



MANAGING RISK

Bolting materials subsea



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Bjarte Lillebø, Det Norske Veritas, Bergen, Norway

- The high integrity bolted connections used in the offshore industry are often critical parts of the plant or piping system. Failure of such connections has been found to be a major cause of gas/oil leakage on offshore installations.
- High strength materials for bolting are needed for subsea use by the offshore industry. However, several candidate materials may be susceptible to failure due to hydrogen and associated cracking caused by the cathodic protection system.

Subsea / submerged systems

- Wellheads
- Xmas tree flanges
- Structural connections
- Flanges

“Bolting Technology” - an interdisciplinary subject

- Connection type /flange design /pre-loading requirement
- Bolting standards
- Bolting material properties:
 - Strength
 - Corrosion resistance
 - Galling properties
 - Susceptible to hydrogen effects
- Bolting manufacture (incl. quality control)
- Bolting installation methods:
 - Hydraulic torque (accuracy +/- 25%)
 - Hand torque (accuracy +/- 30%)
 - Hydraulic tension (accuracy +/- 10%)
- Corrosion protection (CP, coating system)
- Maintenance of bolted connections in service

- Cathodic protection (CP) is normally applied to steel structures
→ bolting material selection is essential
- Inspection and maintenance may be difficult (and costly), e.g.:
 - detect leakages/vibrations and observe bolting failures (visually)
 - repair coating defects
- Controlled installation of bolts (first time) is crucial to ensure correct pre-tensioning, and thus avoid failures caused by vibrations/fatigue.
Critical factors:
 - pretension method (accuracy): uncontrolled tightening, manual/hydraulic torque control or tension control
 - lubricant product: significant effect on actual preload if pretensioning is performed by torque control (low friction may increase tension in bolt)
 - quality assurance (documentation, verification)

Use experienced personnel and qualified procedure for installation/tightening!!

Bolting materials (common standards)

Alloys and chemical/mechanical requirements:

- ASTM A 193 "Alloy steel and stainless steel bolting materials for high temperature service" (eks. ferritic steels Grade B7, B7M)
- ASTM A 320 "Alloy steel bolting materials for low temperature service" (eks. ferritic steels Grade L7, L7M)
- ASTM A 354 "Quenched and tempered alloy steel bolts, studs and other externally threaded fasteners"
 - These standards refer to AISI designations for chemical composition (e.g. AISI 4140, 4142 or 4145). SMYS will depend on heat treatment, shape and dimension.
 - In general "quenched and tempered" low alloyed bolts are frequently used for offshore applications
- ISO 898-1 "Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs

Bolting materials (common standards) cont.



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Dimensions, threads, tolerances:

- ISO 898 Part 1 to 7

Additional requirements:

- mechanical testing
- inspection/quality control

Examples - coating systems (offshore bolts)



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DNV

Type of coating	Application method	Comment
Dip galvanised	Dipping	For large size bolts. Zinc thicknes: 10-200 micron
Dip-spin galvanised	Special equipment	Even coating thickness Zinc thikness: about 40 microns
Sherardizing	Special equipment	Even coating thicknesss. Zinc thikness: 10-50 microns
Electrodeposited (Zn, Cd)	Electrolytic	Low zinc thicknesss. Zinc thikness: 2-25 microns
Phosphate	Dipping	As pre-treatment to additional coating application
Al-based coating	Spraying techniques	Low coating thickness
Zinc-silicate	Spraying techniques	
Fluoropolymer (PTFE)	Spraying techniques	
Thermoplastic	Spraying techniques	With inhibitor. Can also be used for maintenance
Wax-system	Spraying techniques	Also for maintenance use

ANSI/API RP 17 & ISO 13628-1:2005

- ANSI/API RP 17 Design and Operation of Subsea Production Systems – General Requirements and Recommendations
- ISO 13628-1:2005, Petroleum and natural gas industries-Design and operation of subsea production systems-Part 1: General requirements and recommendations

ANSI/API RP 17 & ISO 13628-1:2005 (cont.)

- If cathodic protection (CP) is ensured, bolting material used for piping system and equipment should generally be carbon or low-alloy steel, ref. ASTM A320 (L7 and L43) and ASTM A193 (B7 and B8M). Bolts with a diameter less than 10mm may be stainless steel type 316 (*ISO 3506-1, Type A4*) at temp. below 60 °C.

Structural applications:

- *strength class should not exceed class 8.8 for bolts (ISO 898-1) and class 8 for nuts (ISO 898-2)*
- *maximum actual allowable hardness: 300 HBW or 32 HRC (verified by spot testing)*

ANSI/API RP 17 & ISO 13628-1:2005 (cont.)

- In high corrosive environments and/or where CRA materials are used, corrosion-resistant bolting is recommended.
 - Alloy 625 (Ni-based) are required at ambient temperature in aerated seawater (if CP cannot be ensured).
 - Other alloys can be used if properly documented

ANSI/API RP 17 & ISO 13628-1:2005 (cont.)

■ Coating

- Carbon steel or low-alloy bolting material should be galvanised or have similar corrosion protection
- If there is a risk that dissolution of zinc layer, such as obtained by hot-dip galvanising, can cause loss of bolt pre-tension, electrolytic galvanizing or phosphating should be used. Electrolytic galvanizing should be followed by post-baking.
- PTFE-based coatings can be used as one alternative, provided electrical continuity is verified by measurements.
- Cadmium plating should not be used (due to environmental and worker health problems associated with the coating process).

■ Other issues to be considered (if relevant)

- Bolts screwed into component bodies: compatible with the body w.r.t. galling and ability to disassemble for maintenance.
- Risk of galvanic corrosion, effect of thermal coefficients, effect of CP.

NORSOK Standard M-001 Materials selection (Rev. 4, August 2004)

- **General: Carbon or low-alloyed bolting materials**
 - maximum hardness of 300 HB (32 HRC) – verified by spot testing of each delivery, batch and size
 - for structural applications, strength class shall not exceed ISO 898 class 8.8
 - hot dip galvanised (ASTM A153) or similar corrosion protection
 - if dissolution of zinc layer may cause loss of bolt pretension, phosphating shall be used
 - PTFE based coatings can be used (electrical continuity need to be verified by measurements)
 - compatible to component bodies w.r.t. galling and ability to disassemble the component for maintenance

- **Ambient temperature: Alloy 625 (seawater, no cathodic protection)**

Corrosion

- Hydrogen related mechanisms (cracking)
 - Hydrogen induced stress cracking (HISC)
 - Hydrogen embrittlement (HE)
- Stress corrosion (SCC), ref. e.g. chloride stress corrosion
- Corrosion fatigue
- General corrosion
- Local corrosion (pitting/crevice corrosion)
- Galvanic corrosion

Galling, Fatigue, Overloading

HISC

- Progressive cracking under influence of external or internal stresses, starting at metal/environment interface and propagating by absorption of nascent hydrogen at the crack tip. Electrochemical process (e.g. corrosion or cathodic protection) as hydrogen source. Bulk charging of hydrogen *not* required. Non-reversible process.

HE

- Loss of ductility due to absorption of nascent hydrogen in bulk material (“bulk charging”). Electrochemical or metallurgical process as hydrogen source. Reversible process, but may lead to cracking (surface or non-surface breaking) by brittle fracture under influence of external or internal stresses.
 - Electroplating is generally considered to be a major cause of hydrogen absorption in bolts due to the release of hydrogen in this process. Absorbed hydrogen can be removed by post-baking (temperature >200 C).

Hydrogen induced failure mechanisms

- **HISC** (hydrogen induced stress cracking) is caused by interaction between metal lattice and atomic hydrogen dissolved in the steel. External or internal stresses required.
- **HPIC** (hydrogen pressure induced cracking) is cracking/fracture caused by pressure buildup due to recombination of hydrogen atoms in accessible positions *. External or internal stresses not required.
- **SOHIC** (Stress Oriented Hydrogen Induced Cracking) is a combination where longitudinal HPIC cracks are connected by transverse HISC cracks.
- If the cracking is related to a corrosion process the description **HISCC** (hydrogen induced stress corrosion cracking) is sometimes used.
- **SSC** (sulphide stress cracking) is a sort of HISCC.
- **Hydrogen attack** is reaction between hydrogen and carbides that causes a reduction in strength / cracking.

*) E.g. at pores, grain boundaries and inclusions.

Hydrogen sources:

■ Steel manufacturing

- Large quantities of hydrogen may be dissolved in liquid steel
- Humidity in air and chill moulds etc.

■ Coating

- Acid cleaning
- Electrolytic plating (metallic coatings)
- Hydrogen may be removed by baking $>200^{\circ}\text{C}$

■ In service

- Cathodic protection system (CP)
- Corrosion processes

Hydrogen Induced Stress Cracking (HISC) in bolts with CP

- HISC may occur in:
 - high strength low alloy steels
 - stainless duplex steels,
 - Titanium alloys,
 - Nickel-based alloys

- Critical factors:
 - Material grade (chemistry, microstructure, manufacturing process)
 - Stress level (ref. pre-tension, local yield, strain)
 - CP potential (-0,80 til -1,10 V vs. Ag/AgCl) NB! hydrogen production increases exponentially with decreasing potential

- Access to hydrogen can be influenced (or limited) by coatings:
 - electrochemical coatings
 - PTFE based coatings
 - paints
 - calcareous deposits

Austenitic stainless steel and Nickel based alloys:

- Considered immune to HISC if in the solution annealed condition
 - moderate cold work and welding/hot forming according to an appropriate procedure do not induce HISC sensitivity (except UNS 30200 / UNS 30400)
- Some grades are sensitive to HISC if precipitation hardened:
 - certain nickel based alloys (e.g. UNS N05500 and N07750)
 - austenitic stainless steels with hardness higher than 300-350 HV *

*) In the intermediate hardness range, i.e. 300 to 350 HV, the susceptibility to HISC is reduced by avoiding local yielding or if a reliable coating system (paint) is applied as a barrier to hydrogen absorption

- Bolts in AISI 316 stainless steel
Bolts in UNS 31600 (AISI 316) stainless steel manufactured according to ISO 3506, part 1, grade A4, property class 80 and lower (SMYS < 640 MPa) have proven compatibility with galvanic anode CP (ref. DNV-RP-B401).

Material grades – HISC sensitivity

Ferritic and ferritic-pearlitic structural steels

- Considered immune to HISC if:
 - SMYS < 500 MPa (extreme conditions of yielding may induce HISC sensitivity)
 - hardness < 300 to 350 HV *

*) In the intermediate hardness range, i.e. 300 to 350 HV, the susceptibility to HISC is reduced by avoiding local yielding or if a reliable coating system (paint) is applied as a barrier to hydrogen absorption

Martensitic carbon, low-alloy and stainless steels

- Sensitive to CP induced HISC if:
 - AYS > about 700 MPa
 - hardness > about 350 HV *
 - untempered martensite (especially prone)

*) Hardness in the range 300-350 HV: design to avoid local yielding and/or apply a reliable coating system (paint) as a barrier to hydrogen absorption

- Bolts in martensitic steel:
 - Bolts in martensitic steel heat treated to SMYS up to 720 MPa (e.g. ASTM 182, type B7 og ASTM A320, type L7) have well documented compatibility with CP (for critical applications, adequate heat treatment has to be documentet with batch wise hardness testing (<350 HV))

Ferritic-austenitic (duplex) stainless steel

- Regarded as potentially susceptible to HISC
 - independent of SMYS (typically 400 to 550 MPa) or specified minimum hardness
 - forgings are more prone to HISC than wrought material due to the coarse microstructure allowing HISC to propagate preferentially in the ferritic phase
 - CP potential should be limited to -800 mV vs Ag/AgCl (special anode alloys)

Copper and Aluminium alloys

- In general immune to HISC

Titanium alloys (high-strength)

- Limited documentation

Stress corrosion cracking (SCC)

- Chlorid stress corrosion cracking in high temp., oxygen containing seawater, without CP
 - stainless steel grades
 - Nickel alloys
 - Titanium grades, etc.

Fatigue (corrosion fatigue)

- Caused by vibrations and missing pre-tensioning

Prevent fatigue failures:

- controlled tightening
- select materials with improved fatigue properties

Galling

- Mechanism:
 - a severe form of adhesive wear which occurs during sliding contact of one surface relative to another.

- Most sensitive materials
 - austenitic stainless steel, Ni-Cr alloys (and some Titanium alloys), galvanized steel

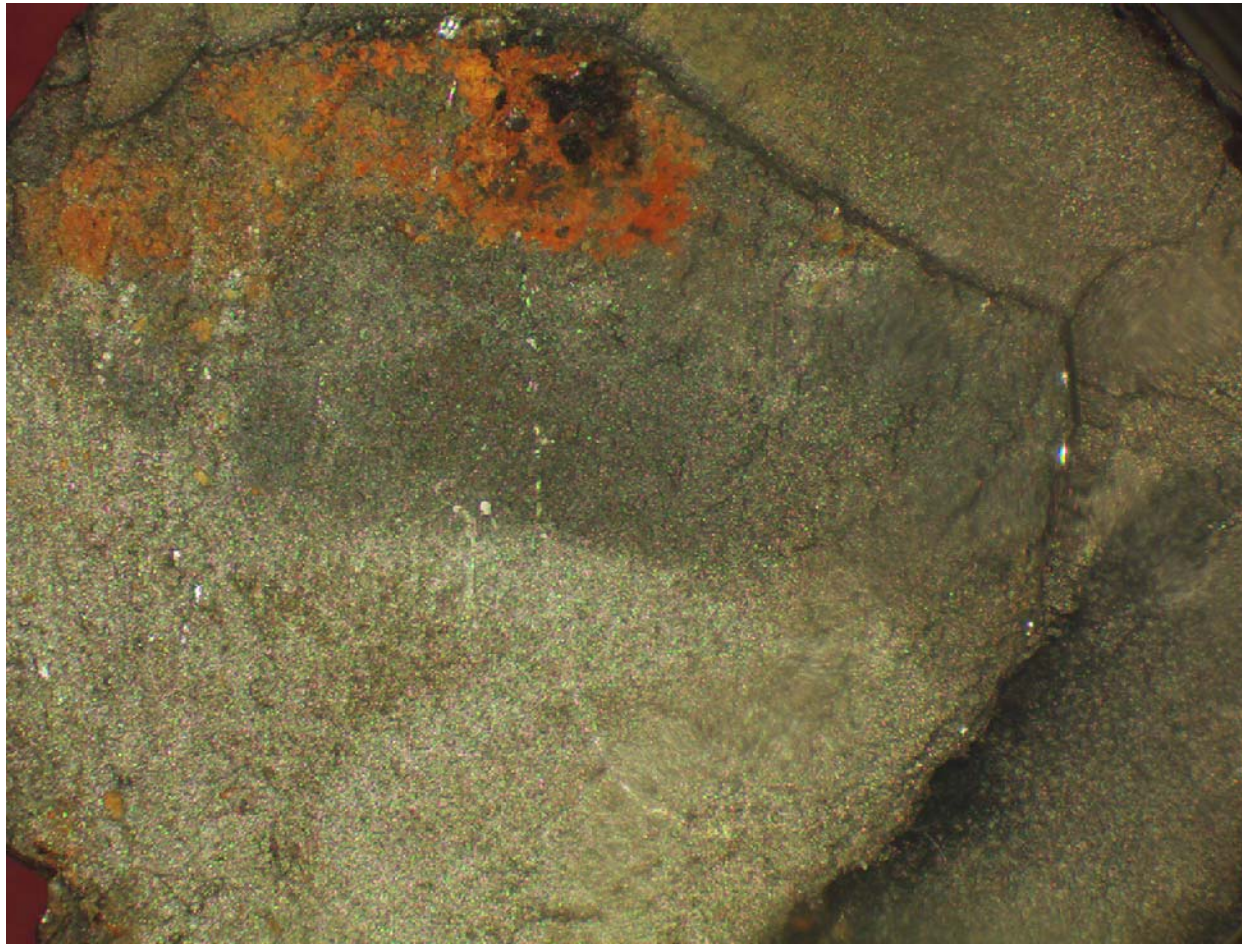
- Problem reduced by
 - using coarse threads
 - using appropriate lubricants
 - selecting material combinations (bolt-structure / bolt-nut) with different resistance (property)
 - qualifying procedure for tightening

Overloading

- High strength bolts are frequently used for structures and pressure systems to avoid overloading
- If low friction lubricants are applied pre-tensioning of bolts may cause overloading

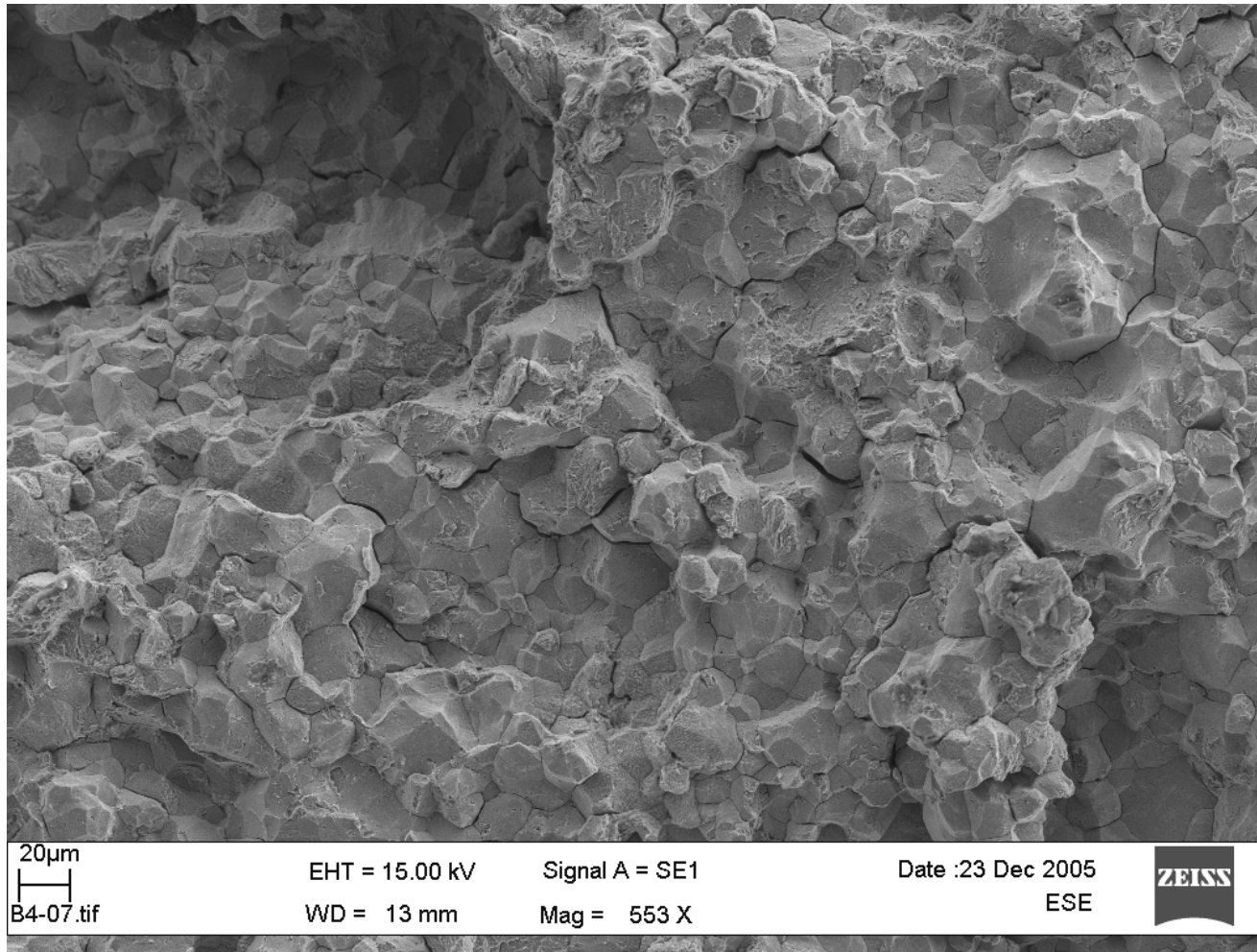
Example 1: Failure analysis – bolt fracture

- Fracture surface (macro)



Example 1: Failure analysis – bolt fracture

- Fracture surface in SEM (Scanning Electron Microscope)



Example 1: Failure analysis – bolt fracture

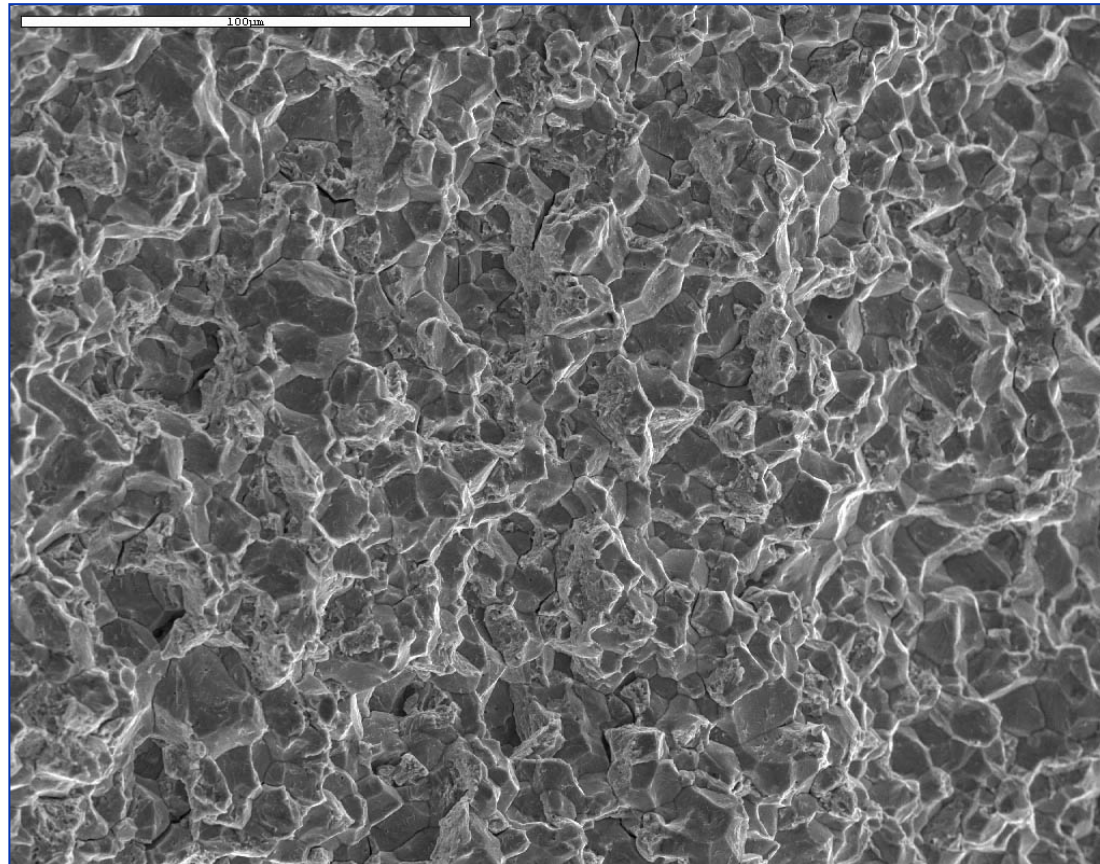
Observations:

- Hardness up to 44 HRC, estimated UTS up to 1410 MPa
- Mikrostructure: tempered martensite
- Fracture initiated in area towards bolt head (highest stresses after preloading)
- Crack propagation transverse to longitudinal direction of bolt
- Intergranular fracture surface (characteristic for HISC)

Conclusion

- Most probably, the bolt has been exposed to hydrogen (from CP system). In combination with high stresses and a sensitive material this has resulted in Hydrogen embrittlement and HISC.

Example 2: Fracture surface from bolt (HISC)



Intergranular fracture in galvanized M6 12.9 bolt

HISC

Bolting materials for subsea applications (with CP)

- Need to qualify candidate materials with respect to susceptibility to HE and HISC (combination)
- However, no test methods are generally “accepted” to verify CP compatibility for materials/systems
- Alternative test methods:
 - SSRT (compare relative sensitivity of similar materials, e.g. martensitic steels)
 - Tensile testing (constant load) and bend testing (constant strain) in e.g. seawater with CP may be applied for more quantitative testing
 - CTOD (with CP)
 - Full scale comparative testing of material candidates in simulated environments

Coating (paint systems)

- Standard test methods to determine resistance to cathodic disbonding

Example: SSRT of 22Cr duplex / API 5L X-65

- **Pre-exposure**

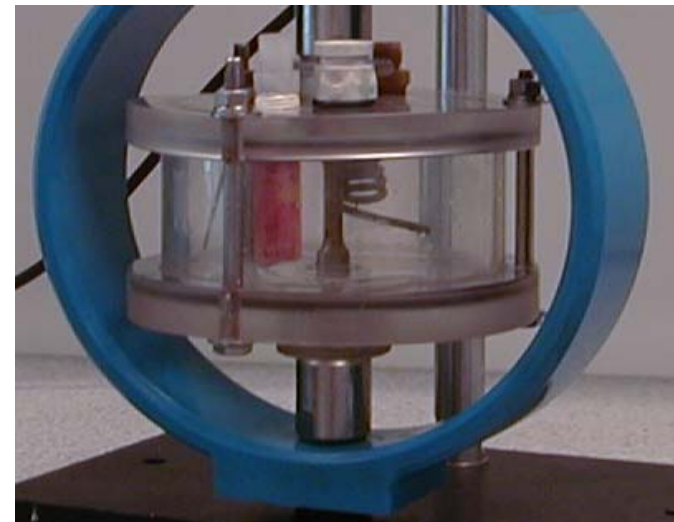
4 weeks cathodic protection in seawater at -1.10 V rel. Ag/AgCl/seawater and 110 °C.

- **Test conditions**

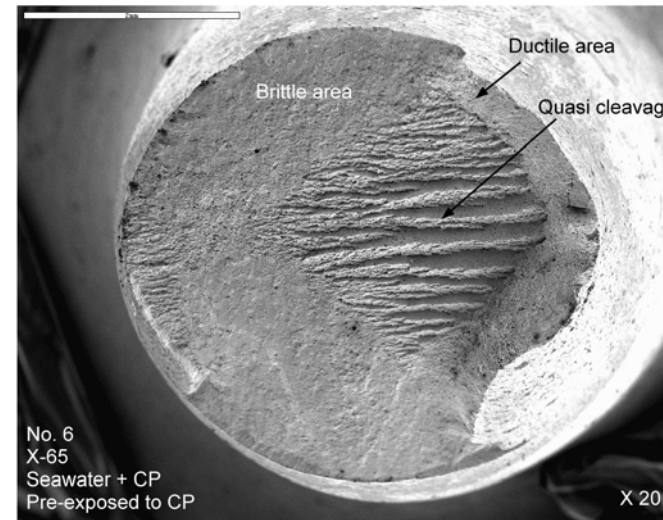
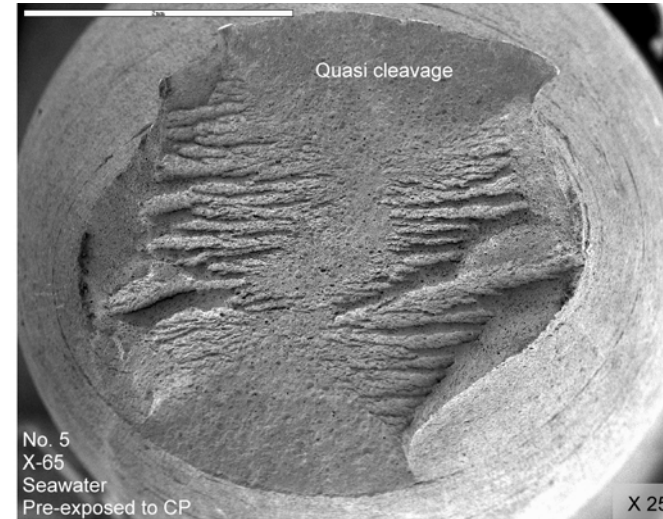
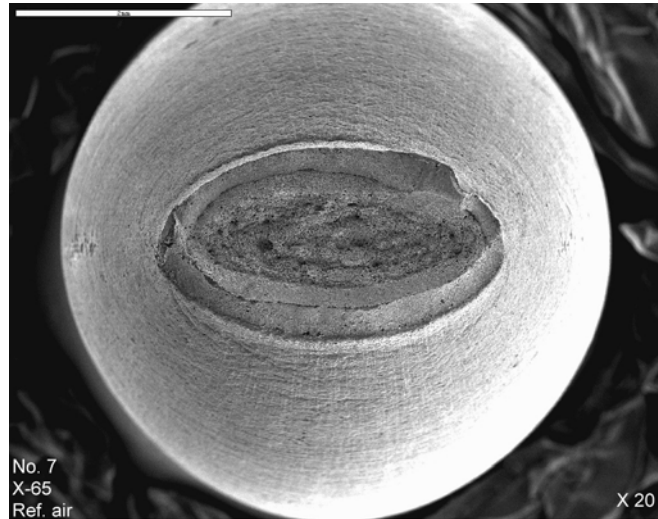
SSRT (CERT) in natural seawater, with and without cathodic protection at -1.10 V rel. Ag/AgCl/seawater

Extension rate 2×10^{-6} s $^{-1}$

Reference testing in air



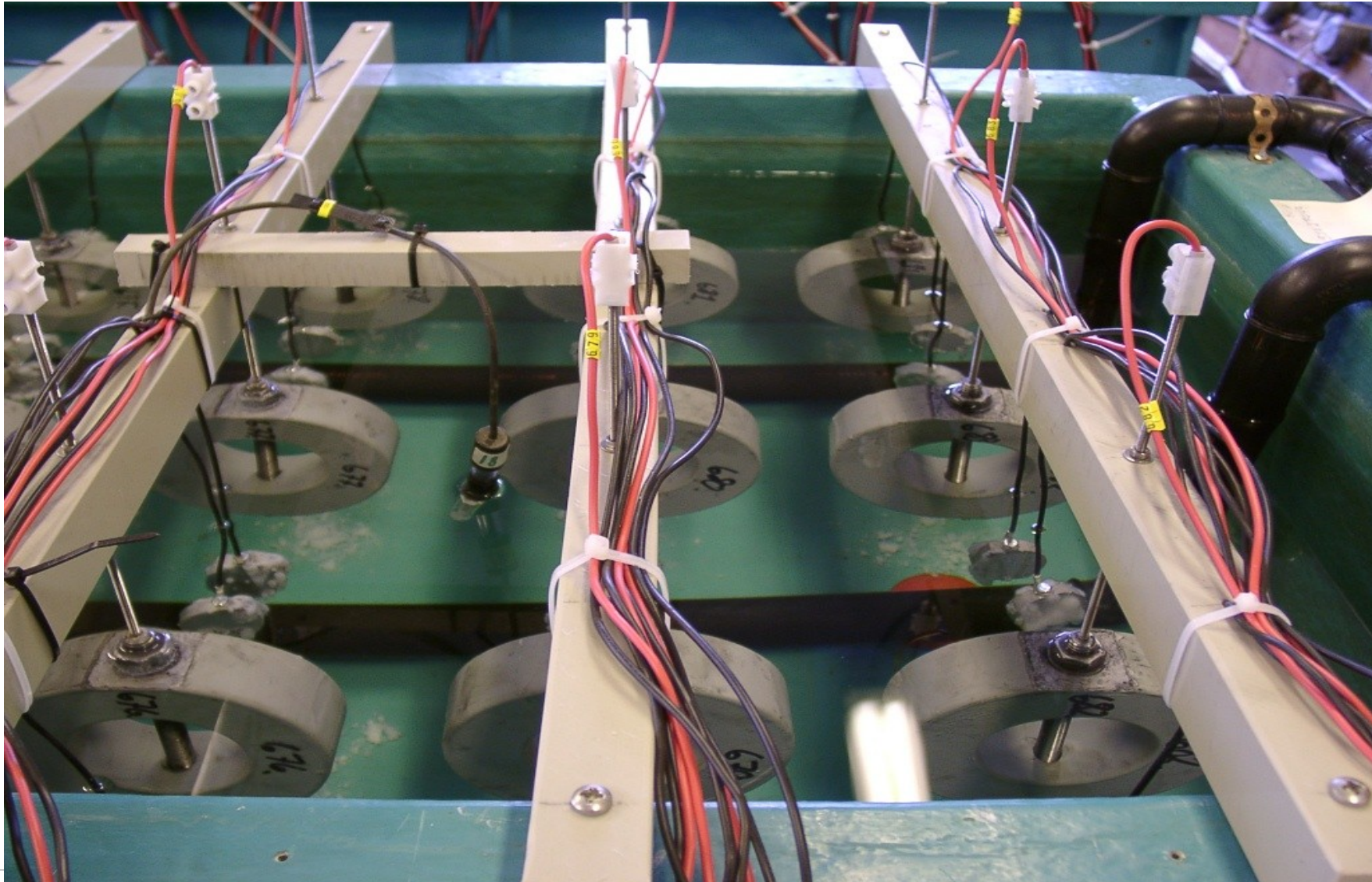
Example: SSRT of 22Cr duplex / API 5L X-65



Conclusions

- Hydrogen charging causes slight/moderate HE of both materials.
- Both materials are susceptible to HISC but the intrinsic susceptibility of duplex stainless steel is higher.
- Pre-exposure to CP has no effect on HISC of API 5L X65.
- Pre-exposure to CP may enhance HISC of duplex stainless steel significantly.
- Simultaneous plastic straining and hydrogen adsorption is required for HISC of these materials.

Example: Submerged testing with CP, DNV Bergen





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