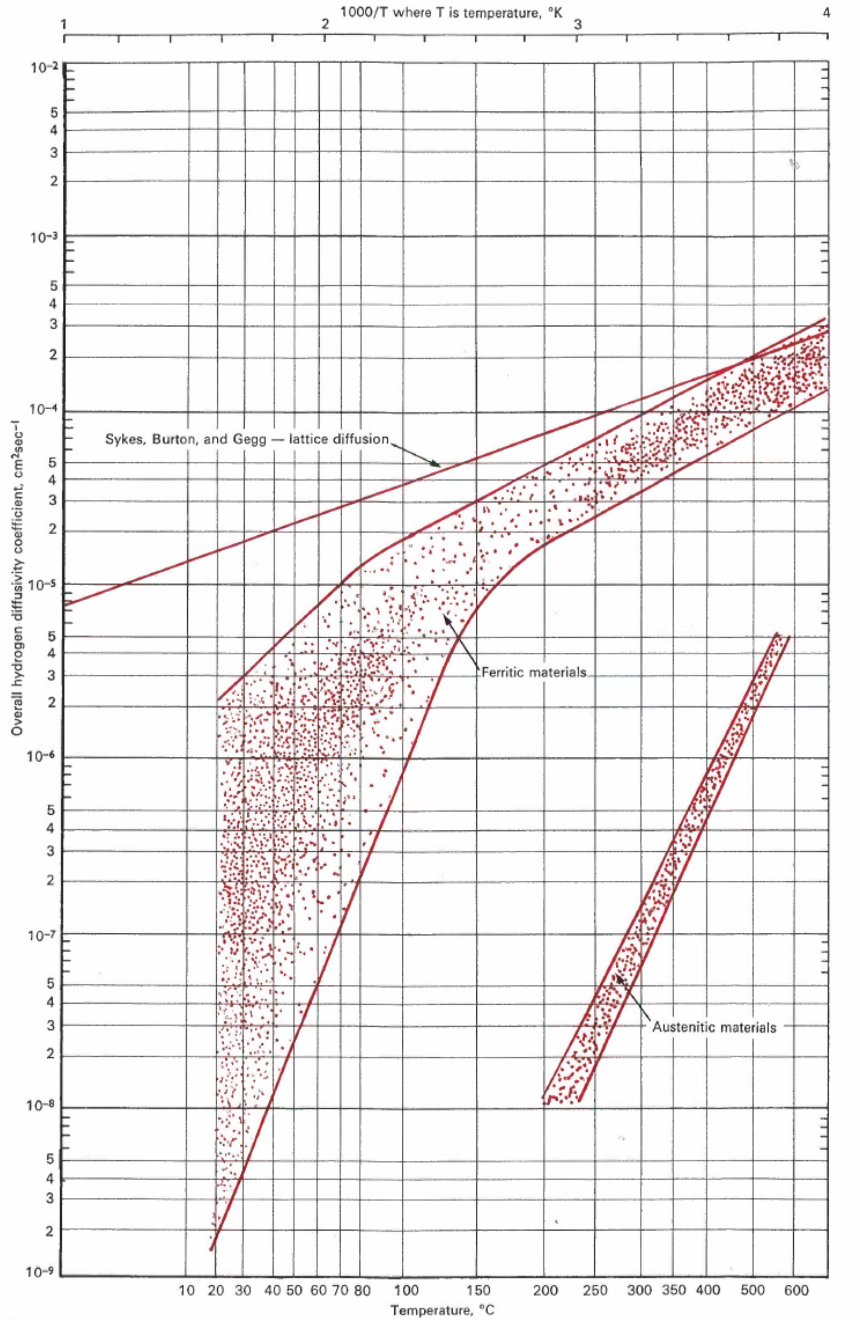


Figure 5-1 Hydrogen diffusivity as a function of temperature showing a significant impact of heating to 150-200 °C [34].

## 5.2 Cathodic protection

As previously mentioned, cathodic protection (CP) consists of lowering the electrode potential of the steel to sufficiently low potential to stop corrosion Figure 5-2 illustrates the influence of potential on the corrosion rate of steel in seawater. In neutral seawater, a potential around -0.8 V (Ag/AgCl) is sufficient to prevent corrosion.

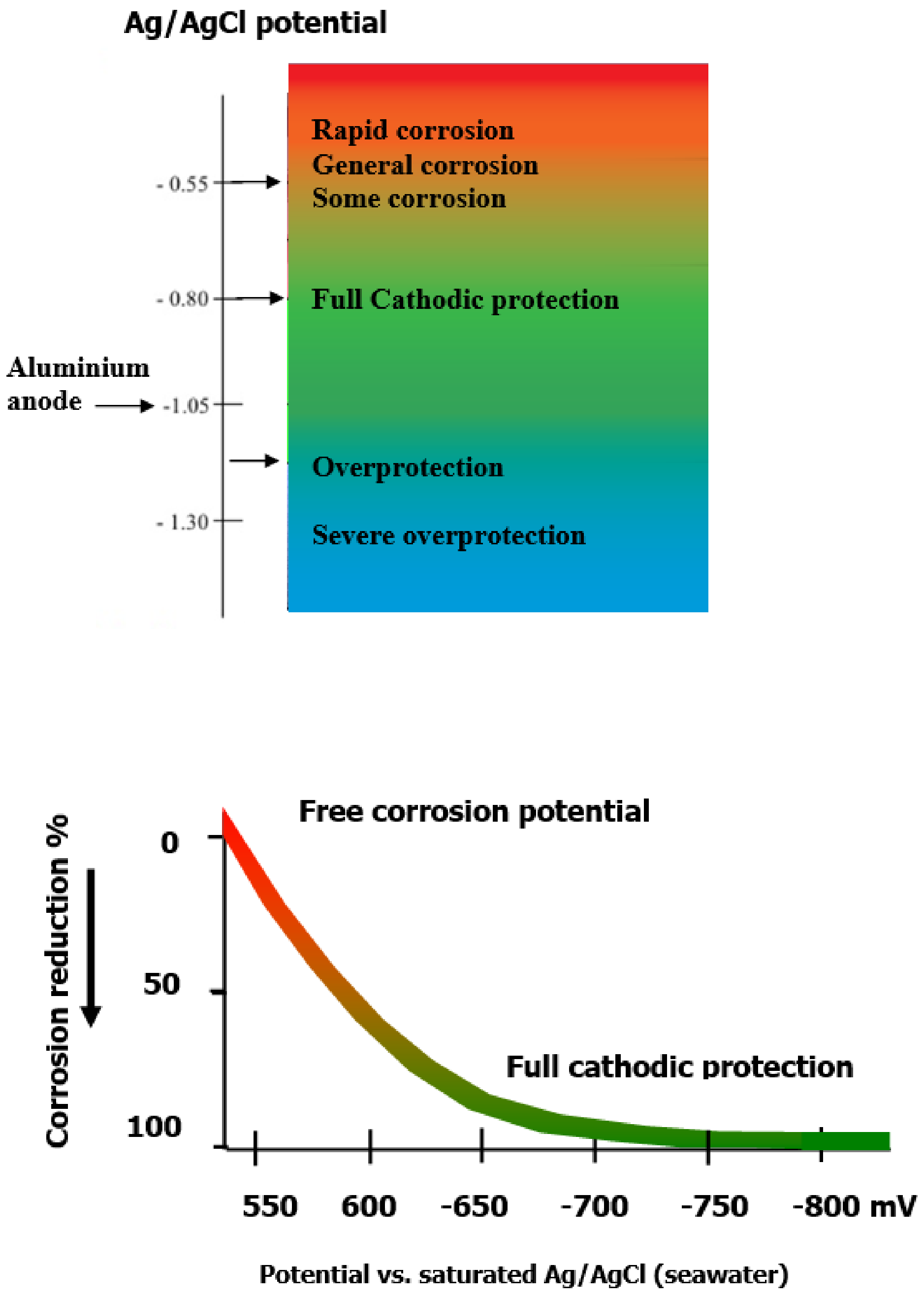


Figure 5-2 Illustration of by cathodic protection in seawater.

While a potential around -0.75 V (Ag/AgCl) is sufficient to prevent corrosion, CP systems designed to comply with recommendations and codes applicable to offshore structures [5] [35] [36] require a potential below -0.8 V (Ag/AgCl) for protection of steel structures in seawater. Additionally, aluminium sacrificial anodes with an output potential of -1.05 V (Ag/AgCl) are commonly used to ensure full polarisation of the structure and to account for potential drop in seawater and thereby enable some distance between the anodes. Furthermore, the anodes have to supply enough current throughout the design life also accounting for coating degradation. Over time, the anodes will be consumed because the current supply corresponds to corrosion of the anodes. Hence, enough anode material (anode mass) must be installed. A CP system designed according to class rules will provide a potential of between -900 and -1050 mV most of the time, but the penalty is that the liberation of hydrogen atoms at local bare steel surfaces increases exponentially, when the potential lowered from -0.80 V towards -1.05 V. Because of coating degradation and anode consumption the potential will gradually increase towards -800 mV at the end of the lifetime.

The simplified Potential-pH (Pourbaix) diagrams in Figure 5-3 identifies thermodynamically stable iron phases and the stability of hydrogen in water dependent on pH.  Immunity, i.e. solid iron being the thermodynamically stable phase, is achieved only at potentials below the reversible hydrogen electrode at any given pH. Accordingly, hydrogen evolution is irreversibly connected to cathodic protection. The hydrogen evolution during cathodic protection is illustrated in more detail in the hydrogen electrode equilibrium diagram in seawater at 25 °C in Figure 5-4. Before going into detail in the figures it should be mentioned that potential measurements require use of a reference electrode and that different reference electrodes are in the figures. The universally accepted reference electrode is known as the standard hydrogen electrode (SHE). However, this electrode is impractical to use for sea water applications. Hence, secondary reference electrodes are used, e.g. silver/silver chloride (Ag/AgCl) which has a stable, well-defined electrochemical potential over a large span of potentials in seawater. Another commonly used reference electrode is a saturated calomel electrode (SCE). The correlation between the potentials is:

$$\text{Ag/AgCl} = \text{SHE} - 0.222\ \text{V}$$

$$\text{SCE} = \text{SHE} - 0.241\ \text{V}$$

Potentials relevant cathodic protection of jack-up structures are shown in Table 5-1

Table 5-1 Surface potentials in natural seawater at 10 °C

| **Potential** | **SHE** (Volt) | **Ag/AgCl** (Volt) |
|---|---|---|
| Steel at free corrosion | -0.38 | -0.60 |
| Steel fully protected | -0.58 | -0.80 |
| Aluminium anode | -0.83 | -1.05 |

The sloping lines (isobars) in Figure 5-4 represent the intensity of hydrogen atom liberation expressed as the hydrogen gas pressure that corresponds to the same hydrogen activity. The dashed line represents the hydrogen activity corresponding to 1 bar hydrogen. The slope of the lines is given by the hydrogen equilibrium potential ($E_H$):

$$E_H = 0.059 \times \text{pH (Volt)}$$

At a given pH, a potential change will alter the hydrogen activity by a factor of 10 for every 0.059 V (100 per 0.118 mV) as shown by the sloping isobars. Hence, lowering the potential to achieve cathodic protection of the steel surface will increase hydrogen evolution. The isobaric lines represent the maximum possible pressures, but these pressures will never build up in practice because most of the liberated hydrogen will recombine to molecular hydrogen (hydrogen gas) and hence bubbles away. The theoretical pressures are only included to visualise the intensity of the hydrogen charging dependent on the protection potential.

The corrosion potential of steel in natural seawater at pH 8 is indicated with a dashed red line in Figure 5-4, that is around -0.35V (SHE) or -0.55 V (Ag/AgCl). The figure shows that the activity of atomic hydrogen on a bare steel surface corresponds about 0.01 bar hydrogen pressure. If the steel is connected to aluminium anodes the potential will be lowered towards the potential of the aluminium anodes -0.77 V (SHE) or -1.05 V (Ag/AgCl). At this potential, the hydrogen activity corresponds to $1x10^6$ bar hydrogen gas. Initially during polarisation of the structure, the potential will drop to a potential close to the anode potential resulting in rapid absorption of hydrogen in the steel.

However, due to the cathode reaction taking place at the steel surface $H^+$ ions are consumed. Thereby, the local pH will shift towards higher values. Moreover, if the steel is coated hydrogen evolution will only take place at locations exposing bare steel, e.g. surface braking cracks. In a narrow crack with restricted volume the pH shifts to higher values between pH 10 and 11 and the potential drop (IR drop) can easily increase the potential by more than 0.06 V as shown in Figure 5-5 and Figure 5-6. Due to the combined result of IR drop and concurrent alkalisation the hydrogen activity is reduced to more modest values as indicated by the green arrow in Figure 5-4. The net result can be hydrogen activity corresponding to 2–300 bars hydrogen.

Hydrogen atom activities corresponding to several hundred bars may sound as a huge amount of hydrogen atoms potentially in contact with the steel surface. It is, however, only 1-2% of the liberated hydrogen atoms that actually becomes absorbed in the steel as illustrated in Figure 5-7. showing current density and hydrogen absorption (uptake) in cathodically protected steel at varying potentials. The vast majority of the liberated hydrogen recombines to molecular hydrogen that is released from the steel surface. The rate of hydrogen uptake through the steel surface depends on the atomic hydrogen activity, surface condition, temperature and pressure of the environment in which the component is located. Nevertheless, the amount of absorbed hydrogen at low potentials is high enough to cause cracking if the material is simultaneous exposed to high stresses around flaws and defects.

In coated marine structures under cathodic protection the hydrogen evolution is not sufficient to cause hydrogen charging to critical levels. However, at coating defects exposing bare steel, the hydrogen activity can be sufficient to charging the material particularly at low potentials. Once the hydrogen atom is absorbed in the steel it is free, unless trapped, to migrate through the steel structure, i.e. diffuse to locations with lower hydrogen concentration and to leave the steel through surfaces exposed to environments with low hydrogen concentration, i.e. coated areas. This reduces the hydrogen concentration at the crack tip, but due to the stress concentration at the crack tip, the hydrogen concentration can be sufficient for crack growth by HISC.

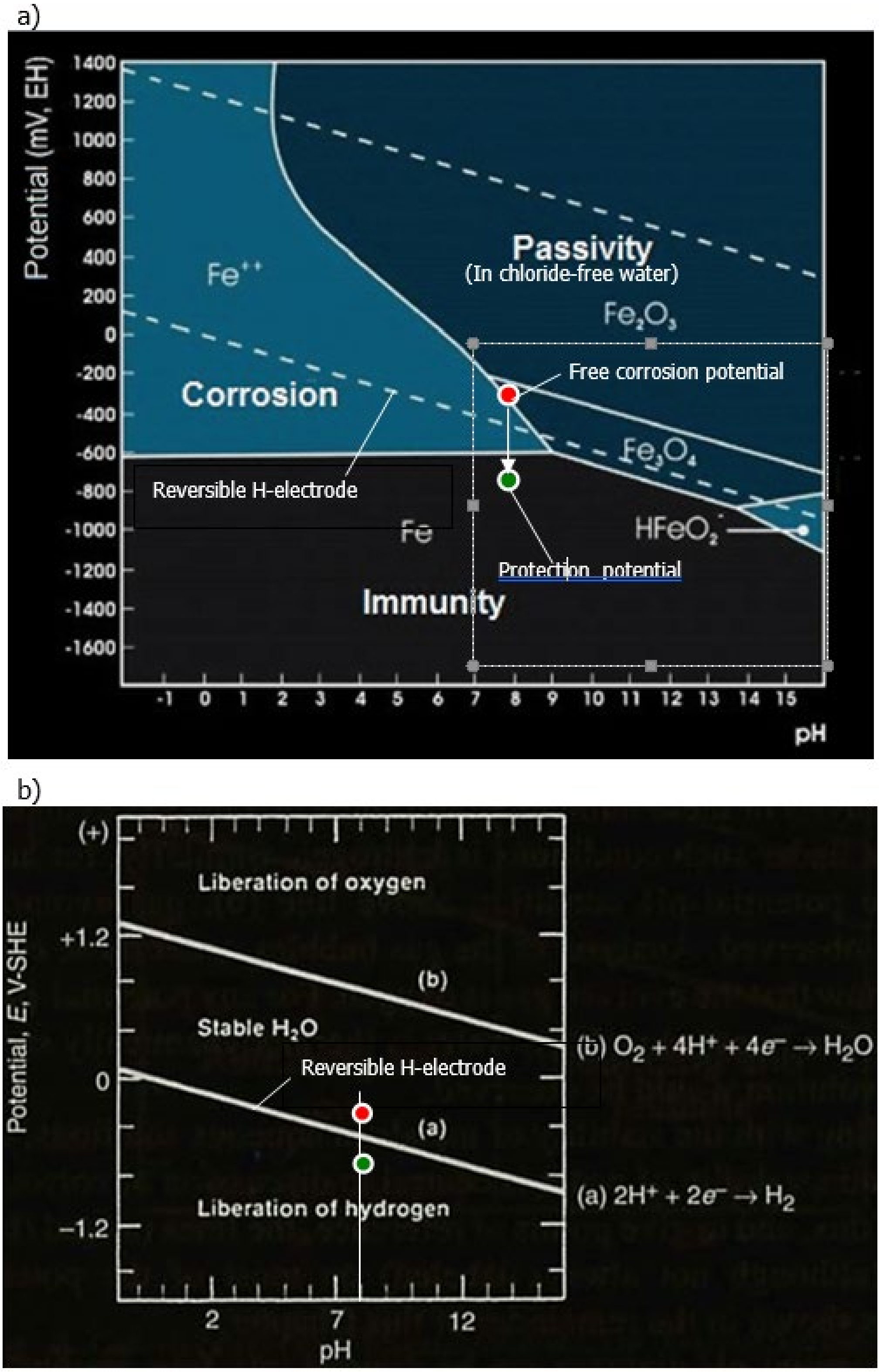


Figure 5-3 Pourbaix diagram, steel in water (a) and hydrogen equilibrium diagram (b).

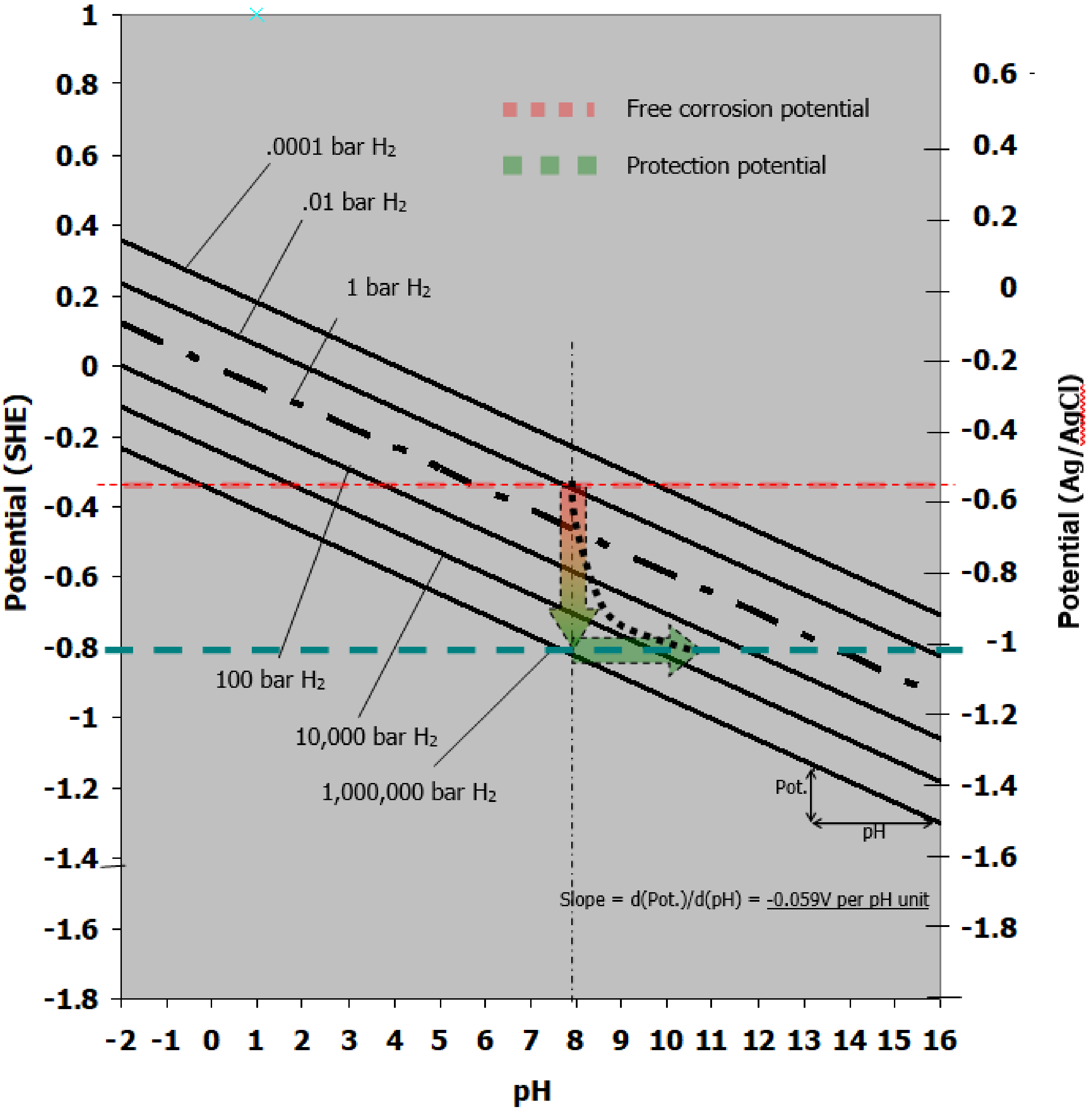


Figure 5-4 Free corrosion (red line) and protection potential (green line) versus pH in aerated seawater. The sloping lines marks the equilibrium lines for hydrogen atom activities expressed in equivalent hydrogen gas pressures [37].

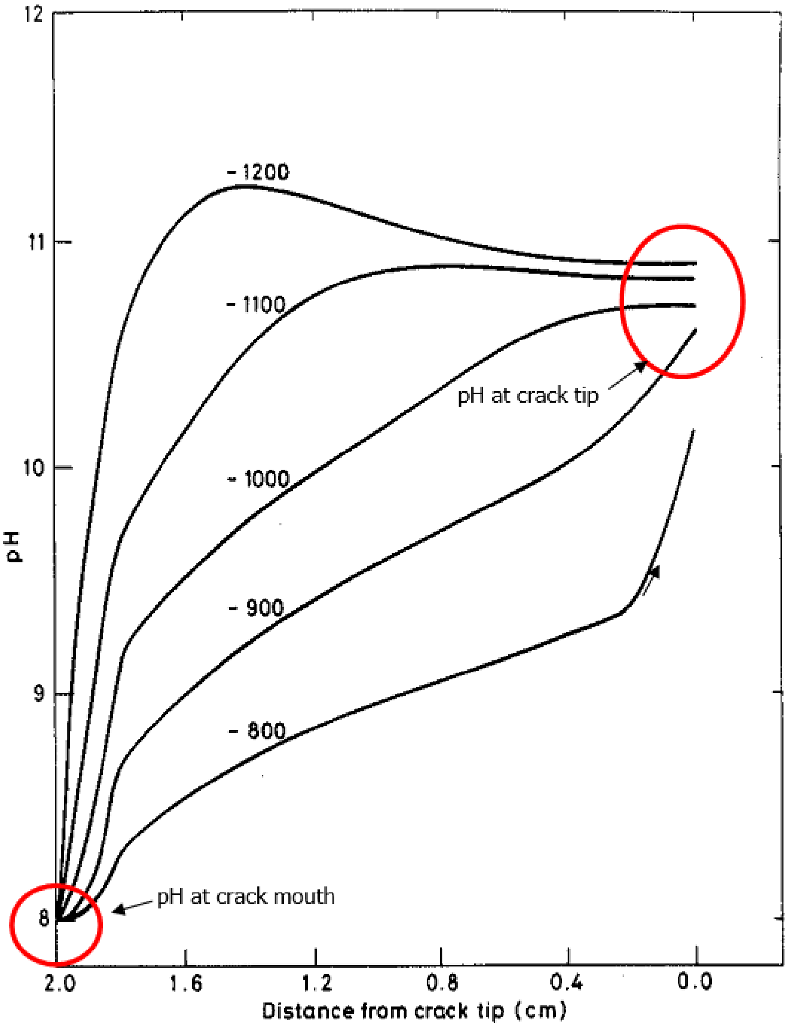


Figure 5-5 Variations of pH with distance from the crack tip for steels cathodically protected at different applied potential (mV SCE) in seawater [10].

It is possible to reduce the hydrogen absorption considerably by use of diode-controlled anodes to maintain surface potential between -0.75 and -0.85 V (Ag/AgCl) and thereby minimise the hydrogen charging of the steel to benign levels and preventing HISC. More information is provided in Section 9.5. However, this solution is considered impractical and opted out as it requires the structure to be electrically isolated from any nearby CP with sacrificial anodes protecting other structures or components.

To put the hydrogen absorption corresponding to a pressure of several hundred bars in perspective, the steady state hydrogen flux through the 7.4 mm thick steel wall of a standard 240 bar pressurised hydrogen gas cylinder at 20 °C is less than 15 $x10^{-12}$ $l/cm^2/s$, (i.e. 0.000000015 $ml/cm^2/s$ or 0.47 $ml/cm^2/year$) [38]. The cylinders are made of high strength steel type AISI 4140 (similar to 690 MPa steel) but there are no safety issues in handling and storing hydrogen gas cylinders unless the material is severely flawed.

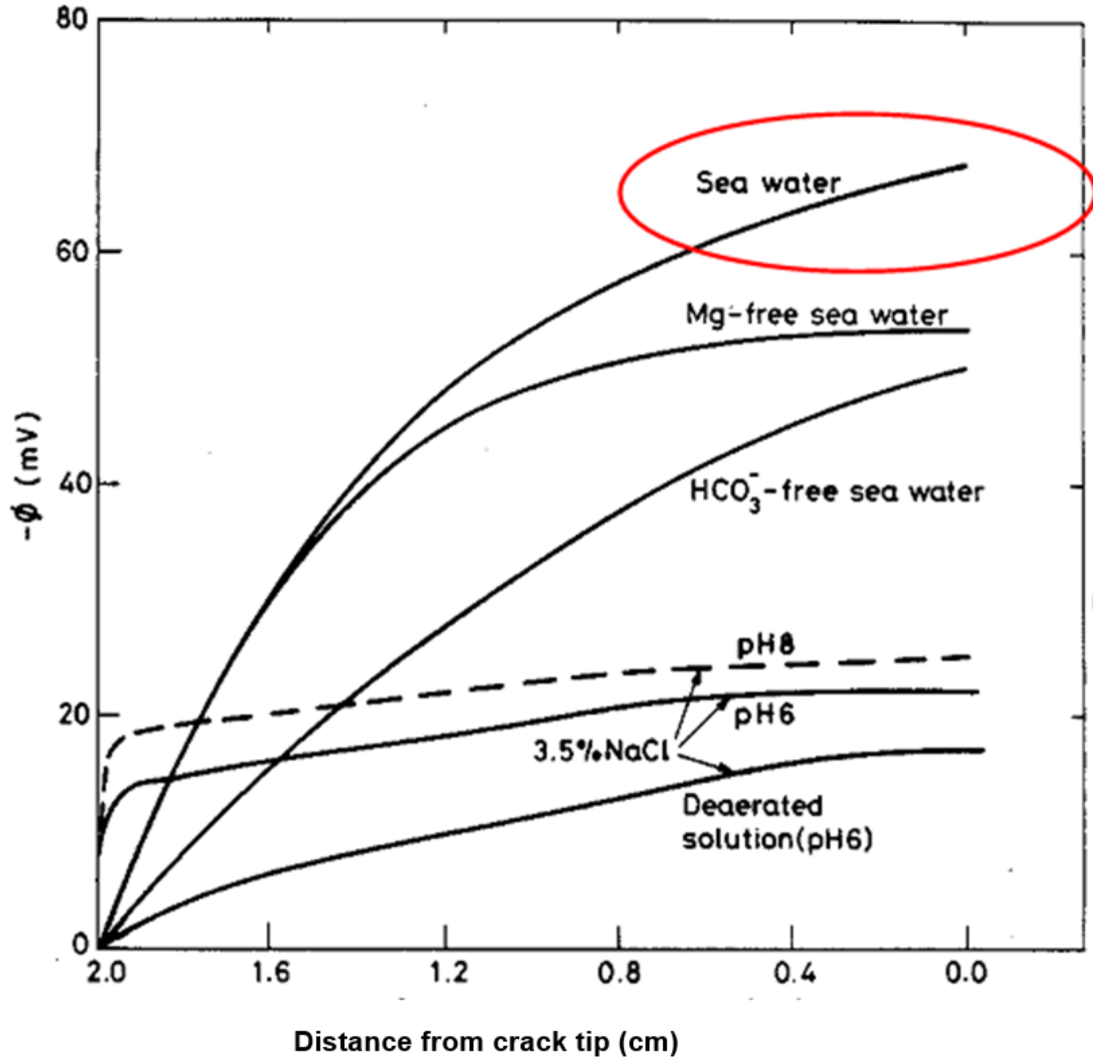


Figure 5-6 Variations of the potential drop with distance from the crack for different bulk solution chemistries [39].

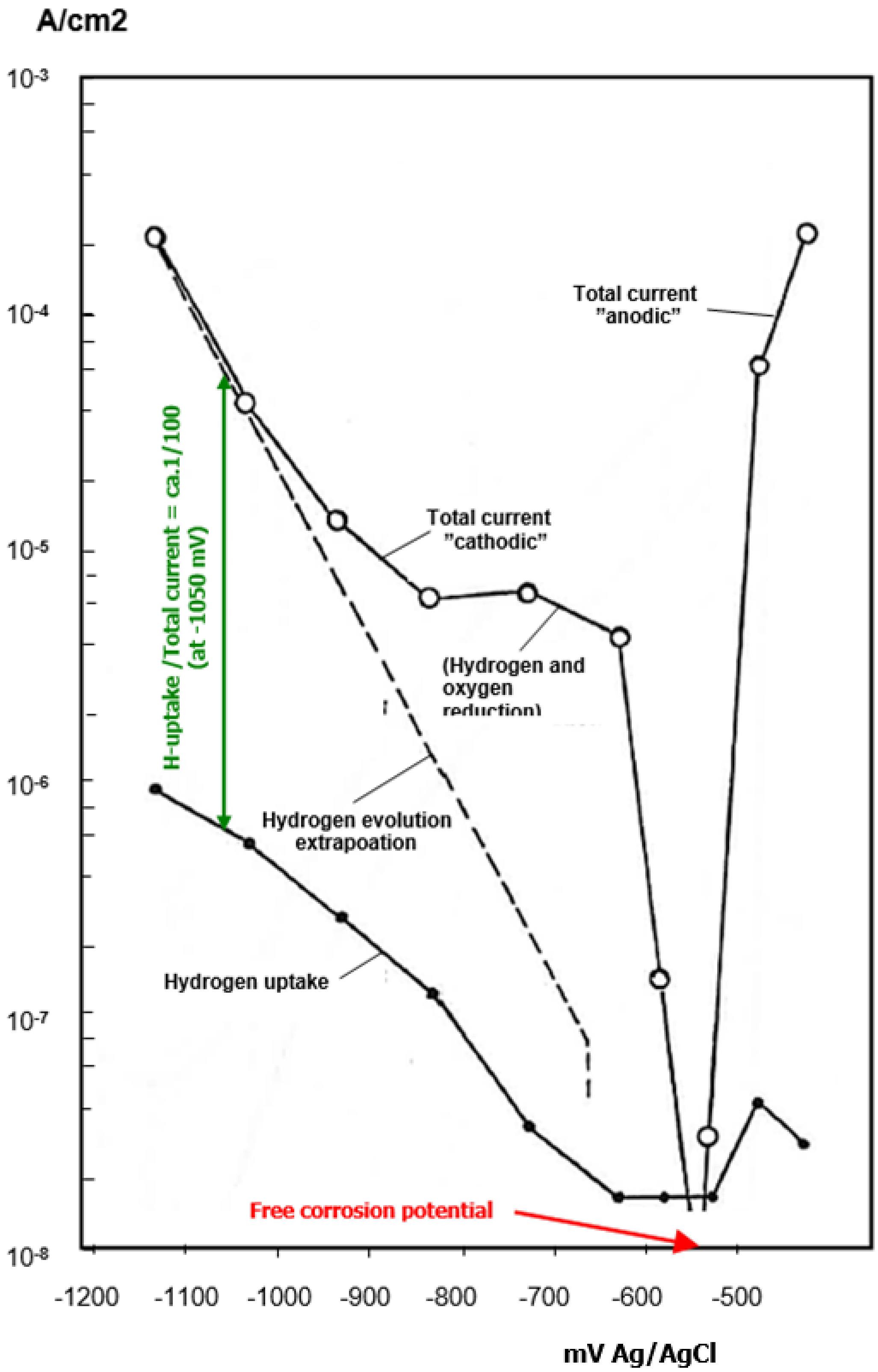


Figure 5-7 Hydrogen uptake and applied current versus potential for steel in seawater. 1 uA/cm² is equivalent to 1.25 x $10^{-7}$ mL $H_2$/second [37].

# 6 Material susceptibility

It takes a sufficient amount of hydrogen at a certain stress level in a susceptible material to cause hydrogen induced cracks. The present section concerns the susceptibility of the 690 MPa material focusing mainly on the welding process.

## 6.1 High strength steels in jack-up structures

Hydrogen can be considered an alloying element in steel on equal terms with e.g. carbon, oxygen and nitrogen but unlike these elements, hydrogen is undesirable as it can change the ability of the metal to absorb energy (ductility) and even tensile stress below yield strength (but above the proportionality limit) may cause crack initiation and propagation. Multiple phenomena such as hydrogen dissolution, hydrogen diffusion, hydrogen redistribution and hydrogen interactions with vacancies, dislocations, grain boundaries and other phase interfaces are involved in cracking process.

The use of high strength steels in jack-up rigs is not new, and field surveys have found cracking in drilling jack-ups, irrespective of the rig type. There is consensus that the cracking was caused by fabrication related defects in combination with hydrogen cracking (HISC) in service due to CP [1] [3]. Quite a few cases back in the 1980’s involved cracking inside the spud cans. Remedial measures such as removing anodes from the spudcans, regular flushing, the use of inhibitors/biocides and diode-controlled anodes to obtain more favourable cathodic protection potential did reduce the cracking incidents. However, in most cases where cracking occurred the level of cathodic protection (CP) was not measured. Several defects have been found during routine dry dock inspections in areas not covered by offshore inspection programmes.

Traditionally the use of 690 MPa steel was introduced in the jack-up construction through mechanical design to obtain sufficient strength and reduce weight. The use of 690 MPa steels limits the choice of shipyards due to extensive use of preheating during welding and requirements to quality assurance and quality control, QA/QC. Newer designs tend to increase the use of 355, 500 and 550 MPa steels in various structural elements related to the spudcan structure. Lower strength steel grades are cheaper to purchase, and production and welding cost is lower, but it has to be balanced with the weight increase.

Table 6-1 provides an overview of the high strength steels traditionally used in offshore structures [2]. Issues with hydrogen embrittlement in moorings have been encountered and elucidated in previous Ptil studies [40].

In addition to standard steels, quenched and tempered low alloy steels with minimum specified yield strengths in the range of 315 to over 690 MPa are used in the fabrication of jack-up legs. Moreover, standard shipbuilding steels are exemplified by ABS steel grades A to E with minimum specified yield strengths of 235 MPa. High strength steels with yield strengths in the range 550 to 690 MPa are also used for a variety of marine applications. Furthermore, 900 MPa steel has been proposed for future jack-ups to operate in deep water [2] [1].

Table 6-1 High strength steels used offshore [1]

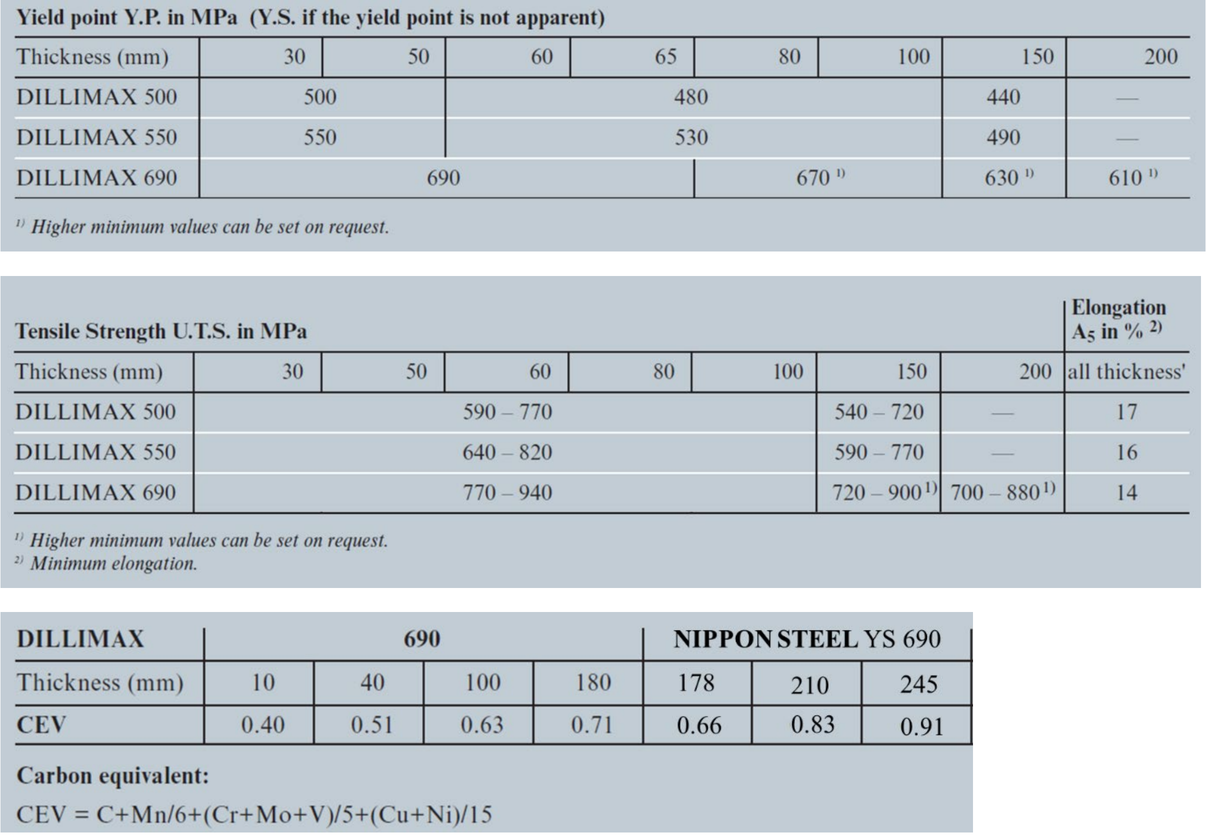
| High strength steels used offshore | | | |
|---|---|---|---|
| Strength (SMYS) MPa | Steel grade | Process Route | Application Area |
| 350 | X52 | Normalised<br>TMCP | Structures<br>Structure & Pipelines |
| 450 | X65 | Q & T<br>TMCP | Structures<br>Pipelines |
| 550 | X80 | Q & T<br>TMCP | Structures & Moorings<br>Pipelines |
| 650 | | Q & T | Jack-ups and Moorings |
| 690 | X100 | Q & T | Jack-ups and Moorings |
| 750 | | Q & T | Jack-ups and Moorings |
| 850 | | Q & T | Jack-ups and Moorings |

Research has repeatedly shown that the susceptibility to hydrogen embrittlement increases with the strength level of the steel, and 690 MPa steels are no exception. In a study on the corrosion behaviour of 690 MPa offshore steels in chloride media, it was found that the susceptibility to hydrogen embrittlement increased with increasing strength level, and that this susceptibility was more pronounced in the presence of cathodic protection [41].

It is further worth noticing that the mechanical properties and composition can vary significantly within a steel grade, as also shown in Figure 6-1. Especially the impact toughness in 690 MPa steels is an important parameter and previous studies have shown a variation from 74 J to above 120 J on impact toughness for 690 MPa steels [2].

High fracture toughness is needed to reduce hydrogen embrittlement effects as it helps to resist the initiation and propagation of brittle cracks in the steel, i.e. the material has the ability to undergo deformation before fracture, which gives time for the hydrogen to diffuse out of the stressed region, thus reducing the embrittling effect [31].

Regarding safe welding parameters, attention is drawn to the fact that the high strength steel class labels, 500, 550 and 690 MPa merely states the specified minimum yield strength (SMYS) of each class in its delivery condition (referring to the lowest thickness range). The actual mechanical properties and carbon equivalent can vary with plate thickness as illustrated by information from steel manufacturer data sheets copied in Figure 6-1. The thickness related changes are caused by a need to adjust the processing route and alloy elements, to ensure adequate mechanical properties throughout the plate thickness. These adjustments can have a significant influence on carbon equivalent CE which can increase from 0.40 at 20 mm thickness, to 0.91 at 250 mm thickness.



**Yield point Y.P. in MPa (Y.S. if the yield point is not apparent)**

| Thickness (mm) | 30 | 50 | 60 | 65 | 80 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|---|---|
| DILLIMAX 500 | 500 | | 480 | | | | 440 | — |
| DILLIMAX 550 | 550 | | 530 | | | | 490 | — |
| DILLIMAX 690 | 690 | | | | 670 1) | | 630 1) | 610 1) |

*1) Higher minimum values can be set on request.*

| Tensile Strength U.T.S. in MPa | | | | | | | | Elongation $A_5$ in % 2) |
|---|---|---|---|---|---|---|---|---|
| Thickness (mm) | 30 | 50 | 60 | 80 | 100 | 150 | 200 | all thickness' |
| DILLIMAX 500 | 590 – 770 | | | | | 540 – 720 | — | 17 |
| DILLIMAX 550 | 640 – 820 | | | | | 590 – 770 | — | 16 |
| DILLIMAX 690 | 770 – 940 | | | | | 720 – 900 1) | 700 – 880 1) | 14 |

*1) Higher minimum values can be set on request.*
*2) Minimum elongation.*

| **DILLIMAX** | 690 | | | | **NIPPON STEEL** YS 690 | | |
|---|---|---|---|---|---|---|---|
| Thickness (mm) | 10 | 40 | 100 | 180 | 178 | 210 | 245 |
| **CEV** | 0.40 | 0.51 | 0.63 | 0.71 | 0.66 | 0.83 | 0.91 |

**Carbon equivalent:**

CEV = C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15

Figure 6-1 Copies from steel manufacturer brochures. Upper tables show specified minimum yield stress and tensile strength ranges. The lower table shows carbon equivalents for two high strength steel used in the offshore industry [42] [43].

It is important to take the actual strength and hardness into consideration to get an overview of the materials HACC susceptibility. Figure 6-2 illustrates the change in hydrogen embrittlement susceptibility of quenched and tempered high strength low alloy steels in terms of ratio of reduction of area (RA) at fracture versus hardness and ultimate tensile strength. The shape of the curves matches the curve previously presented in Figure 4-5, representing the change in fracture toughness against tensile strength. The hatched area illustrates the boundary for high strength steels (690 MPa). The figure also shows with a dashed green line the maximum hardness considered acceptable for ISO property class 8.8 and subsea carbon steel and low alloy fasteners which are generally considered acceptable for exposure to cathodic protection. Reduction of area is a measure for ductility. As a minimum, it is recommended to determine reduction of area of the base metal, HAZ and weld metal by constant strain rate testing (at 8.3 x 10-6 mm/mm/s) in air and seawater at -1050 mV (Ag/AgCl). As indicated in Figure 6-2 it appears that an acceptance criterion of $RA_H/RA_{Air} > 0.90$ where $RA_H$ and $RA_{Air}$ are reduction of area at break in hydrogenated condition and in air, respectively, can be appropriate.

Maintaining $RA_H/RA_{Air}$ above 0.90 gives credit to the intrinsic material properties. Resistance to weld cold cracks and hydrogen embrittlement can be obtained by careful selection and testing of steels, weld consumables and welding parameters. Furthermore, a qualified welding procedure specification (WPS) is required for each steel to control the thermal cycle during welding and eliminate excessive hydrogen absorption.

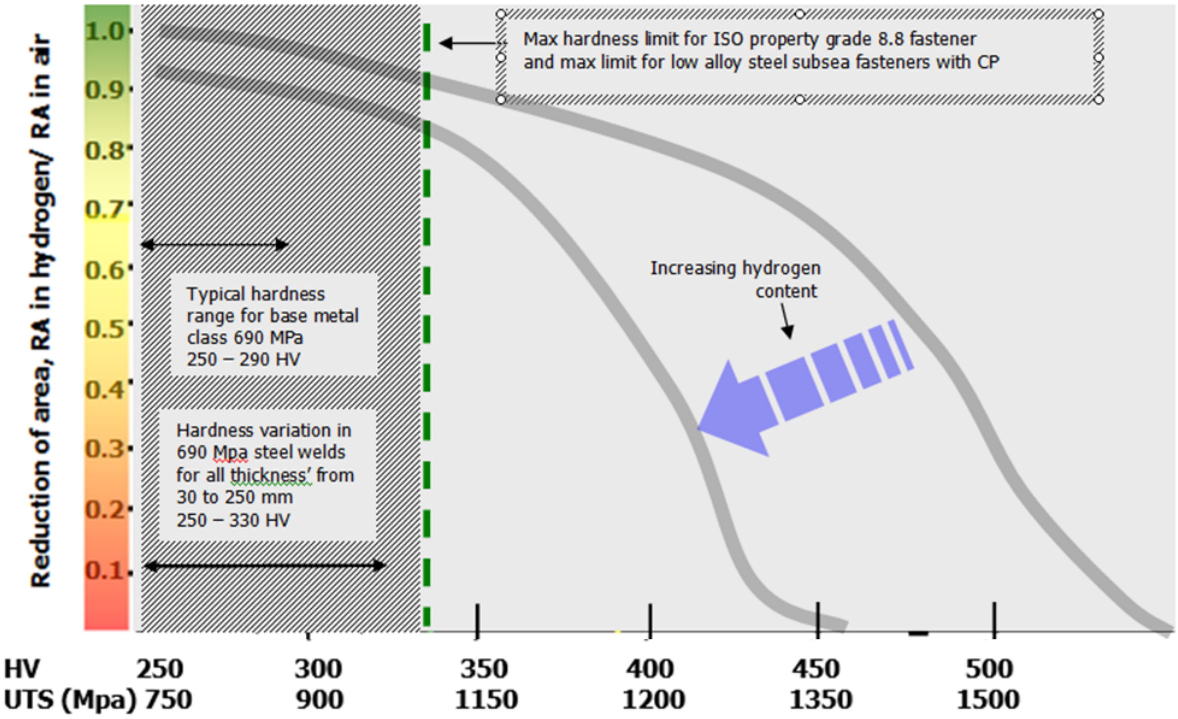


Figure 6-2 Susceptibility to hydrogen embrittlement expressed as ratio of reduction of area at fracture in slow strain rate testing in hydrogen and air, versus hardness.

The risk of fabrication related HACC and HISC can be reduced by selecting materials for the critical parts in the leg and spudcan area with actual yield strength below 700 MPa and with hardness in the completed weld zones below 330 HV (350 HV as an absolute upper limit). The 350 HV limit is based on practical experience with high strength steels under cathodic protection in seawater as per DNV [5] and ABS [4]. As indicated Figure 4-5 and Figure 6-2 these experienced based limits are substantiated by fracture toughness testing based on ratio of RA in hydrogen and air showing that quenched and tempered high strength low alloy steel with hardness < 350 HV can retain more than 90% of the fracture toughness of steels with hardness 250 HV. Furthermore, the experience is that ferritic/ferritic-pearlitic and low alloy steels with actual yield strength and tensile strength below 700 MPa and 750 MPa respectively have proven compatibility with subsea CP systems [5], i.e. they are intrinsically HISC resistant in flawless condition. Steels that exceed these limits either in base metal, HAZ or weld metal may contain un-tempered martensite and should be used only if the actual material and deposited weld metal is shielded from low potentials or is validated by fracture mechanics testing at the applied level of cathodic protection (reference is made to Section 3.10). Steels are normally not purchased by maximum specified yield strength or hardness, but it is worthwhile to discuss these issues with the steel supplier and to request that all mechanical properties in the materials certificates, i.e. yield strength, ultimate tensile strength, yield ratio, elongation, hardness, impact toughness values (surface, ¼ wall and mid wall), and carbon equivalents (CE), shall be presented as histograms like in the example in Figure 6-3 to illustrate the distribution of properties for each plate thickness group of the delivered steel and thereby provide guidance for the selection of material for weld procedure qualification (WPQ).

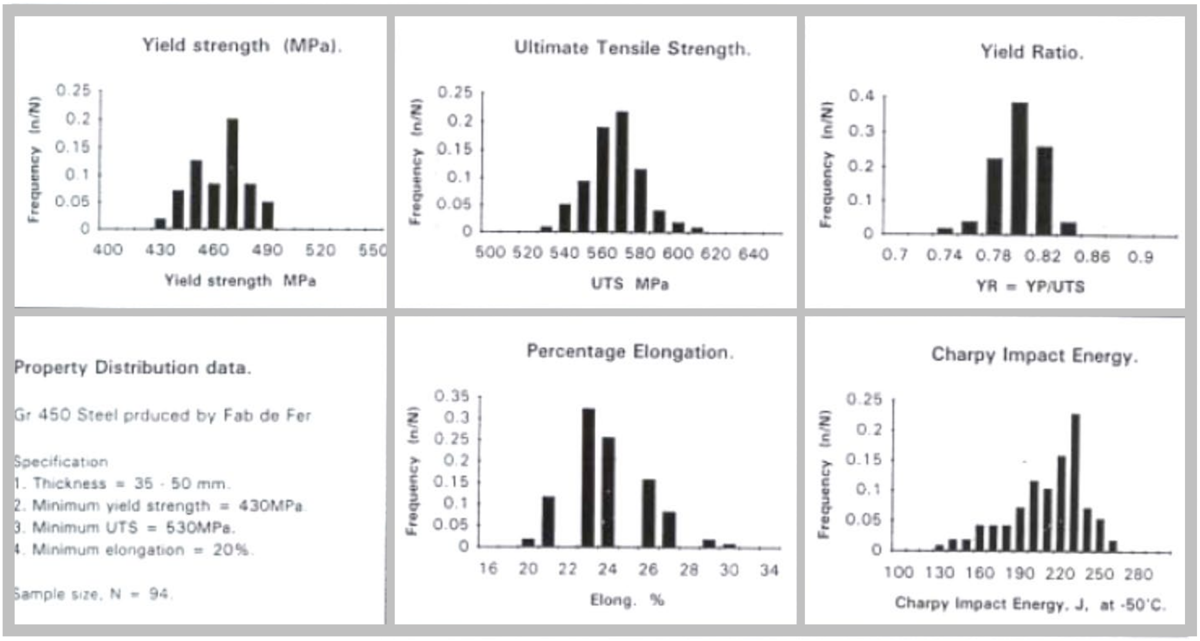


Figure 6-3 Example of variations in mechanical properties for450 MPa steel.

## 6.2 Welding high strength steels

It is well known that high strength steels can be susceptible to hydrogen assisted cold cracking (HACC), also known as weld cold cracks, during the welding process. The term delayed cracking is also used as the cracking takes place after the weld has cooled down and sometimes occurs several days after welding. The tendency to cracking is strongly related to the steel quality and quality of the weld consumables especially as a relatively high carbon equivalent is required to obtain the sufficient mechanical properties by hardening and tempering in heavy plates. Thus, high strength quench and tempered steels like class 690 MPa is more adversely affected by the weld thermal cycle than conventional carbon and carbon-manganese structural steels which can be produced by thermo-mechanical rolling.

Typical appearances of weld cold cracks are illustrated in Figure 6-4. The combined effect of the following factors is responsible for cracking:

- Hydrogen generated by the welding process
- A hard brittle structure which is susceptible to cracking
- Tensile stresses acting on the welded joint

In C-Mn steels, transgranular cracks tend to form in the coarse grained HAZ, but the cracks can also run into the weld metal.  This is because the HAZ normally has a more brittle structure than the weld metal because electrodes (filler metal) with a lower carbon equivalent (CE) than the parent metal and is selected to reduce the hardenability of the weld metal. Opposite, if the risk of cracking is increased if the weld metal carbon content exceeds that of the parent steel. Weld metal cracks can also be observed, especially when welding thick section components.

In low alloy high carbon steels intergranular, rather than transgranular, cracks are typically formed in the coarse grain and hard HAZ region. In fillet welds, cracks in the HAZ are usually associated with the weld root and parallel to the weld. In butt welds, the HAZ cracks are normally oriented parallel to the weld bead. In low alloy steels, as the weld metal structure is more susceptible than the HAZ, cracking may be found in the weld bead.

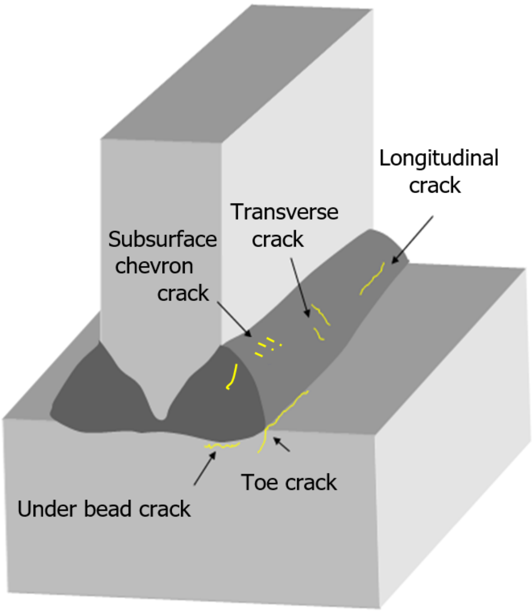


Figure 6-4 Examples of hydrogen assisted cold cracking in high strength steel.

Phase transformations do not only take place in the weld metal. Also the HAZ close to the fusion line has been exposed to a high temperature and martensite can form in this region. Further away from the fusion line both the maximum temperature in the weld thermal cycle and the cooling rate are reduced.

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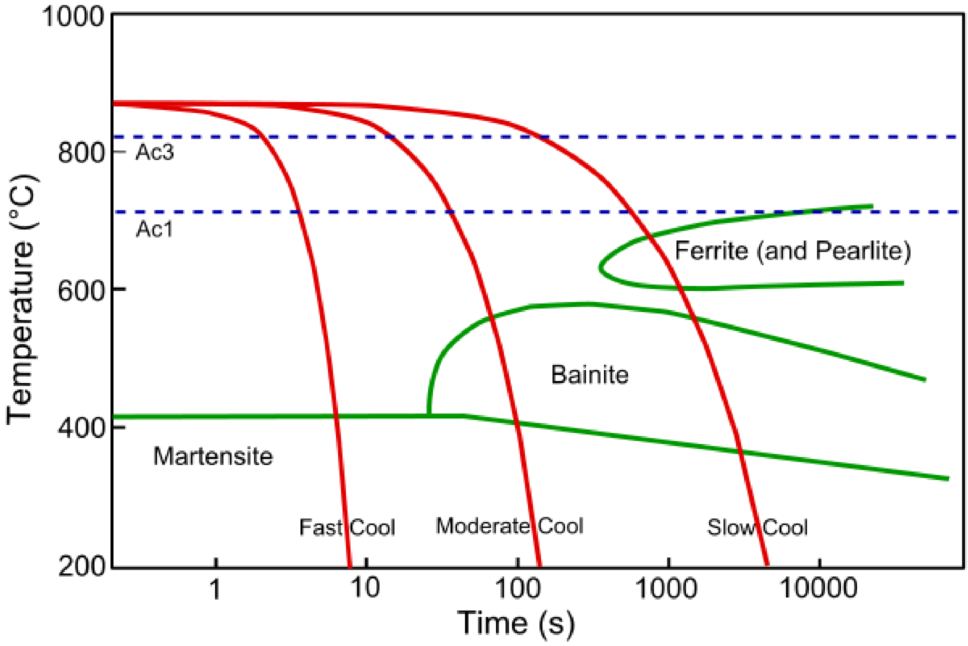


Figure 6-5 Schematic CTT diagram.

Weld residual stresses are those stresses that remain in the welded component in the absence of external stresses. When the weld is cooled from a high temperature thermal contraction takes place. The shrinkage introduces residual stresses after cooling down the welded structure. Due to differences in local cooling rate through the body (surface or interior) there will be local variations in thermal contraction introducing non-uniform residual stresses. In addition phase transformation will result in additional stresses because of volume difference between the phases. The stresses generated across the welded joint as it contracts will be greatly influenced by external restraint, material thickness, joint geometry and fit-up. Poor fit-up (excessive root gap) in fillet welds markedly increases the risk of cracking. The degree of restraint acting on a joint will increase as welding progresses, due to the increase in stiffness of the fabrication. A simplified distribution of weld residual stresses is shown in Figure 6-6.

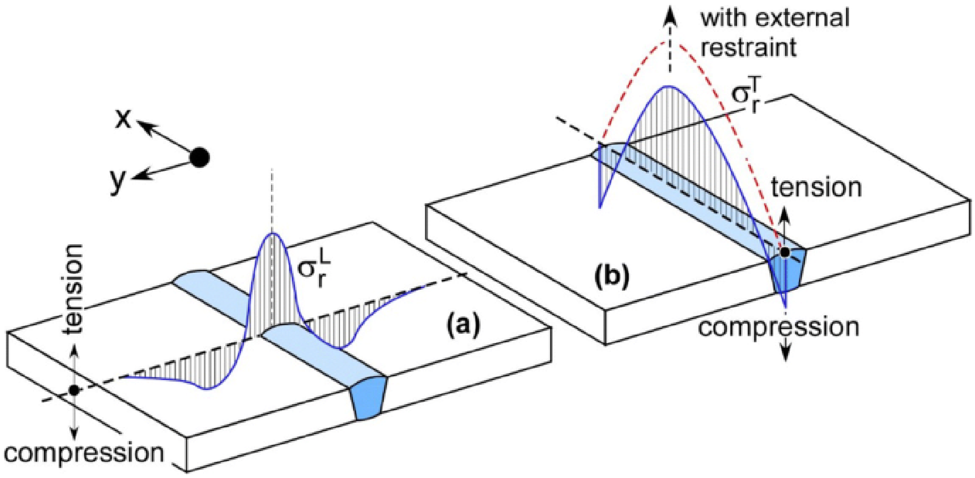


Figure 6-6 Weld residual stresses.

The weld residual stresses can be at the level of the yield stress of the material. Combined with a brittle microstructure and diffusion of hydrogen to these highly stressed areas cracking can take place. Cracks are more likely to initiate at regions of stress concentration, particularly at the toe and root of the weld.

Material thickness will influence the cooling rate and therefore the hardness level, the microstructure produced in the weld metal and HAZ. The thickness of the joint, together with the joint geometry and the cooling rate of the is decisive for the microstructure and the hardness of the weldments (weld metal and HAZ). Consequently, a fillet weld is likely to have a greater risk than a butt weld in the same material thickness.

The heat input to the material from the welding process, together with the material thickness and preheat temperature, will determine the thermal cycle and the resulting microstructure and hardness of both the HAZ and the weld metal. Increasing the heat input will reduce the hardness level, and therefore reduce the risk of HAZ cracking. However, as the diffusion distance for the escape of hydrogen from a weld bead increases with increasing heat input, the risk of weld metal cracking is increased.

The higher the CE value, the greater is the risk of hydrogen cracking. High strength steel does not only have high strength. Often the ductility is reduced. To suppress weld cold cracks it is necessary to control the welding process to eliminate excessive hydrogen absorption and ensure an appropriate thermal cycle during welding. Thus, a qualified welding procedure specification (WPS) defining adequate preheat, weld heat input, interpass temperature and post weld soaking at suitable time and temperature for each design is required to ensure high quality welding.

It is recommended that the weld procedure qualification (WPQ) includes hardness testing and constant strain testing as described above. WPQR testing should include service usability test by constant strain rate testing (at 8.3 x 10-6 mm/mm/s) of weld transverse (HAZ-WM-HAZ) as well as longitudinal, all weld metal, reduced diameter specimens, in air and in seawater at – 1050mV (Ag/AgCl). A maximum hardness of 330 HV should be the target for both base metal and weld zone (HAZ and weld metal), and 350 HV as absolute upper limit [4]. These limits can also be adjusted if the welds are further qualified by fracture mechanical testing and metallurgical evaluations focusing on susceptibility to cold cracking of the welded structure. Figure6-7 illustrates the total weld heat input relationship for welding of quench and tempered steel. Keeping the combination of preheat, interpass temperature, weld heat input high enough to reduce the cooling rate and thereby suppress martensite formation is essential for the prevention of cold cracking in the weld and HAZ. Delaying the cooling is decisive for the final microstructure in the weld metal and HAZ. This longer cooling time results in lower hardness and a less sensitive microstructures, but also reduces the hydrogen levels and allow for easier diffusion of hydrogen out of the metal while temperature is still high, and before the martensite transformation starts. Also upon further cooling more hydrogen will diffuse out and less hydrogen retained in the weld.

A final post weld soaking further allows more hydrogen to escape before the full effect of residual stresses and possible applied stresses affect the structure. On the other hand, the total heat input must be kept low enough to avoid over-tempering or grain growth in previous weld runs, as this will lower the strength and toughness.

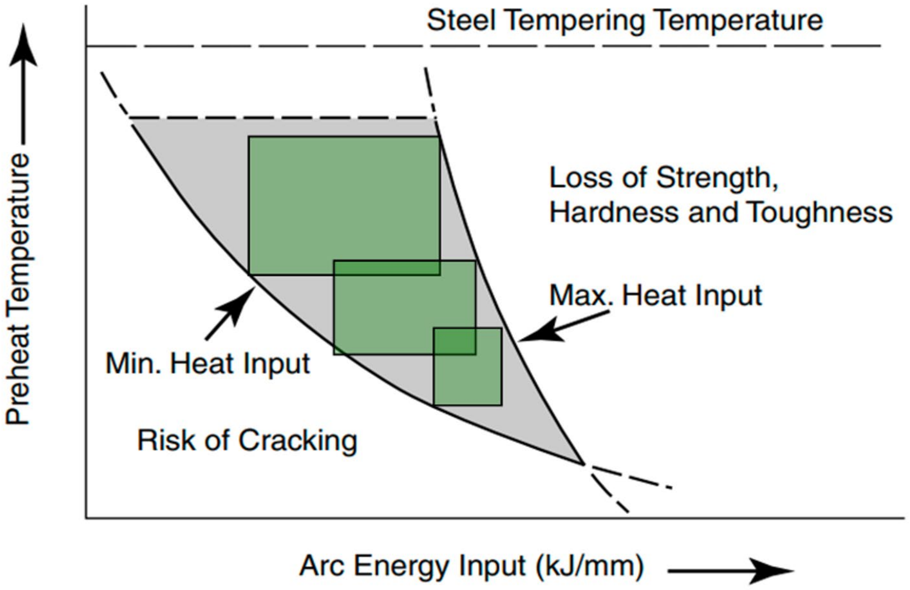


Figure 6-7 Schematic diagram illustrating limitation of maximum and minimum weld heat inputs for welding of quench and tempered steels [44].

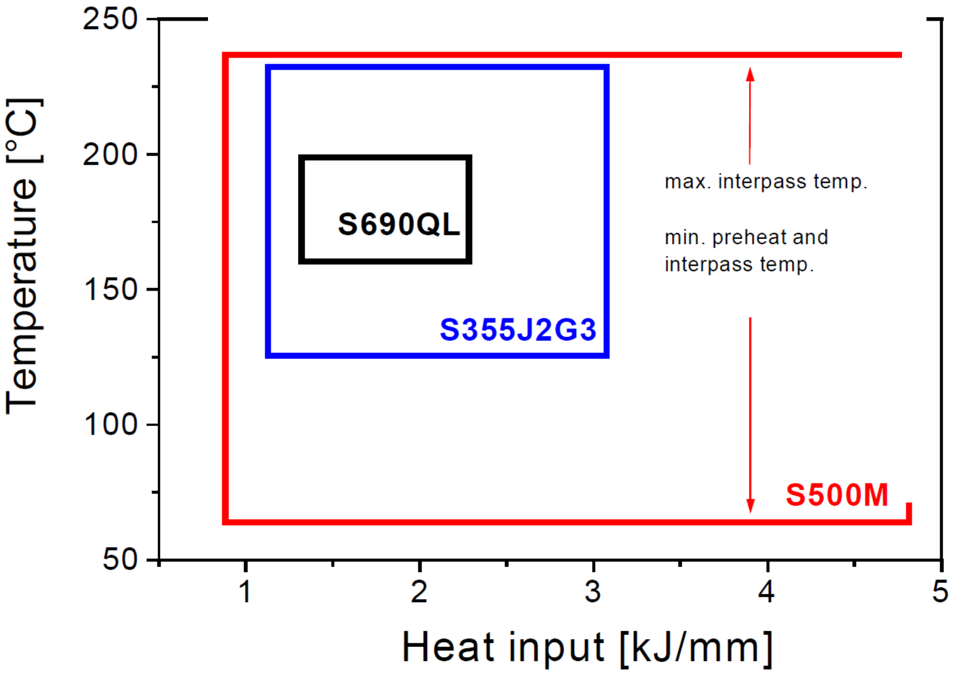


Figure 6-8 Examples of working ranges ("safe windows") for welding of different structural steels with plate thickness providing equal load carrying capacity [45].

The desire to prevent cracking and over-tempering results in the tornado shaped "safe window, as can be seen in Figure 6-7. The shaded areas illustrate the increased narrowing in arc energy input with lowering of preheat and interpass temperature or the increased need of preheating with expansion of the arc energy range. The green shaded areas illustrate the development of limitations in arc energy input with decreasing preheat temperature. The exact position and width of the safe window varies with the actual chemical compositions, mechanical properties of the base metal and the deposited weld metal. This is illustrated in Figure 6-8 showing typical working ranges for welding of structural steels in varying plate thickness providing same load bearing capacity. Selection of a steel grade with an inherent larger welding window has several advantages and also major implications on cost lowering. It will also make it easier to find and use weld consumables with sufficient resistance to hydrogen cracking.

Regarding the weld metal itself, the general requirement for the weld metal is to match the strength of the steel. This necessitates an increase of weld metal alloying elements which, however, also increases the tendency of HACC to the extent that it is often the weld metal that defines the safe combination of preheat and heat input levels. Thus, upon rapidly cooling a cast microstructure is formed in weld metal.

The following measures are recommended to avoid hydrogen cracking during welding:

- Preheating
  - Preheating the base material before welding can be an effective method for reducing the risk of hydrogen cracking. Preheating reduces the cooling rate during welding, which can help prevent the occurrence of hydrogen-induced cold cracking.
- Heat input control
  - Controlling the heat input during welding is another effective method for preventing hydrogen cracking. A higher heat input can reduce the cooling rate and prevent the formation of cracks.
- Soaking
  - Soaking of the weld upon weld completion at a temperature above 150 °C and typically around 200 °C for an extended period is widely used as a safeguard to avoid diffusible hydrogen in the structure during new-build or repair. The meaning of soaking is continuation of the preheat and the rise from preheat temperatures normally in the range 110-150ºC to approximately 200ºC for a given period in order to diffuse hydrogen from the weld metal before cooling down to ambient temperature where HACC can initiate. This is also a well-known method applied to high-strength steel bolts during manufacturing to mitigate the risk of HE after installation, when stress is applied.
- Post-weld heat treatment
  - Post-weld heat treatment can reduce residual stresses and modify the microstructure of the weldment, making it less susceptible to hydrogen-induced cold cracking. Post-weld heat treatment should be done at high enough temperatures (550 to 600°C) to be effective. However for the leg structures on a jack-up rig this is not an option. Dimensions are large and patch-wise post-weld heat treatment introduces loss of dimensional control due to warping. Dimensions in these structures are critical for the jacking operations.
- Low-hydrogen welding consumables
  - Using low-hydrogen welding consumables can reduce the risk of hydrogen cracking. Low-hydrogen consumables have a low potential for hydrogen contamination, which can help prevent the formation of cracks.

- Careful handling and storage of welding consumables
  - Welding consumables should be handled and stored carefully to prevent exposure to humid environments and subsequent uptake of atmospheric moisture. Welding consumables should be baked according to recommended re-drying procedures, and any consumables showing rust appearance on the wire surface should be disregarded.
- High-quality shielding gases
  - Selection of high-quality shielding gases containing a minimum level of moisture can reduce the risk of hydrogen cracking.

As outlined above, the welding process is essential to obtain a tough weld microstructure with better resistance to hydrogen cracking than a harder and more brittle structure. In a relatively hard, alloyed weld metal, the cracking is usually transverse and perpendicular to the weld surface. The as-welded structure should be inspected for cracks, and NDT should be delayed at least 48 hours after welding to increase the probability of detecting almost all of cracks that are likely to form.

Following these recommendations can ensure sound welds and help prevent hydrogen cracking, but it may not easily when welding the complex jack-up structures in large shipyards, at different locations (countries). Accordingly, meticulous NDT is required.

# 7 Stress

Hydrogen induced stress cracking inherently requires a certain stress level. The magnitude and type of stresses are a driving factor. The following sections aim at describing the causes and the magnitude of tensile stresses that can cause hydrogen embrittlement and trigger hydrogen-induced cracking.

## 7.1 Tensile and residual stress

Thermodynamic driving forces will aim for a state of equilibrium and will therefore drive (or attract) hydrogen towards energetically favourable areas within the microstructure. During this migratory process, the hydrogen will interact with other features, and it is this migratory process of monatomic hydrogen through the matrix which is believed to form the basis for HACC (Oriani, 1994) [19]. These microstructural features (such as second phase particles and dislocations) will have attractive and repulsive energies that produce compressive, shear and tensile stress fields.

Tensile forces tend to increase the area around microstructural features, which will provide more space for the diffusing hydrogen to accumulate. Thermodynamic evaluations performed by Li et al. (1966) showed that that under equilibrium conditions, when there is uniform chemical potential, dissolved hydrogen will tend to concentrate on the tensile side of an obstacle and not on the compressive side. The reasoning is that an increase in stress (on the tensile side) will lower the chemical potential in that vicinity, therefore creating attractive interactions in order to reach equilibrium.

The process in which molecules move from a region of higher concentration to a lower concentration is called diffusion and is governed by Fick's Law. In order to achieve equilibrium, atomic hydrogen will diffuse to areas of high tensile stress, as these areas will have lower chemical energy states.

Plastic strain fields around discontinuities (i.e. voids, non-metallic inclusions and grain boundaries) will also provide areas of lower chemical potential, which then attracts the migrating hydrogen atom. Under certain circumstances, the hydrogen atom will become trapped around these discontinuities, which can either ensure a more even distribution of hydrogen or, more detrimentally, provide a source of hydrogen for other regions of high stress.

The distribution of hydrogen in welded regions will however not be homogeneous and will be in a continuous state of flux. It is likely that a state of equilibrium can eventually be achieved, but the equilibrium will be sensitive. Subsequent reorientation of stresses, whether they are external or internal, may be sufficient to reintroduce repulsive and attractive forces acting upon the atomic hydrogen, thereby re-starting the embrittling process.

In summary, the presence of residual stresses in a welded structure can increase the risk of hydrogen-induced cracking, and preventative methods such as preheating and post-weld heat treatment can reduce this risk.

## 7.2 Fatigue

Jack-up rigs have extensive service experience offshore and have suffered many accidents over the years, including foundation problems, ship collisions and fatigue. Fatigue problems have been experienced during tow, due to the wind loading on the legs. Jack-ups have been subjected to extensive field surveys for damage and cracking, and studies have been undertaken to assess their performance, particularly in relation to the use of high-strength steels [2]. In relation to the reported in-service hydrogen related cracks, i.e. HISC, there is no reporting of fatigue being involved neither in the initiation phase nor in the propagation phase in the submerged lower leg and spudcan region. Fatigue cracking has been observed in the brace to chord welds higher up the legs under influence of vortex induced vibration and bending stresses, and some of these cracks can be connected to pre-existing HACC or influenced by atmospheric corrosion.

However as shown previously in Section 4.2, Figure 4-8 and Figure 4-9 hydrogen can accelerate fatigue crack growth, but only when the ΔK threshold for onset of fatigue is already superseded.

Figure 7-1 shows fatigue test results of offshore structural steel type 50D (YS>355 MPa), tested in 5 °C seawater at a frequency of 0.2 Hz utilizing single edge Charpy V notched specimens [37]. Tests performed under cathodic protection at different potentials are compared with testing in seawater (free corrosion potential) and in air. Several observations are made:

- CP at -800 mV (SCE) corresponding to -778 mV (Ag/AgCl) the fatigue crack growth is only slightly reduced compared to the growth rate at free corrosion.
- CP at -1000 mV (SCE) (-978 mV (Ag/AgCl) effectively reduces initial fatigue crack growth. Subsequent fractographic examinations indicated that the beneficial effect was partly influenced by crack closure effects due to calcareous deposition inside the crack.
- CP at -1200 mV (SCE) (-1178 mV (Ag/AgCl) accelerates the crack growth rate considerably.

The significant acceleration once the crack is at the lowest potential confirms the existence of hydrogen accelerated fatigue crack growth (HAFCG) previously mentioned in Section 4.2. Fatigue is however only relevant when the ΔK threshold for onset of fatigue is exceeded.

Overprotection has a surprisingly strong influence on the fatigue performance of a 355 MPa steel. This material is not expected to be susceptible to hydrogen embrittlement. In case of 690 MPa steel, known to be embrittled by hydrogen charging at the crack tip, an even more pronounced reduction of the fatigue life under overprotection must be expected. Accordingly, coated structures, welds without hydrogen cold cracks and other imperfections as well as cathodic protection at modest potentials are emphasised. The fatigue loads on the jack-up lower leg structure are however low.

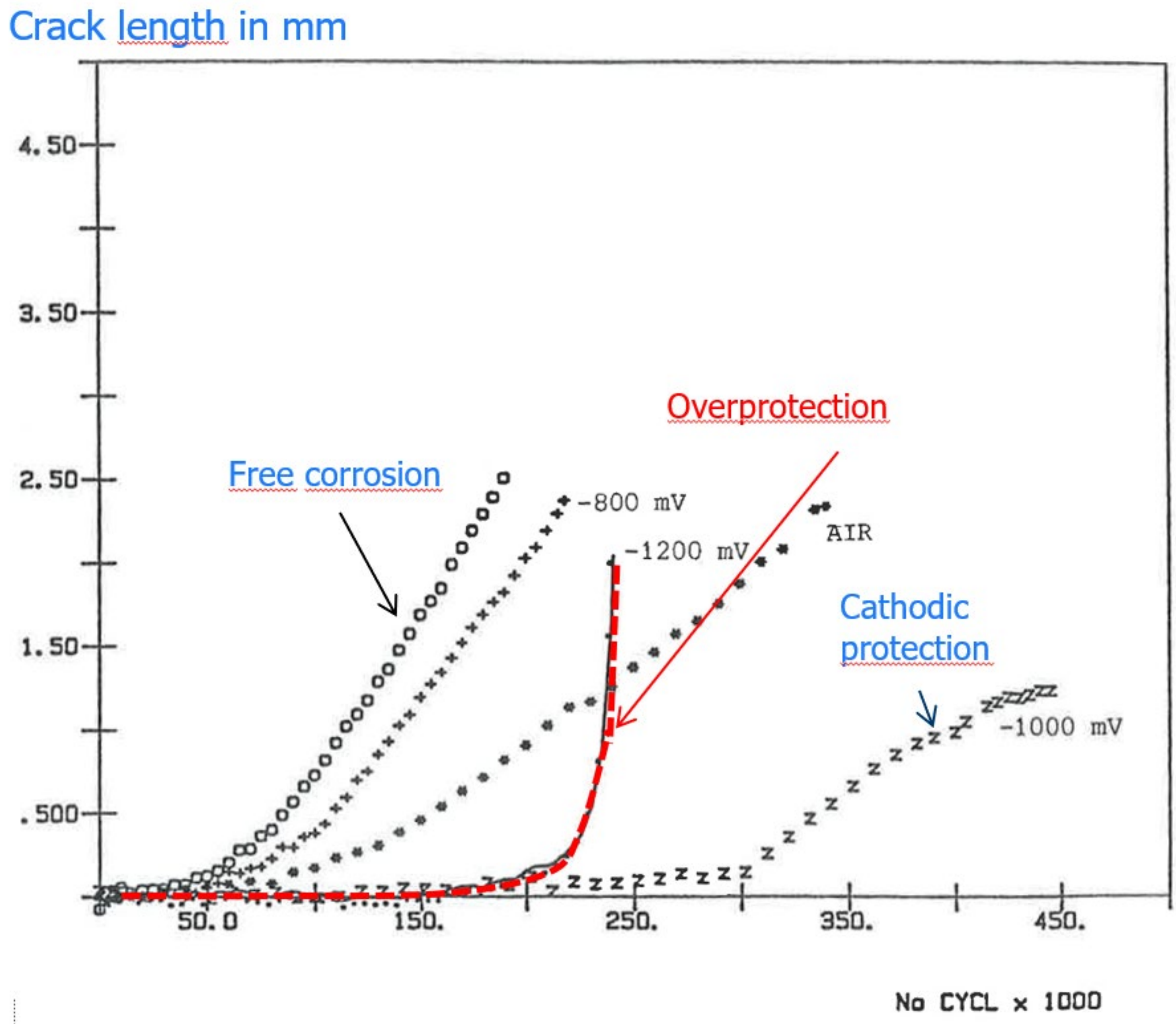


Figure 7-1 Crack length versus number of load cycles in fatigue tests of 50D steel in seawater at 5 °C at various potentials (SCE) [37].

## 7.3 Fracture mechanics assessment

The applied stresses (primary stresses) to be considered in a fracture mechanics assessment, are those which are calculated by a stress analysis of the unflawed structure. The actual stress distributions may be used, or the stresses (or stress ranges) may be linearized. Linearization may be carried out across the flaw or across the section containing the flaw. Linearization across the section normally provides overestimates but has the advantage that linearization does not need to be repeated with crack growth.

Account should be taken of the primary membrane and bending stresses, the secondary stresses and the magnification of the primary stresses caused by local or gross discontinuities or by misalignment. In an assessment of the effect of a single or steady state applied load, it is important to distinguish between primary and secondary stresses, as only primary stresses contribute to plastic collapse.

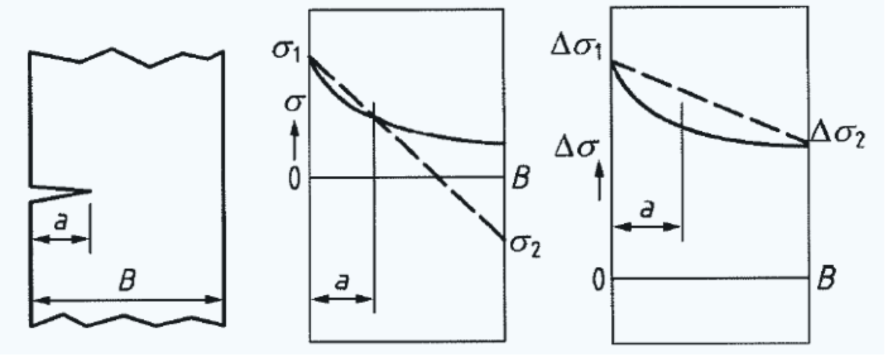


Figure 7-2 Linearization of stress over crack length and section length [46].

In a fatigue assessment, the important distinction is between static and fluctuating stresses and all fluctuating stresses are treated in the same way as primary stresses. Primary stresses are stresses that can, if sufficiently high, contribute to plastic collapse (secondary stresses do not). They can also contribute to failure by fracture, fatigue, creep or SCC. They include all stresses arising from internal pressure and external loads. The primary stresses are divided into membrane and bending components as follows.

- Membrane stress is the mean stress through the section thickness that is necessary to ensure the equilibrium of the component or structure.
- Bending stress is the component of stress due to imposed loading that varies linearly across the section thickness.

The secondary stresses are self-equilibrating stresses that can be relieved by local yielding, heat treatment, etc. Thermal and residual stresses are usually secondary. In fatigue assessment, fluctuating thermal stresses are treated as primary stresses. Secondary stresses do not cause plastic collapse as they arise from strain/displacement limited phenomena. They do however contribute to the severity of local conditions at a crack tip, and, when it is necessary to include them in an assessment, they should be included in calculations of $K_I$ and $\Delta K_I$. The secondary stresses may be divided into membrane and bending components as for primary stresses. In summary, the stresses that influence the crack tip are both the primary stresses and the secondary stresses. When evaluating against plastic collapse, only primary stresses are relevant.

### 7.3.1 Importance of stress field at crack tip

Hydrogen related cracking is closely connected with stress or rather strain. In flawless material the damaging effect of hydrogen will be activated only in co-presence of plastic straining. However, flawless material, especial flawless welds, are a hard to find. Micro fissures, HACC and even minute weld defects can act as embryo for hydrogen damage because even low nominal stresses below yield stress may result in plastic straining and initiation of the hydrogen damaging process.

The stress at a crack tip is theoretically infinitely high and is not possible to evaluate analytically or numerically. Instead, a crack is evaluated using the stress intensity factor $K_I$. The stress field at the crack tip is dependent on whether plane stress or plane strain conditions are dominating. For thinner sections in a structure, plane stress is typically dominant, allowing for strain (deformation) in the thickness direction. For thicker sections, plane strain will become dominant through the thickness, and a tri-axial stress state will be present.

For a given stress intensity, $K_I$, the plastic zone at the crack tip will be smaller where plane strain is dominant compared to a similar stress intensity at a crack tip where plane stress is dominant. As the stress intensity is the same in the two sections, the section where plane stress is dominant, is more ductile due to the larger plastic zone, compared to the section where plane strain is dominant, which will show a more brittle behaviour.

In relation to the stress field at a crack tip, several methods for determining a materials resistance to fracture are available. A fracture toughness test requires a very small and insignificant plastic zone at the crack tip, to be valid. If the test is valid, the material parameter $K_{IC}$ is obtained, which is conservative fracture toughness independent of material thickness.

If significant plasticity is present at the crack tip, other test methods are used to determine material toughness, like CTOD or J-integral. Blunting of the crack tip is a consequence of the plasticity at the crack tip. The blunting of the crack increases with the toughness of the material. When the stress intensity at the crack tip reaches the toughness of the material, tearing at the crack tip initiates.

Under fatigue loads, a crack will propagate if the applied stress intensity range is larger than the fatigue threshold value of the material. If a component or structure with a crack that has been propagating due to fatigue loads is subjected to high tensile load which blunts the crack tip, crack propagation may stop for some time. The fatigue loads will start to sharpen the crack again. This sharpening of the crack may take many fatigue cycles before crack growth rate reaches the value before the tensile overload. Crack sharpening may also occur at a tensile-compressive overload, where the tensile overload blunts the crack tip, the compressive overload re-sharpens the crack.

Crack tip blunting is illustrated in fatigue crack growth is shown in Figure 7-2. Left most is a crack growth curve under normal fatigue load. The centre crack growth curve is with fatigue, tensile and compressive overload, and crack growth curve to the right is with fatigue and tensile overload only [47].

Crack arrest happens when a rapidly growing crack stops propagating. There are several occasions where crack arrest may occur. The reason the growing crack stops, is due to the crack driving force (stress intensity), becoming smaller than the material resistance to crack growth (toughness). Examples are the following: If the crack initiates in a brittle area, a weld for example, and grows into a more ductile region of the material, the crack may arrest. Temperature gradients may affect the toughness in materials, and if a crack starts in colder part of the structure and propagates into a warmer area, the crack may arrest.

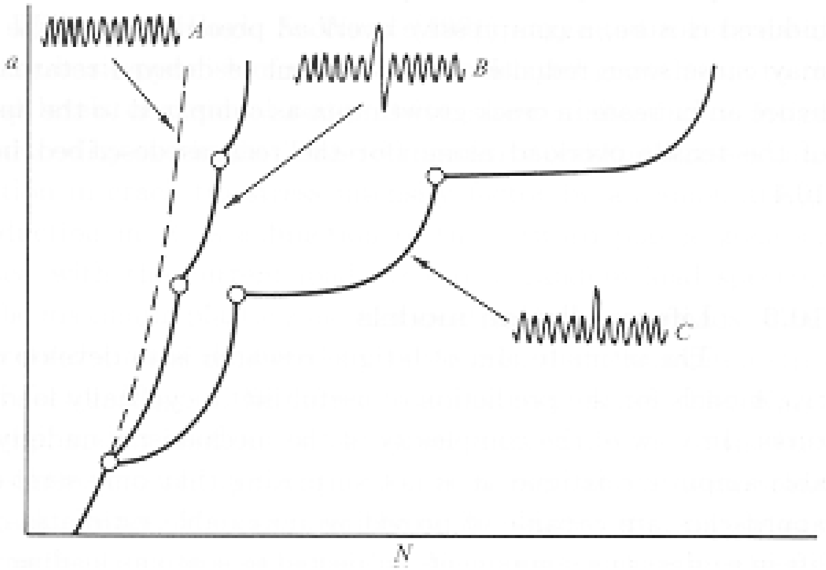


Figure 7-2 Crack tip blunting illustrated in fatigue crack growth [47].

### 7.3.2 Analytical models

BS 7910 and API 579 have extensive methods to solve different crack problems analytically. The methods in these works account for type of flaw, sizes, stresses, stress concentrations, residual stresses, fatigue crack growth etc. The simplest method in API 579, is using diagrams to assess critical flaw sizes for the different flaw types. The more analytical approach is found in the next level assessment in API 579 and first level assessment in BS 7910, where a more detailed assessment is carried out. If cracks are detected on a jack-up structure, it is essential to perform a redundancy analysis to ensure structural integrity. The use of analytical methods to determine critical defect size and crack growth rate if the jack-up rig is not to be repaired in near future, is an option to be considered. Detailed knowledge of the service stress and understanding of the structure in order to set realistic boundary conditions in the model is essential to obtain useful results.

# 8 Failure mechanism

Reference is made to the incident on the Norwegian Continental shelf in 2022 were cracking of 690 MPa steel was observed in the welded joints between the legs and the spudcans. All cracks were initiated in the weld metal and most cracks had propagated within the weld zones while some had also propagated into the base material. The welding of 690 MPa steels produces a hard microstructure, residual stresses and unfortunately also susceptibility to hydrogen weld cold cracking (HACC) and other defects in the weld zone. In the weld metal and HAZ there are high residual stress caused by the welding process and the crack initiation takes place in the areas with high stress concentrations. Additional stresses due to external loads during building and during subsequent service may have caused the subsurface cracks to break open and at the same time crack the coating. Cathodic protection is responsible for production of hydrogen causing hydrogen absorption at the crack tip thereby allowing HISC to initiate and grow. HISC crack growth in the weld material/HAZ proceeds only at a critical combination of stress and hydrogen exposure, and if the cracks propagate into an area with relieved residual stresses or a sound microstructure, i.e. the base material, the driving force for crack propagation is reduced and the cracks eventually stops growing. Hydrogen charging of the steel due to cathodic protection mainly takes place at bare steel surfaces. On an epoxy coated steel surface bare metal is only exposed to seawater and CP at locations accidentally without coating. The initial exposure to the CP results in low potential at the steel surface but the electrochemical potential will gradually increase due to polarisation of the structure and inside the narrow cracks also due to slight alkalisation. Accordingly, the hydrogen generation is reduced thereby making the initial exposure to high loads and CP the most critical period in terms of HISC development from pre-existing surface breaking cracks

It can be questioned why cracks are formed in some installations, while others remain unaffected. This may be explained by use of different high strength materials, differences in the hydrogen charging due variations in the potential and design related stress levels. Hence, the conditions for hydrogen induced cracking are not the same. However, comparing the positions, numbers and length of the observed cracks relative to the total length of the welds within the legs of the entire jack-up structure it appears that the cracking is neither generic to design details nor to the material and welding process as such. The experience clearly points out that observed cracks results from weld cold cracks that later on grow due to hydrogen charging within the crack. The cold cracks are formed during fabrication are due to deviations from proper preheating, interpass temperature, too low arc energy and/or omission of post weld soaking. This scenario fits with the observed random occurrence of cracks.

While a potential around -750 V (Ag/AgCl) is sufficient to prevent corrosion, the CP standards [5] [35] [36] require a potential below -800 mV (Ag/AgCl) for full cathodic protection of carbon and low alloy steels. When sacrificial anodes are used, the anode potential is about -1050 mV (Ag/AgCl) and the steel potential somewhat higher. A potential of -950 mV (Ag/AgCl) is more than sufficient to provide full corrosion protection. At this potential, the hydrogen evolution is considered not to cause fast propagating hydrogen embrittlement in a flawless material. Still at the same time, if hydrogen charging is not considered in design, the effective capacity of the structure can be significantly reduced due to HISC.

## 8.1 Development of surface breaking cracks

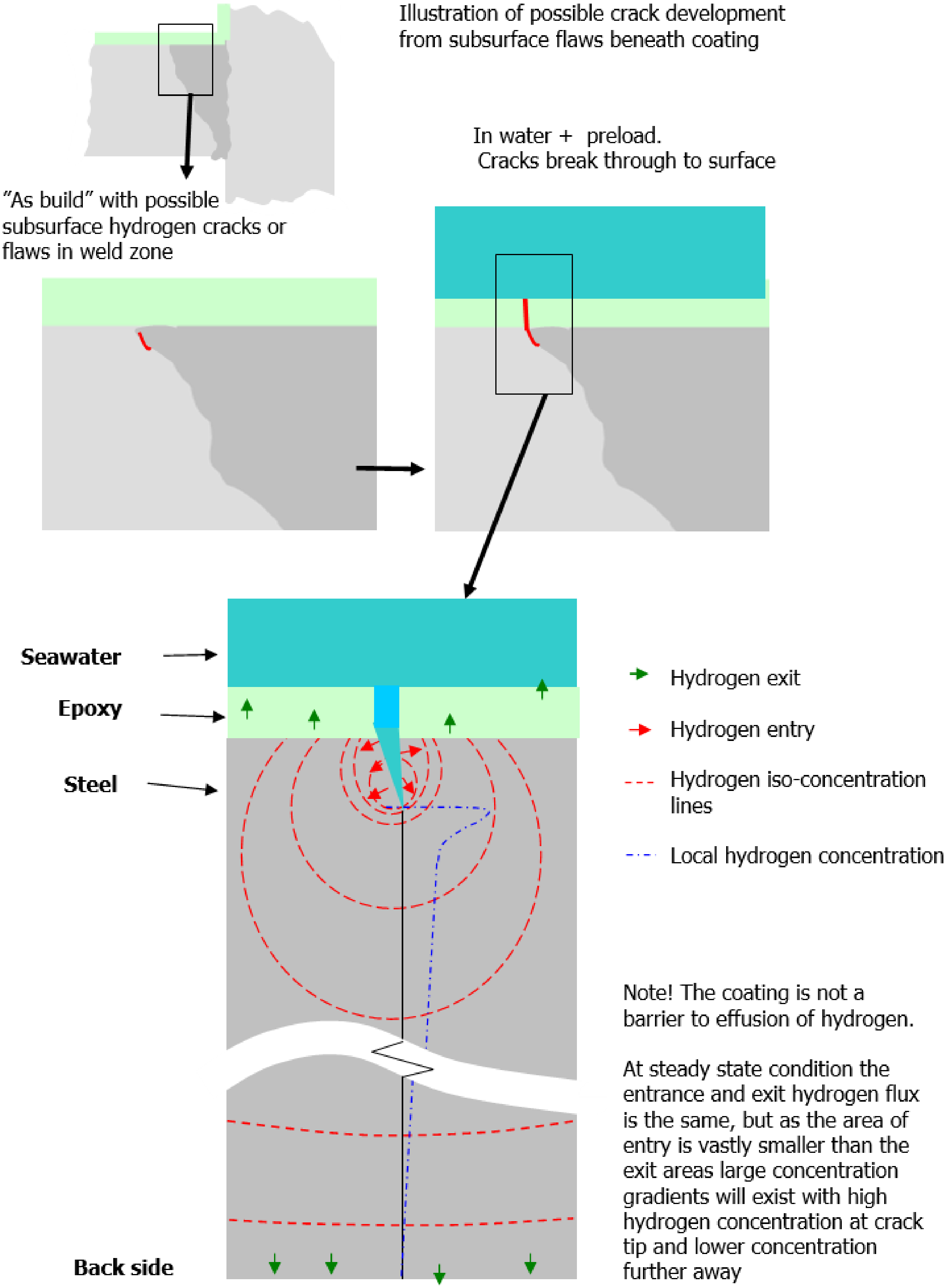
Crack growth by HISC requires presence of diffusible hydrogen in sufficient concentrations in a crack sensitive material exposed to high stress/strain. The two latter requirements can be present in the weld metal and in the narrow high temperature heat affected zone (HAZ) of the base metal. Sufficient concentration of diffusible hydrogen is harder to maintain because the cathodic reaction imposed by CP providing hydrogen only take place at bare metal surfaces, i.e. within surface breaking cracks (or where the coating is otherwise damaged or missing). Once into the steel the hydrogen atoms will disperse in the massive amounts of metal surrounding crack and migrate (unless trapped) in all directions towards areas with less or no hydrogen and escape through any free surface not affected by CP (including the epoxy coated surfaces) as illustrated in Figure 8-1 and Figure 8-2. As the cathodic reaction steadily produces hydrogen feeding the crack surfaces it may in the worst case provide enough hydrogen for charging of a small volume of strained material ahead of the crack tip. In this small volume HISC can progress, but at low crack growth rate because the feed of hydrogen is not high enough to cause embrittlement of the bulk material.

Crack growth caused by HISC of coated high strength steels under cathodic protection is likely to proceed in several steps:

1. Presence of subsurface cracks
    - Typically, cold cracks in brittle zones of the weld (weld metal and HAZ) caused by hydrogen absorbed during welding
2. Cracks break to the surface
    - Upon loading the coating cracks revealing bear metal
3. Hydrogen charging starts
    - The cathodic reaction enhanced by CP on bare metal surface produces hydrogen
4. Crack propagation
    - The crack propagation proceeds whenever the requirements for crack growth is met, i.e. hard zones, hydrogen charging, sufficient stress

Hydrogen charging occurs through the crack surface and collects in the strained zone ahead of the crack tip. Interactions of the absorbed hydrogen and local straining results in non-steady conditions controlled by a time-dependent hydrogen diffusion versus crack tip strain rate as illustrated in Figure 8-3. The crack jumps through the stress field and the high hydrogen concentration zone ahead of the crack tip when hydrogen concentration, stresses and material susceptibility so dictate. Hydrogen escapes through the new crack surfaces but starts to rebuild the concentration again in the strained zone ahead of the new crack tip to repeat the cracking processes.

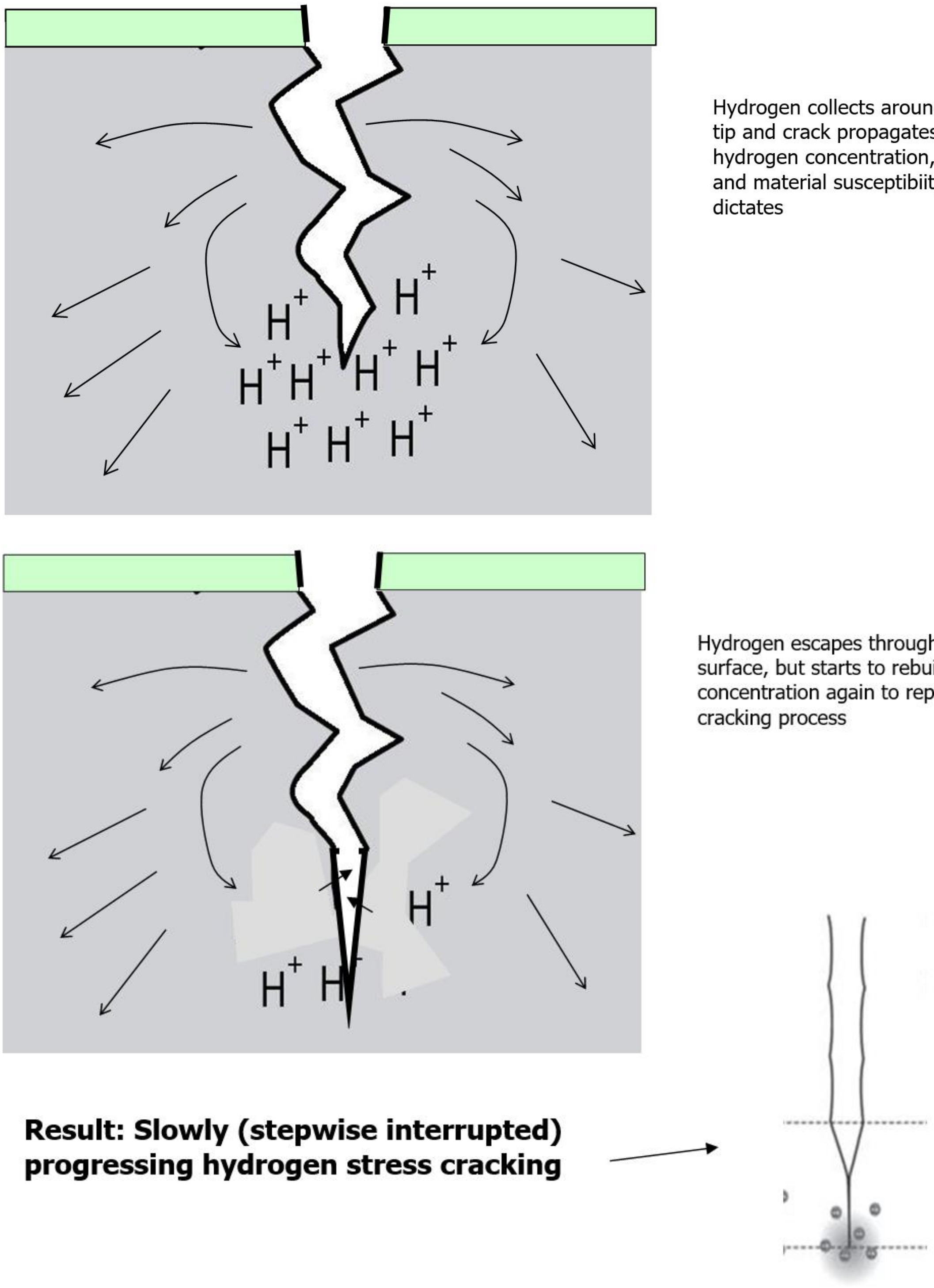
The contribution of stress to the hydrogen embrittlement mechanisms is treated in greater detail in Section 7, including a discussion of fracture mechanics assessments determining the critical defect size at which crack growth will occur. Other aspects of the failure mechanisms involved in the observed cracking on jack-ups are discussed in the respective sections of the report.



Note! The coating is not a barrier to effusion of hydrogen.

At steady state condition the entrance and exit hydrogen flux is the same, but as the area of entry is vastly smaller than the exit areas large concentration gradients will exist with high hydrogen concentration at crack tip and lower concentration further away

Figure 8-1 Schematic illustration of hydrogen absorption, diffusion, concentration and effusion in cathodically protected, coated steel structures.



Hydrogen collects around crack tip and crack propagates when hydrogen concentration, stresses and material susceptibiity dictates

Hydrogen escapes through new crack surface, but starts to rebuild high concentration again to repeat the cracking process

**Result: Slowly (stepwise interrupted) progressing hydrogen stress cracking**

Figure 8-2 Slow HISC crack growth.

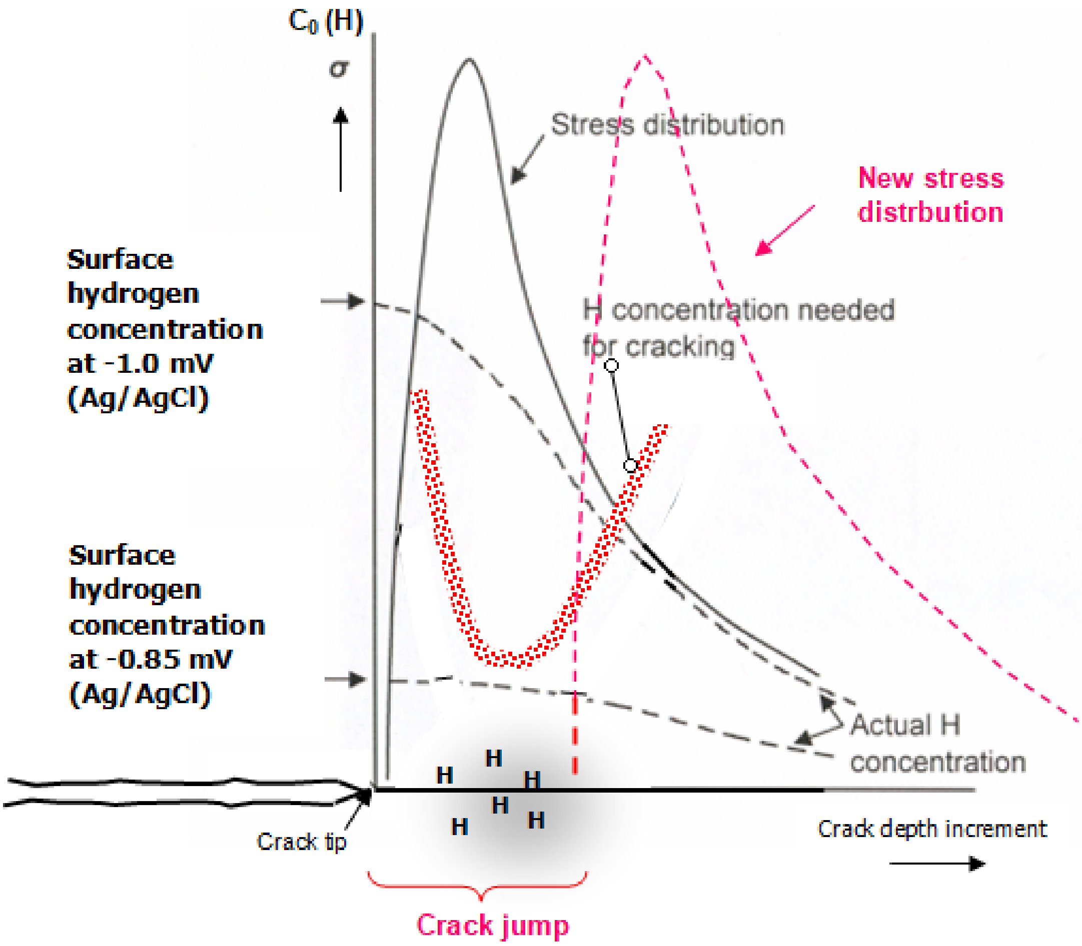


Figure 8-3 Illustration of crack growth sequences in HISC propagating from surface breaking cracks. Schematic illustration based on [48].

# 9 Design considerations

## 9.1 General design considerations

Crack growth by HISC is caused by the interaction between stresses, a hydrogen charging system (cathodic protection most common) and a susceptible material. Design principles to avoid HISC in duplex stainless steels are presented in DNV-RP-F112 [12]. These design consideration and principles are generally applicable and can be applied for low alloy high strength steels as well.

All relevant loads that can be transferred to the component from connected systems during installation and operation shall be considered. Be aware that deformation loads, such as thermal stresses, seabed subsidence effects and residual stress, shall be included when designing for HISC resistance.

Most HISC failure are located near welds and stress raisers, and precautions to ensure robustness is emphasised in design and construction. To reduce the risk of HISC it is recommended to locate welds away from geometrical stress concentrations. Design with fillet welds, sharp edges, sharp stress raisers should be avoided. Constraints can be very high for weld repairs. Special attention should be paid to single pass welds. In particular, single pass girth welds, especially in relation to start stop areas, repair welds, and thin walled (<10 mm) structures, may result in significant residual stresses. Moreover, transitions or misalignments will give rise to secondary bending moments that again will lead to additional surface stresses which shall be included in the HISC assessment.

Critical weld features expected to experience the highest loads or stresses (or applied loads with uncertainty) need special attention. Practical measures should be taken to manage stresses at welded joints, ensure good access for welding, and produce a build sequence that maintains good fit up and ensures ready access for non-destructive testing (NDT).

Epoxy coatings have primarily been applied to reduce the current demand from the sacrificial anodes and/or for thermal insulation. They are not expected to act as a 100% effective barrier against hydrogen charging and HISC. Even quite narrow crevices associated with cathodic disbanding of the coating or other coating damage can lead to significant local hydrogen production and absorption. If the locations with damaged coating coincide with highly stressed locations, HISC can occur. A high integrity thick insulation coating on the other hand may mitigate the threat of HISC, but insulation coatings are not used on the lower leg and spudcan areas of jack-up installations.

## 9.2 Material requirements

The DNV standard for design of offshore steel structures [49] states that the susceptibility to HISC shall be considered, especially when the steel is used for critical applications (such as jack-up legs and spudcans). Also, the use of steels with a specified minimum yield stress (SMYS) > 550 MPa shall be subject to special considerations when anaerobic conditions may predominate [49]. The offshore standard states that cathodic protection may cause HISC of components in high strength steels exposed to severe straining in service. As a result it is recommended that the welding of these steels is qualified according to DNV-OS-C401 [50]. The standard states that the maximum hardness for materials exposed to environments with risk of HISC is limited to 350 HV, unless otherwise agreed or specified in the standard [50].

The susceptibility to failures by hydrogen embrittlement is inherent in the welds of high strength steels. Failures due to CP induced HISC have been encountered for martensitic steels with yield stress and hardness around 700 MPa and 350 HV, respectively. Especially martensite in the un-tempered condition is susceptible to HISC. As a consequence, welding of materials susceptible to martensite formation should be followed by post weld heat treatment (PWHT) to reduce heat-affected zone (HAZ) hardness and residual stresses from welding [5]. Furthermore, it is recommended that the welding is performed in accordance with a qualified procedure having a maximum hardness in the range 300 to 350 HV.

If the structure is designed according to the DNV specifications, the WPS and WPQR shall comply with DNV-OS-C401 [50] and the susceptibility to HISC shall be specially considered for critical applications [51]. Hardness testing of welds is a requirement for steel grades with a SMYS > 265 MPa [50]. However, bolts in martensitic steel heat treated to SMYS up to 720 MPa has shown compatibility with CP. As a result of some failures related to inadequate heat treatment, batch testing to verify a maximum hardness of 350 HV is recommended [5].

While there is no generally accepted test method to verify material compatibility with CP, slow strain rate testing (SSRT) is applicable for material comparison. For quantitative testing, uniaxially loaded tensile specimens (constant load), 4-point bend specimens (constant displacement), crack tip opening displacement (CTOD) and other testing configurations have been applied at controlled CP conditions [5]. Billingham et al. [2] also includes double cantilever beam testing and specifies that SSRT does not accurately represent the conditions found offshore. Also NORSOK M-503 [35] states that for high strength steels (SMYS>700MPa) a special evaluation is required with respect to hydrogen impact.

Fortunately, there is no history of fast-propagating brittle fracture on jack-up rigs in the North Sea. An elaborate investigation was performed by Cranfield University as well as through an ABS survey, showing no examples of brittle fractures in the spudcans of jack-up rigs, hence the record is good for structures with 690 MPa steel.

## 9.3 Coating design

Materials selection standards prescribe the use of coating on carbon and low alloy steel submerged in seawater [7] [52], but corrosion protection of the steel surfaces is achieved cathodic protection (CP) in combination use of coating. The coating provides a barrier between the seawater to the steel surface, while cathodic protection to prevent corrosion at coating defects or damage. The CP design shall account for coating degradation (coating breakdown) over time. The coating can also contribute as a barrier for hydrogen diffusion into steel, but this requires high quality coatings. To ensure optimal coating quality, it is crucial that all application work is carried out in accordance with the recognised standards and following the guidelines described in the technical data sheet for the coating system. Qualified supervision by e.g. FROSIO or NACE qualified coating inspectors in recommended in both NORSOK M-501 and DNV-RP-0416 [8] [53].

All coating systems applied on submerges structures shall shall be pre-qualified in accordance with a recognized standard (i.e. NORSOK M-501, ISO 12944, ISO 20340). ISO 12944-9 deals specifically with the requirements for coating of offshore structures, in corrosivity category CX and immersion category Im4 (defined in ISO 12944-2) and specifies the surface condition and minimum requirements for protective coating systems and their initial performance [54].

The coating must be compatible with cathodic protection, and the qualification should include testing at the applied cathodic protection potential. In particular, resistance of the coating to cathodic disbonding must be verified. For jack-ups leg and the spudcan area application of NORSOK M-501 [8] coating system 7B is recommended. This system consists of minimum two layers of an epoxy coating. Special attention should be paid to critical weld zones. Beware of the pretreatment requirements and coating thickness:

- Surface pre-treatment (prior to coating application)
  - Cleanliness: ISO 8501-1 Sa 2½
  - Roughness: ISO 8503 minimum grade G (50 – 85 µm, $R_{y5}$)
- Minimum dry film thickness of 350 µm for the complete coating system
  - Preferably more on critical weld zones

Coatings deteriorate over time in service, but still it is possible to obtain more than 15 years of service life. Numerous examples of coating degradation have confirmed the necessity to perform proper pre-treatment, cleaning and careful application of the coating system, to avoid corrosion issues and coating breakdown during service life. If the specification is not strictly followed more frequent coating refurbishment must be expected.

According to DNV-RP-0416 [53], the use of coating is mandatory for external surfaces of primary structures for offshore wind turbines. Coating systems to be applied in the splash zone shall be based on manufacturer specific materials that have been qualified for the actual coating system by proven experience or relevant testing. Maintenance of coating systems in the splash zone is not practical, and coating of primary structures shall therefore be combined with a corrosion allowance. This applies to wind turbines and while no such specific recommendation exists for coating of jack-up structures the same basic principles apply. Jack-up rigs may be covered by standards such as NORSOK M-501, ISO 12944, DNV recommendations or the ABS guidance note on cathodic protection of offshore structure, including coating.

For parts of the splash zone located below MWL (Mean Water Level), cathodic protection may be assumed for design purposes to be fully protective, and no corrosion allowance is required. As per [53] coatings for corrosion control in the splash zone shall as a minimum extend to MWL–1.0 m; however, it is considered best practice to apply coating to the entire vertical extension of the splash zone. This approach is supported by general offshore guidelines such as [5] [4] [35].

As mentioned previously steel with actual yield strength and tensile strength ≤ 700 and 750 MPa respectively are by experience considered to be compatible with marine CP system and may therefore be used in areas prone to coating abrasion/damage, but for higher strength materials exceeding these limits the bulk hydrogen charging increases the risk of HISC. This may be counteracted by metalizing the surface with aluminium or zinc in a 200 mm wide zone along and centred on the weld. A thermal sprayed aluminium (TSA) surface shall be sealed only, while a full coating system is applied thermal sprayed Zinc (TSZ) [8]. Metallising is compatible with CP by use of sacrificial anodes. The metallisation will prevent seawater to come in contact with bare steel and at the same time provide a good anchoring of the coating (relevant for TSZ only). The metallisation may provide sufficient protection against corrosion while also preventing gross hydrogen charging of the steel. Surface breaking cracks are still detectable by visual inspection and MT but checking of crack depth or direction by UT of the flaw area need removal of the metallised layer.

## 9.4 Cathodic protection design

Bare steel surfaces exposed to seawater may suffer pitting corrosion, crevice corrosion, thickness reduction, corrosion fatigue and stress corrosion cracking. The traditional approach to counteract these issues is to apply cathodic protection (CP) [4]. Cathodic protection is used in the offshore industry to control corrosion submerged steels structures. In general terms, CP consists of lowering the electrode potential of the steel to sufficiently low potential to stop corrosion by donating surplus electrons to the steel from an external source and thus the actively corroding steel surface become passive by making the surface the cathode of an electrochemical cell. Surplus electrons can be provided by corrosion of sacrificial electrodes (typically aluminium anodes) or by an impressed current. As described in further detail in Section 5.2 the main hydrogen source in service is the cathodic protection system. Hence, the CP potential must be carefully considered to avoid detrimental effects of hydrogen [4].

According to DNV-OS-C101 [49] the CP system shall be designed following a recognised standard, such as DNV-RP-B401 [5]. The same statement is also found in the recommended practice for corrosion protection of wind turbines [53]. The accepted criterion for protection of carbon steels or low-alloy steels in aerated seawater is a protection potential of –0.80V (Ag/AgCl) or more negative [5] [35] [36]. In the case of mild steel with active sulphate reducing bacteria (anaerobic conditions), the protection potential is lowered to –0.90 V (Ag/AgCl). However, it should be noted that increasing negative potentials may lead to adverse effects on the risk hydrogen embrittlement of susceptible steels. It is particularly crucial to avoid excessive hydrogen high strength steel, duplex stainless steels and martensitic steels, and hence restrictions apply on the protection potential [12]. Hence, while cathodic protection is a vital method for preventing corrosion, the potential used must be carefully chosen to minimize the risk of hydrogen embrittlement in high strength steels.

There are discussions as to which protection potential is most suitable to accommodate minimal hydrogen evolution while still maintaining sufficient corrosion protection throughout the lifetime of the structure at all relevant water depths.

It is generally accepted that the potential must be – 0.80 V (Ag/AgCl) or below to achieve cathodic protection of carbon and low-alloy steels exposed in seawater. A correctly designed CP system with sacrificial anodes will usually provide a potential in the range of – 0.90 to – 1.05 V (Ag/AgCl), once the CP system has attained its steady-state potential, i.e. 0.15 to 0.20 V more negative than the design protective potential [5]. Towards the end of the service life, the potential usually increases towards – 0.80 V (Ag/AgCl) or even higher resulting in insufficient protection, called under-protection. The term over-protection is applied to potentials more negative than – 1.15 V (Ag/AgCl). However, such potentials will not apply for CP systems using sacrificial anodes with normal Al or Zn anode alloys.

Billingham et al. [2] summarises some of the work on CP potential values for high strength steels available at the time. Recent work [55] [56] found that a 700 MPa offshore steel was adequately protected (corrosion rate of 0.001mm/year) at potentials in the range - 0.76 to - 0.79 V (Ag/AgCl) in seawater. For steels with yield strengths >700 MPa it is recommended that the CP potentials is within the range - 0.80 to - 0.95 V (Ag/AgCl) and for steels with yield strengths > 800MPa the potential should not be more negative than - 0.80 V(Ag/AgCl) [57]. The ranges described above are illustrated in Figure 9-1.

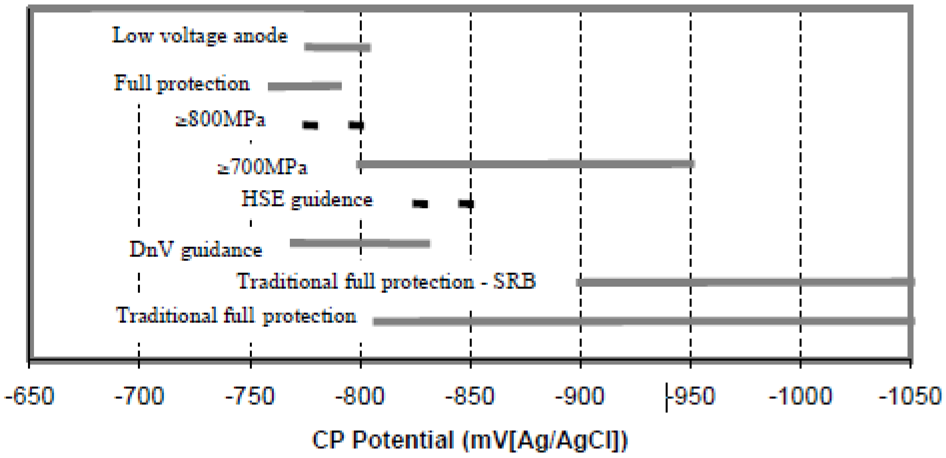


Figure 9-1 Overview of CP potential ranges [2].

## 9.5 Hydrogen mitigation strategies

While corrosion may cause hydrogen ingress into the steel, the corrosion protection by CP may in fact do the same and unfortunately to an even larger extent. Discussion of protection potentials have been ongoing for decades. CP modelling and CP surveys, where the actual potential is measured, may be tools providing some certainty, but solid documentation on the actual CP potential in a certain critical position on a structure, is seldom available.

There are methods to reduce the risk of HISC of components under cathodic protection:

- More positive potential on critical component/parts
  - Anode distribution optimisation
    - Avoid anodes on the critical parts
    - Optimise anode distribution by CP modelling to ensure as positive potential as possible on critical parts
    - Remote CP
  - Force anode potential towards more positive level
    - Use of diodes and/or resistance
    - Change chemical composition of anode material. AlGa anodes are available
- Critical parts can be coated by polymeric or metallic coating

The use of methods changing the active anode potential may require insulate of the structure to avoid connection with an unregulated CP system, which will dominate the protection system and hence cause the critical parts of the structure to be exposed to normal CP levels, i.e. more negative.

### 9.5.1 Diode controlled cathodic protection

The diode controlled cathodic protection (DCP) was developed to reduce risk of HISC for 13Cr flowlines related to a specific project in the Norwegian sector. The DCP system was designed to ensure that the protection potential was maintained at values more positive than -830 mV (Ag/AgCl) [58]. The system was installed on the 13Cr pipeline and measurements on the flowline has shown that the DCP system is working as expected and the risk for HISC has been minimised. The DCP system has been installed on five other offshore 13Cr flowlines; four in Europe and one in Asia. Operational information from these flowlines has been made available.

For the DCP protected systems to work properly, it is important that the DCP system is insulated from other CP systems. If not, any conventional CP system may dominate the protection potential, i.e. is close to normal CP potential at which HISC can be a problem.

Only one jack-up rig is known to have diode-controlled anodes. This rig was in the UK sector and is now decommissioned. The use of a CP system with diode control has been discussed in several project with jack-up rig in high strength steel. However, the conclusion based on thorough evaluations and testing during the design period was that these jack-up rigs were compatible with the use of normal CP. The jack-up CP systems were modelled to check potential distribution and showed that all steel surfaces were exposed to normal CP potential levels. These jack-ups are still in operation.

One specific jack-up installation has legs coated with TSA. The installation has a large oil storage tank to which the legs are connected. Except for the part inside the storage tank all parts of the legs were delivered with high strength steel with a minimum yield strength of 690 MPa. In fact, the actual yield strength was 800 MPa. All anodes are mounted on the storage tank. The CP system of the jack-up has been checked several times by CP modelling and CP inspection [59] [60] [61]. The surface of the legs has been exposed to potentials in the range -900 mV to -1000 mV (Ag/AgCl) for more than 20 years.

### 9.5.2 CP modelling

The main objective of CP modelling is to demonstrate the actual performance of a CP system. CP modelling is also a tool to ensure proper distribution of anodes and document corrosion protection of the entire structure while at the same time avoiding local areas of overprotection. The SeaCorr$^{TM}$ software has been used in the examples below.

The CP performance throughout the service life of structures with or without coating, using sacrificial anodes, impressed current as well as hybrid systems can be simulated. SeaCorr$^{TM}$ utilises a unique database with real life polarisation data. In addition to using a real-life database, CP and Field Gradient inspection data, i.e. from FiGS surveys, are utilised in order to optimise the simulation results based on the actual performance of the structure in question. Specific parameters, like historical over-protection from an impressed current system, may give individual structures polarisation conditions which deviate from the expected conditions. Field gradient data may therefore give valuable input in addition to the SeaCorr$^{TM}$ database in assessing the specific structure.

Typical cases evaluated by CP modelling are:

- Current shadow effects, current drain and anode distribution issues
- Uneven anode consumption
- Over or under-protection
- Protection in confined areas, small annuluses, etc.
- Galvanic corrosion
- Anode interference
- Interaction between connected structures
- Pipeline attenuation

With CP modelling, different scenarios can be simulated to ensure the optimal protection of the installation. Some CP modelling cases are presented below to show why CP modelling is an excellent tool to check a CP system as part of a HISC mitigation strategy.

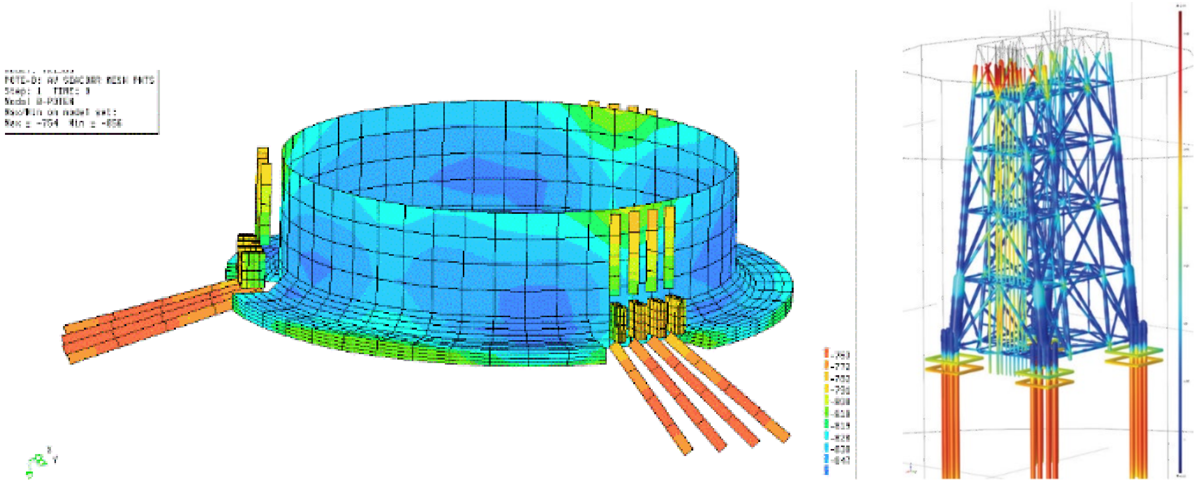


Figure 9-2 CP potential distribution. Red indicates less negative potentials compared to blue regions which at more negative potentials.

### 9.5.3 Case: HISC on FPSO duplex I-tubes

In this study, the potential distribution on I-tubes at a spider buoy was studied to achieve potentials avoiding HISC. [40]. The mooring chains are connected to spider buoy which drain current from the impressed current CP (ICCP) system on the hull. All the mooring lines have been electrically connected and the ICCP system has been adjusted to achieve the most positive potential at the I-tubes without under-protecting the rest of the structure. As can be seen in Figure 9-3 and Figure 9-4, a relatively even potential distribution in around -800 mV is achievable for the FPSO and I-tubes when all the chains are connected.

### 9.5.4 Case study: Trestle structure with high-strength steel

One of the objectives of this study was to avoid HISC of a high-strength steel jack-up, by using AlGa anodes, while at the same time ensuring protection of the trestle structure.

Figure 9-5 and Figure 9-6 show the surface potential and anode wastage (in the same plot) after 2 and 30 years, based on CP modelling. At year 2, the structures have reached full polarization (maximum calcareous deposition) and gone into a steady-state period. Further development of potential from this point is affected by increased steel current density, due to coating breakdown and reduction of anode radius. At the end of the design life (30 years), the structures are still well within an acceptable potential range, except for some areas that in the model are exposed to seawater but in real life is grouted.

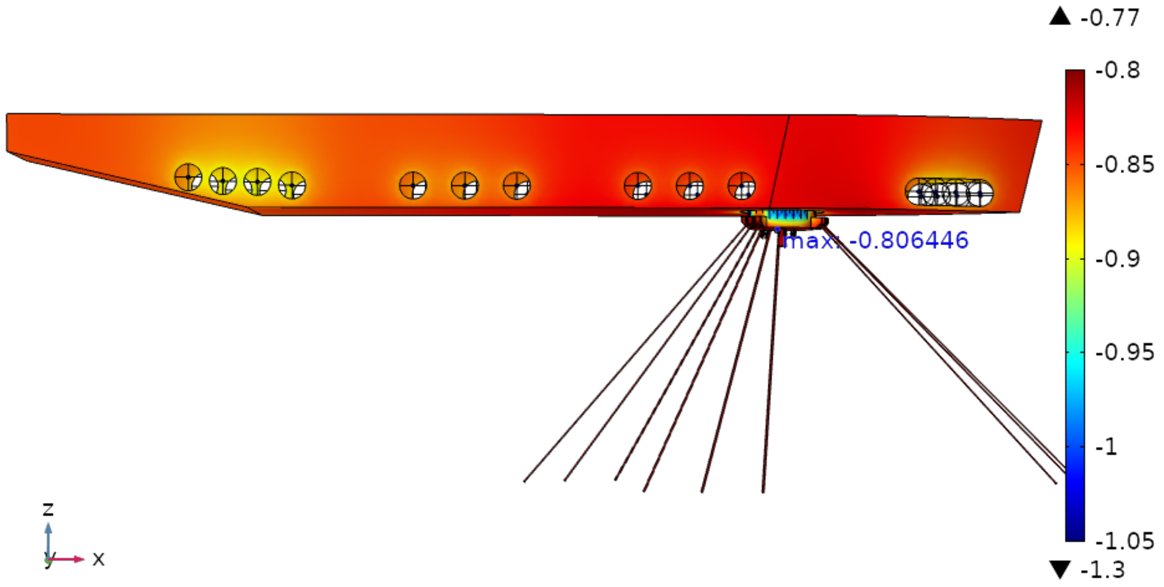


Figure 9-3 Potential distribution – FPSO/Spider Buoy – all mooring chains connected.

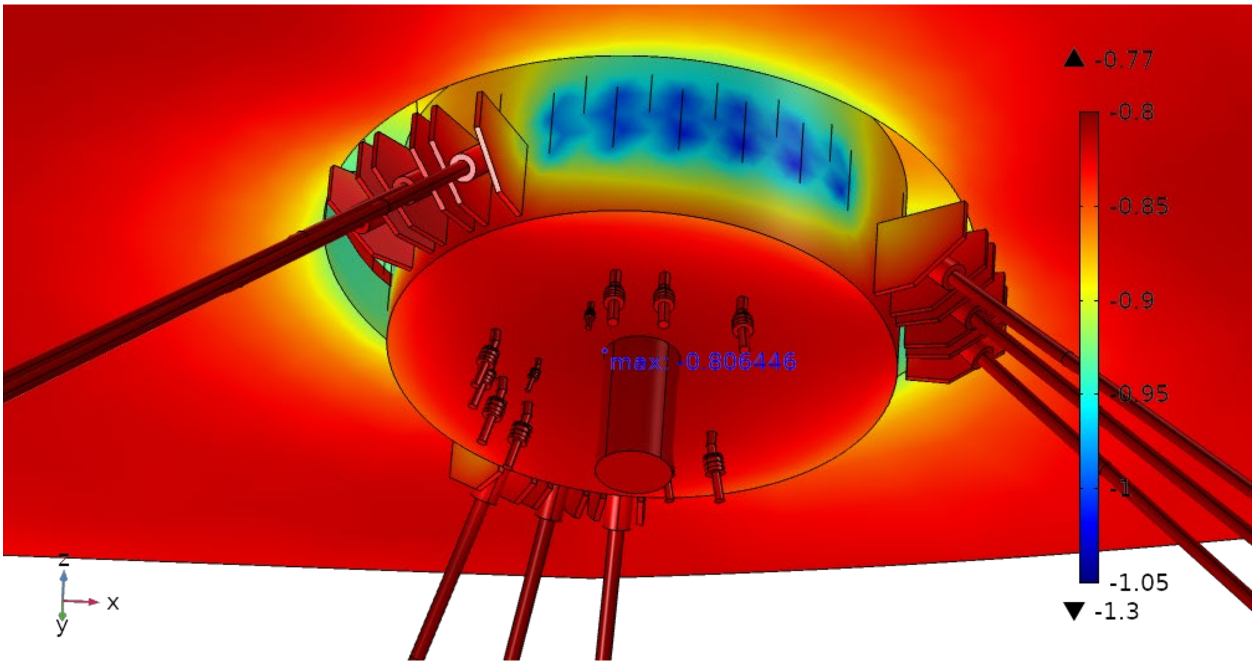


Figure 9-4 Potential distribution – FPSO/Spider Buoy – all mooring chains connected (close up).

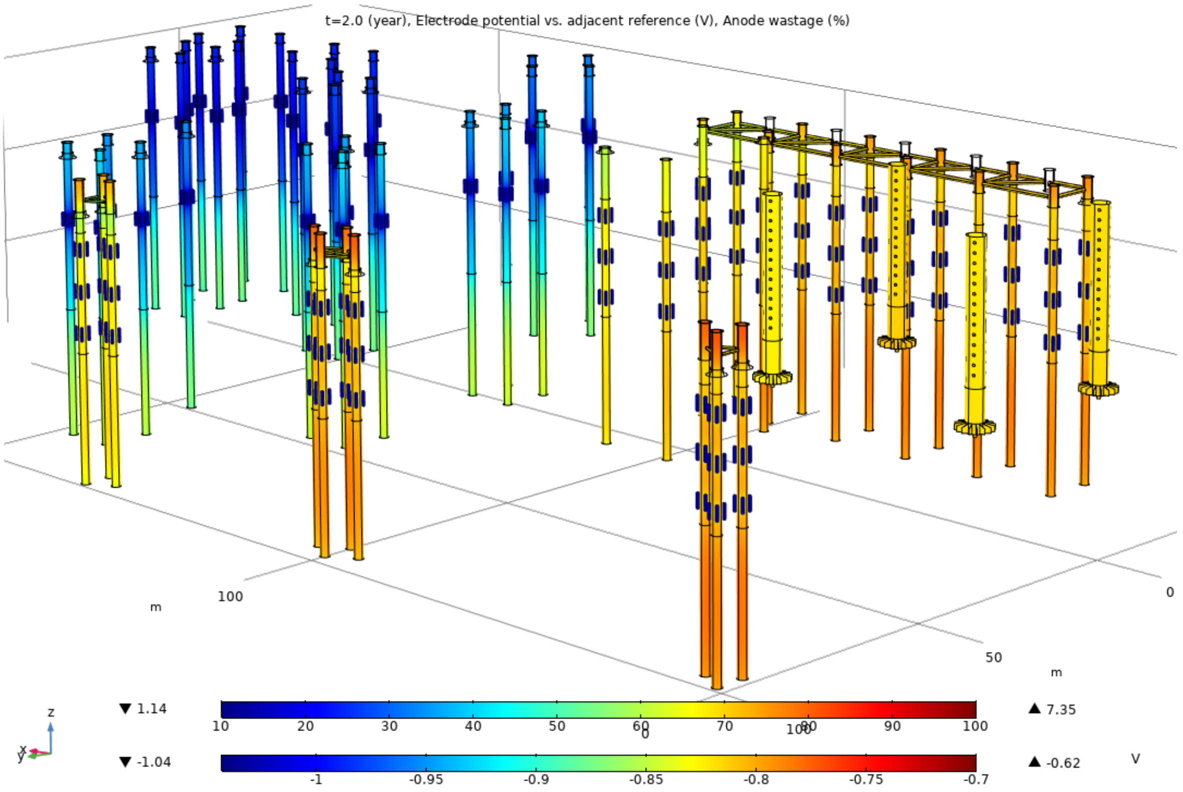


Figure 9-5 Potential distribution (V) and anode wastage (%) at t = 2 (years) seen from north-west side.

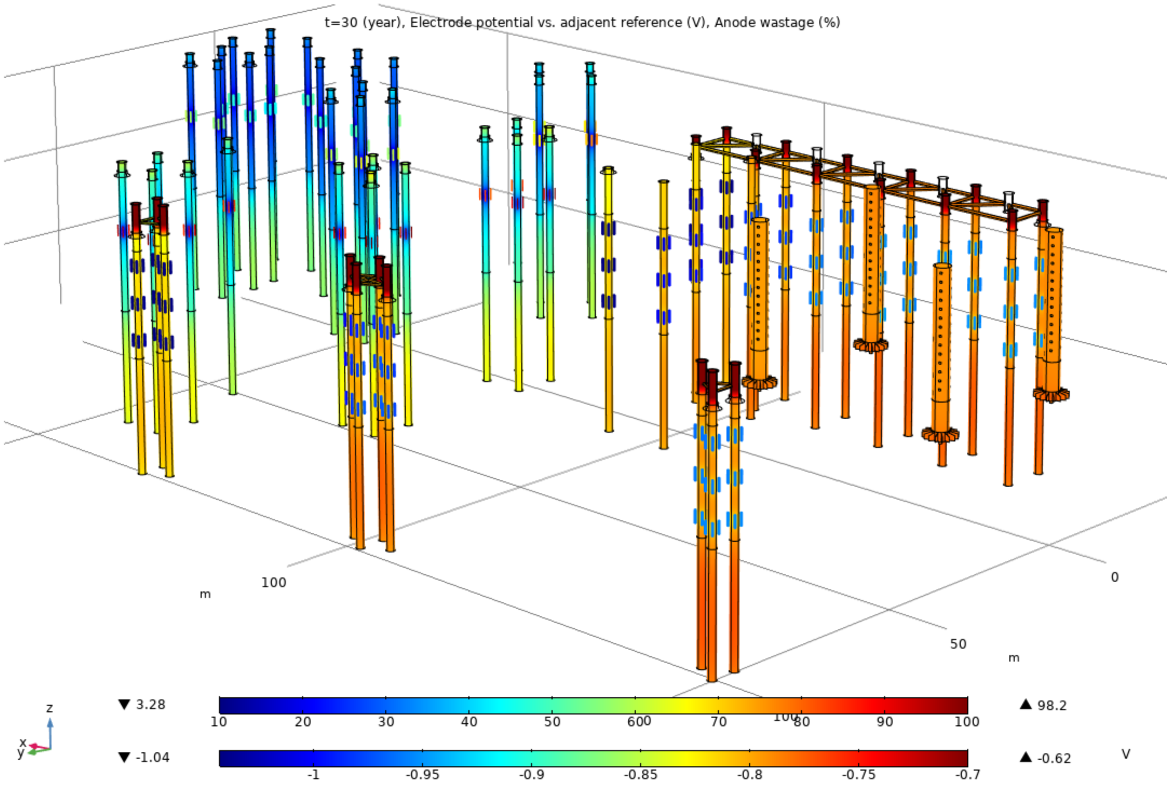


Figure 9-6 Potential distribution (V) and anode wastage (%) at t = 30 (years) seen from north-west side.

### 9.5.5 Selected Jack-Up Projects (Field Experience)

The field experience gained from selected jack-up installations is summarised in Table 9-1. More information is available in published literature [61] [59] [60].

Table 9-1

| Case No. | CP compatibility and mitigating actions for HISC susceptibility |
|---|---|
| 1 | Design<br>〉 Leg material: Uncoated high strength steel<br>〉 CP system: The jack-up legs were fitted with diode controlled bracelet anodes. It was felt necessary to additionally control potentials on the concrete gravity base and the conductors also with diode control<br>〉 Mitigating action (HISC): The diode-controlled anodes are used to control the potential within a limited potential range where the probability for HISC is significant. Electrical isolation from other structures (no influence from other CP systems)<br>Field Experience<br>〉 Long polarization time: 1 year; -720 mV, 6 years; -750 mV, 12 years; -755 to -800 mV<br>〉 No reports of any HISC related issues<br>〉 Negligible corrosion rate at the most positive potentials as indicated by corrosion coupon measurements |
| 2 | Design<br>〉 Leg material: High strength steel<br>〉 Initially proposed CP system: diode controlled anodes (abandoned due to complications related to conventionally protected structure alongside)<br>〉 Installed CP system: Conventional anodes<br>〉 Mitigating action (HISC): Comprehensive programme of material testing to ensure good metallurgy in the critical components. No high-strength steels used in mud zone or under anaerobic environmental conditions<br>Field Experience<br>〉 No reports of any HISC related issues |
| 3 | Design<br>〉 Leg material: High strength steel (690 MPa/800 MPa) and 390 MPa strength steel<br>〉 CP system: Conventional anodes and TSA (TSA coating will reduce the number of anodes required)<br>〉 Mitigating action (HISC): Extensive material testing to ensure good metallurgy. The lower 27 m of the legs are without holes and made of 390 MPa strength steel. The internal lower parts are also filled with grout. Early field inspections are required.<br>Field Experience<br>〉 No reports of any HISC related issues<br>〉 Potential level -950 mV to -1030 mV after 20 years. |

# 10 Non-destructive testing

Although many actions may be performed in the design phase to mitigate the risk of defects in the as-built structure, non-destructive testing is applied to verify that defects were not present prior to service.

Non-destructive testing (NDT) methods are widely used to detect and characterize defects in welds without altering the integrity of the component. The most common NDT methods used for weld inspection include radiography (RT), ultrasonic testing (UT), magnetic particle testing (MT), penetrant testing (PT), Eddy current testing (ET) and visual inspection (VI). Radiography involves passing X-rays or gamma rays through the weld and recording the image on a film or digital detector. Discontinuities such as cracks, voids, porosity, and lack of fusion are visible on the radiograph, can be detected, and evaluated. Ultrasonic testing (UT) is based on the propagation of high-frequency sound waves through the weld material. Discontinuities such as cracks, inclusions, and lack of fusion can be detected and evaluated based on the reflection and transmission of sound waves. Magnetic particle inspection (MT) is a method that relies on the attraction of magnetic particles to areas of flux leakage caused by surface or subsurface discontinuities. The magnetic particles are introduced to the weld surface and are drawn to the areas of flux leakage, creating a visible indication of the location and extent of the discontinuity. Liquid penetrant testing (PT) is a method used to detect surface-breaking discontinuities such as cracks, laps, and porosity. A penetrant is applied to the surface of the weld, and after a specified time, the excess penetrant is removed, and a developer is applied to pull the penetrant out of any discontinuities. Eddy current testing (ET), is one of many electromagnetic NDT methods making use of electromagnetic induction to detect and characterize surface and sub-surface flaws in conductive materials. Visual inspection (VI) is the simplest and most basic form of NDT. It typically involves a trained inspector visually examining the weld for any surface or subsurface defects. VI can be supplemented with tools such as magnifying glasses, borescopes, or other instruments to enhance the inspector's ability to detect defects. Each of these NDT methods has its advantages and limitations and can be used alone or in combination to provide a comprehensive evaluation of the weld. The selection of the appropriate NDT method depends on the type of weld, the material being welded, and the specific defect to be detected.

## 10.1 Non-destructive testing to detect defects

NDT does not in itself improve the weld quality but merely provide documentation for acceptance of the “as welded” structure. Logging of NDT determined weld defect repairs by position, extent and type shall be part of the NDT “as build” documentation.

Experience with steel structures with heavy wall thicknesses indicates that the probability of crack detection in the fabrication welds can be low [6]. One reason can be that the NDT procedures used during new-building concentrates on detecting longitudinal imperfection while transverse and chevron cracking are surpassed due to the surface profiles of the weld cap layers, and the method of investigation. It is possible to increase the probability of detecting of longitudinal, transverse and chevron crack by smooth grinding the weld surfaces followed by application of more elaborate NDT procedures (UT). The horror example of weld surface appearance shown in Figure 3-8 does not lend itself to any NDT test method.

Smooth grinding further has the effect to increase possibility of detecting in-service HISC cracking by UWILD using UT or ET. Qualified personnel for the smooth grinding to avoid over grinding (where notches are formed instead of a smooth transition from the weld to the base material) is essential. If an unqualified grinder is performing the job, repair may be needed afterwards in order to obtain geometric rule compliance.

Methods have been developed to detect transverse indications. However, these methods are not standardised as it is not possible to accurately define the size of the indications, and experience shows that not all indications are detected. The detection problem that arises in production of heavy plate construction, is that the cracks rarely extend to the surface, making detection with MT problematic and the orientation of the cracks does not match the utilised UT investigation methods in the shipyards. Further the cracks are normally located in multiple heights and angles and can be overlapping each other making evaluation of the indications difficult. Reference is made to Figure 3-7. By experience the size of the weld cold cracks from which the HISC cracks later develop are between 2-5 mm wide and 5 – 15 mm long. With the use of standard NDT technics, as requested by classification societies (e.g. UT), these flaws/indications remain undetected or appear much smaller than they are, often so small that they are considered acceptable according to the normal acceptance criteria. In order to reveal these cracks, which can be subsurface cracks, grinding of the weld metal surface required prior to examination by MT or VI is required. Due to the orientation of the cracks, which can be in altering angles and rotation levels, it can be difficult to define if the indications are linear or volumetric, but experience shows that if there are indications in the transverse direction in the weld metal of 690 steels these are often cracks. The cracks rarely penetrate the surface layers or root layers of the weld metal but are located 5 – 10 mm below the surface. In case a surface breaking crack is observed, there are normally multiple cracks in the adjoining weld metal. The fact that subsurface cracks are not detected by MT, is part of the reason structures may leave the yard with cracks that in service can develop into HISC when exposed to hydrogen from the cathodic protection.

The phased array UT technique has been utilised and good results have been obtained. However, the geometry, for example curved surfaces on chord scales, limits this technique to fairly straight surfaces, such as spudcan bulkheads or rack to chord joints due to the size of the probes.

Education of NDT personnel to detect these indications/ cracks on site is crucial as experience shows that non-educated personnel will oversee the indications or deem them to be acceptable as porosities or similar. Knowledge of how these defects can develop during service may also be included in education of NDT personnel to emphasize the importance.

## 10.2 In-service inspection

Demands to in-service inspection include Underwater inspection in lieu of dry-docking (UWILD). The scope for these investigations is made in conjunction with the classification societies. Prior to UWILD inspections, cleaning of the area to be inspected is important to obtain the best results.

Incidents in the industry have revealed cracks in areas that have not been part of the UWILD scope. In some cases, investigations with Eddy Current testing (ET) have been conducted above the top plate of the spudcan on the weld between the bracket member between top plate and chord scale. However, cracks were later detected to a large extent in the structure below the spudcan top plate and in the base material of the lower leg. So far most of the findings have been in the spudcan area and connections, however, experience shows that HISC crack development can appear further up in the leg.

Some areas (the bracket above spudcan top plate) that was part of the UWILD NDT investigation scope and was reported as acceptable, later showed to have long cracks that were not detected by the NDT performed subsea. If cracks are detected on a jack-up structure, it is essential to perform a redundancy analysis to ensure structural integrity. The use of analytical methods to determine critical defect size and crack growth rate if the jack-up rig is not to be repaired in near future, is an option to be considered.

It may be prudent to look into the investigation scope and investigation methods for future UWILD inspections, in order to avoid similar incidents. Depending on design, subsea areas involving heavy 690 MPa steels should be considered as part of the UWILD investigation scope, and occasional use of ROV may be considered.

# 11 Industry experience

The present project was initiated due to an incident with observed cracking in a jack-up on the Norwegian Continental shelf. Industry experience is key to include to elucidate the extent of the issue with observed cracking in the chord-to-spudcan connections on jack-ups.

## 11.1 Rig owner response to notification on incident

Ptil had notified rig owners with rigs placed on the Norwegian Continental shelf of the incident with observed cracking in 2022 along with a request for inspection results from the area of interest on the jack-up rigs. Feedback was received from all by December 2022, and updates were received during 2023. In conclusion, cracking was not a general issue across the jack-up rigs. It is however important to gain more insight into the methods applied to detect possible crack-like indications.

The scope of the UWILD inspections is agreed between rig owner and classification society. Information on the NDT methods used for the inspection reported to Ptil, has not been available. The position at which cracks were observed in the incident, is often not covered by the UWILD inspection scope. The cracks were located below the spudcan top plate, as illustrated in Figure 11-1 and Figure 11-2. Accordingly, there can be undetected cracks.

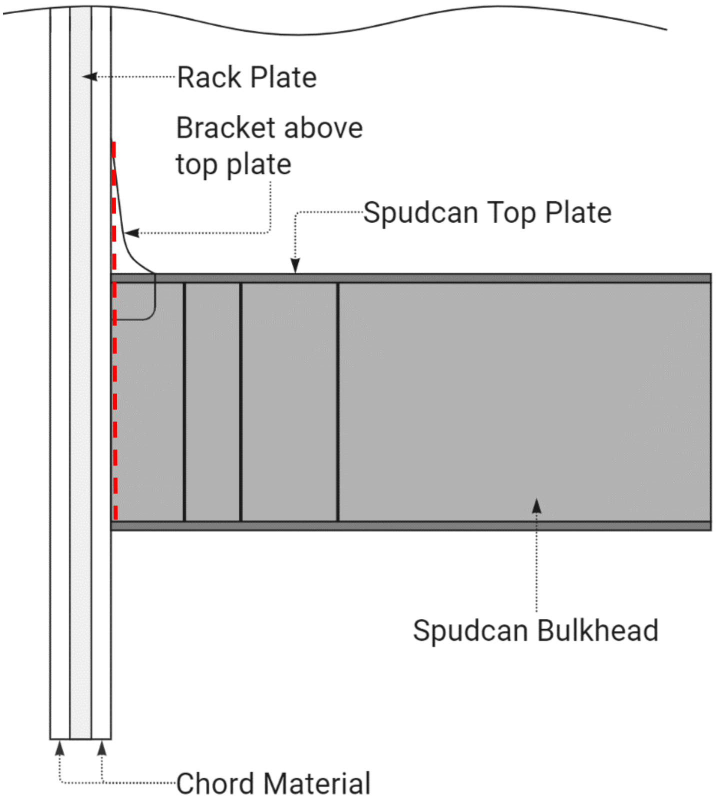


Figure 11-1 Structural details at the spudcan to leg transition. The red line shows positions where cracking has occurred.

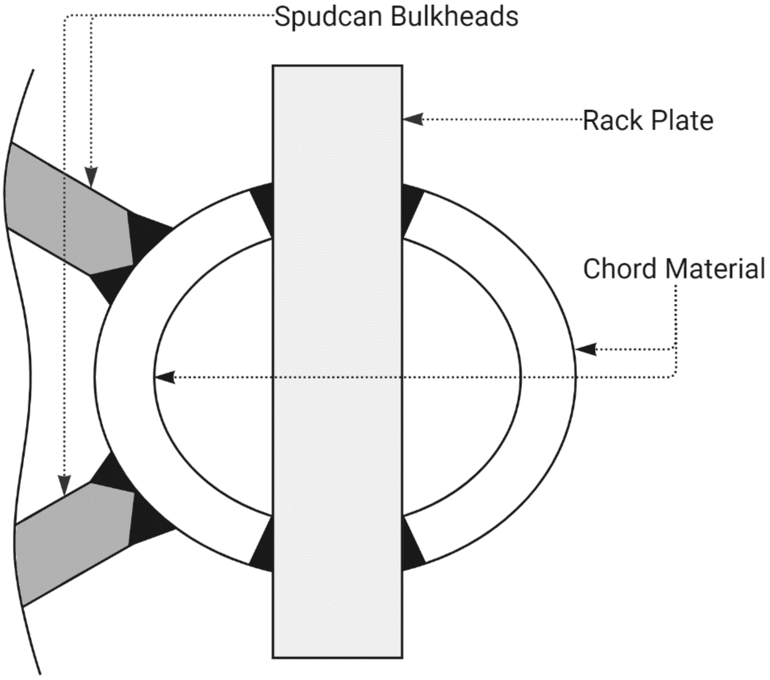


Figure 11-2 Top view through a jack-up leg showing the position of chord, rack and spudcan bulkheads.

## 11.2 Future work

Industry experience is key to elucidate the extent of the issue with observed cracking in the chord-to-spudcan connections on jack-ups. In addition to updated knowledge on performed inspections, a workshop with the participation of industry stakeholders would contribute to gain a palette of input. Further, a workshop would contribute to spread the knowledge about hydrogen induced cracks gathered in this study and thus educate relevant industry stakeholders to avoid future issues. As described, the encountered issues can be avoided by paying close attention to welds and NDT at the construction yard, and hence sharing this knowledge should be prioritised. It is both a matter of safety, economy, possible waste of resources as well as the reputation of the industry come into play. Similar issues can arise in offshore wind turbine installation vessels which essentially are jack-up structures and the same steel grades are used, but with a different and possibly much more severe loading pattern during its service life.

Proposed activities for future work include:

- A workshop with industry stakeholders with the aim of knowledge sharing
- Separate interviews with industry stakeholders as an alternative to a workshop
- A webinar with the aim of sharing learnings and content of the study
- Publication of the report with targeting to ensure the information reaches relevant stakeholders
- Development of investigation scope and method to be used for future UWILD inspections in conjunction with rig owners and classification societies
- Further development of classification society rules for newbuilding

Stakeholders include, but not be limited to:

- Rig owners
- Designers
- Classification societies
- Rig builders, i.e. shipyards
- NDT companies

Including rig designers could aid mitigating issues by setting correct demands to welds and NDT in the design phase or consider using steels with a lower hardness. The classification societies could enter a discussion on the NDT and inspection demands. Including the rig builders could assist in educating them to avoid future issues by increasing the QA/QC level during fabrication. If these are caught prior to setting the rigs in operation, issues may be avoided.

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## FORCE Technology Norway AS:

**Hvalstad: HEADQUARTERS**
Nye Vakås vei 32
1395 Hvalstad, Norway
Tel. +47 64 00 35 00
E-mail: info@forcetechnology.com
www.forcetechnology.com/no

**Post address (Headquarters)**
Postboks 76
1378 Nesbru, Norge

**Invoice e-mail**
NOinvoice@force.no

**Trondheim**
Sluppenveien 19
7037 Trondheim, Norway

**Kristiansand**
Mjåvannsvegen 79
4628 Kristiansand, Norway

## GLOBAL HEADQUARTERS:

**FORCE Technology**
Park Allé 345
2605 Brøndby, Denmark
Tel. +45 43 26 70 00
E-mail: info@forcetechnology.com
www.forcetechnology.com