

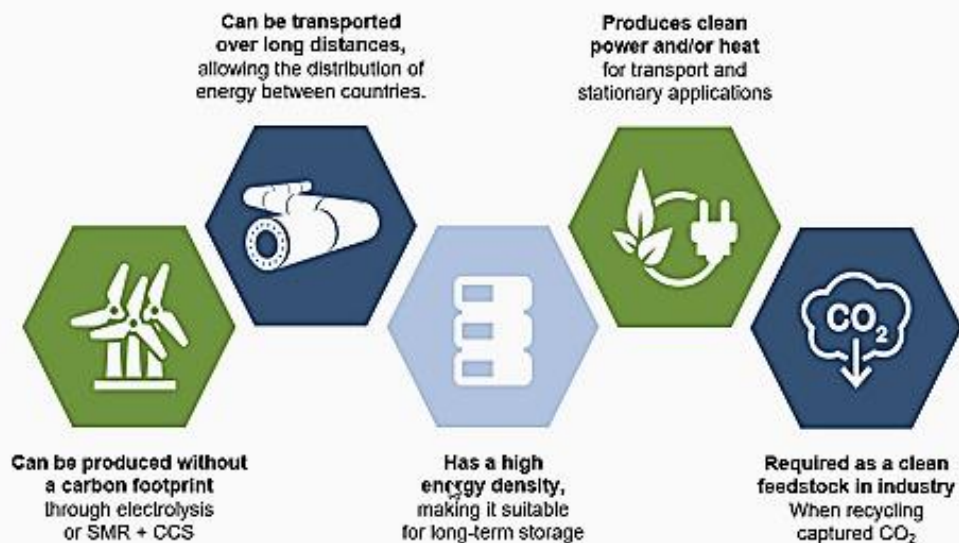
Webminar | Addressing the risk of Hydrogen-Induced Stress Cracking in pipelines

Dr Daniel Sandana . 30th April 2021

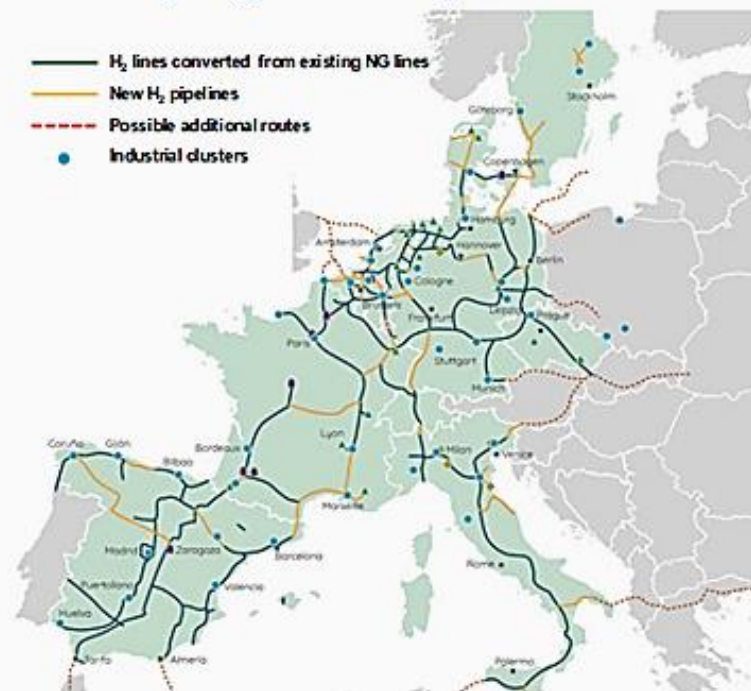
ROSEN
empowered by technology

Introduction... Hydrogen

Clean, safe & flexible



EU Hydrogen vision by 2040



Introduction... Hydrogen

ASME B31.12-2014
(Revision of ASME B31.12-2011)

Hydrogen Piping and Pipelines

ASME Code for Pressure Piping, B31

AN AMERICAN NATIONAL STANDARD



Company	km	Miles
Air Liquide	1936	1203
Air Products	1140	708
Linde	244	152
Praxair	739	459
Others	483	300
World Total	4542	2823
U.S.	2608	1621
Europe	1598	993
Rest of World	337	209

Low grade,
low design factor

Relatively small diameter

Introduction... Hydrogen challenges

Conversion



Can I convert my existing pipelines?

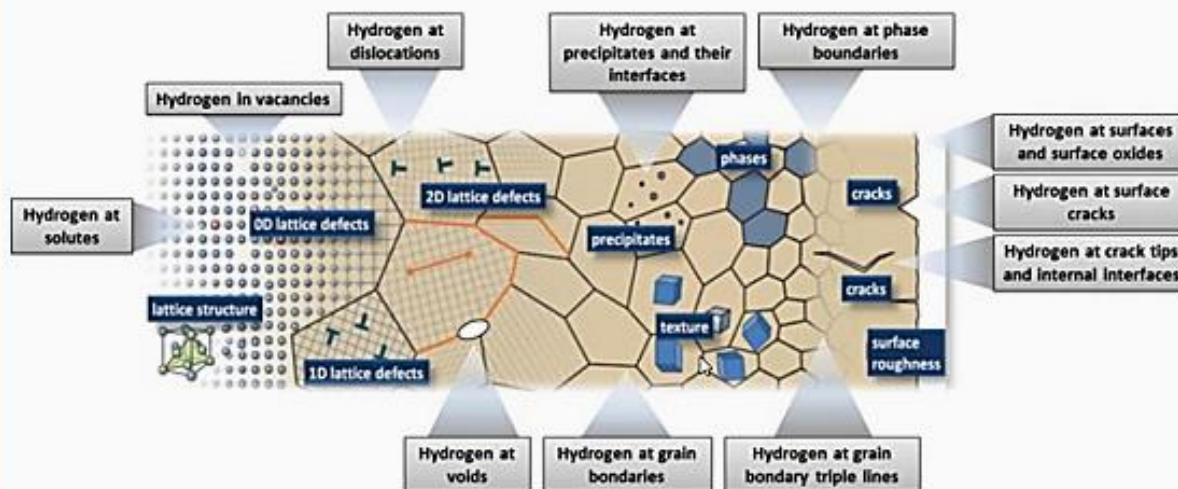
Operations



How I Manage the integrity of my H pipeline?

Introduction... Hydrogen challenges

Hydrogen Interaction



Interaction vs Steel Materials

Hydrogen Embrittlement

Hydrogen-Induced Cracking

Introduction... Hydrogen Cracking in hydrocarbon service?

External



HIC



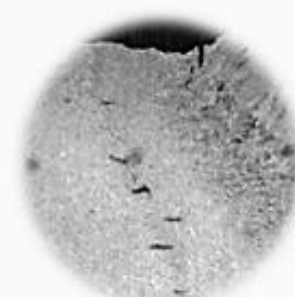
HISC

CP overprotection

Internal



HIC



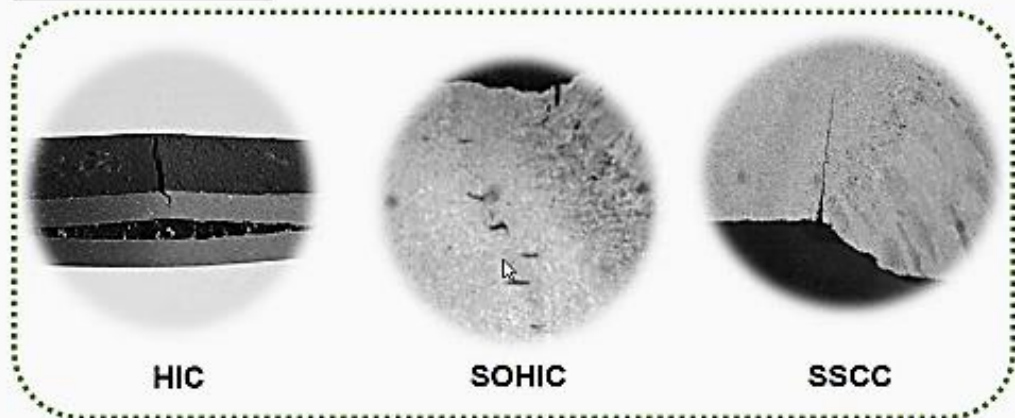
SOHIC



SSCC

H₂S

Introduction... Hydrogen Cracking

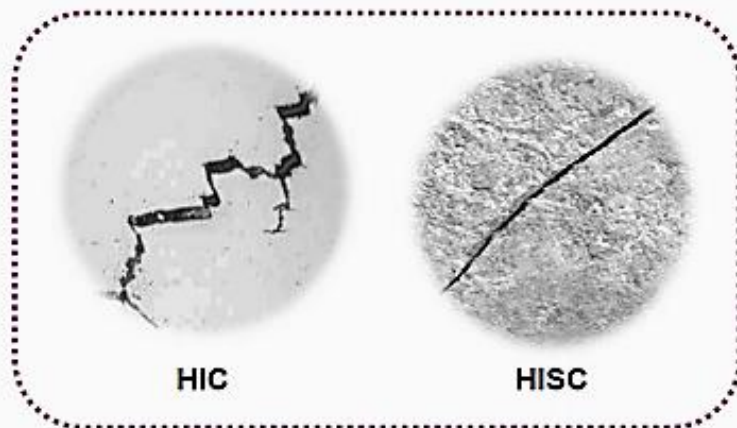


HIC

SOHIC

SSCC

H₂S



HIC

HISC

CP overprotection

Damage at a greater scale
than gaseous H!

...Hydrogen permeation...

Introduction... Hydrogen Cracking

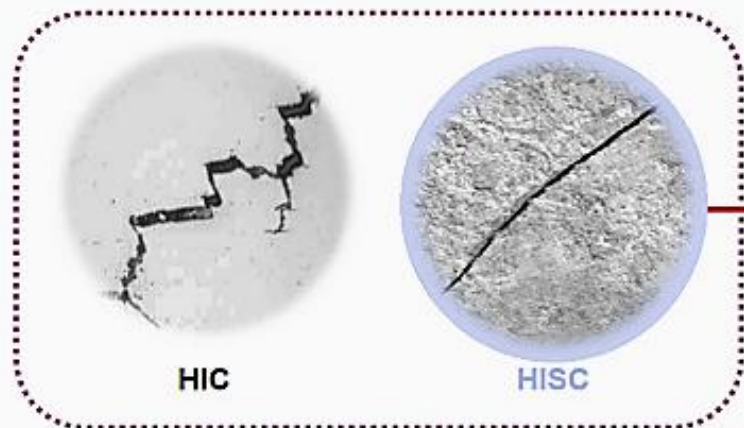


HIC

SOHIC

SSCC

H₂S



HIC

HISC

CP overprotection

H embrittlement

Introduction...

H absorption

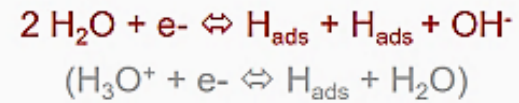
HISC in CS PLs
(onshore)

HE concept

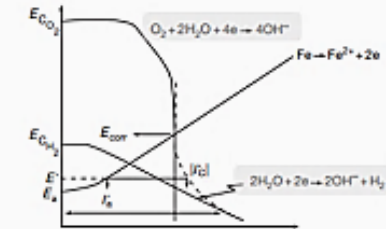
HISC in duplex SS
(subsea)

Atomic H abs... CP

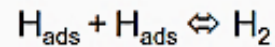
H adsorption (Volmer reaction)



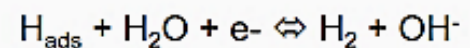
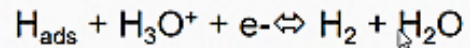
Electronic transfer >> O₂ diffusion



H chemical Desorption (Tafel reaction)



H Electrochemical Desorption (Heyrovsky reaction)



Very alkaline
solutions

Large cathodic
overpotentials

H absorption



Membrane Permeation
 $\propto [\text{H}_{\text{ads}}]$

Atomic H abs... CP

H absorption

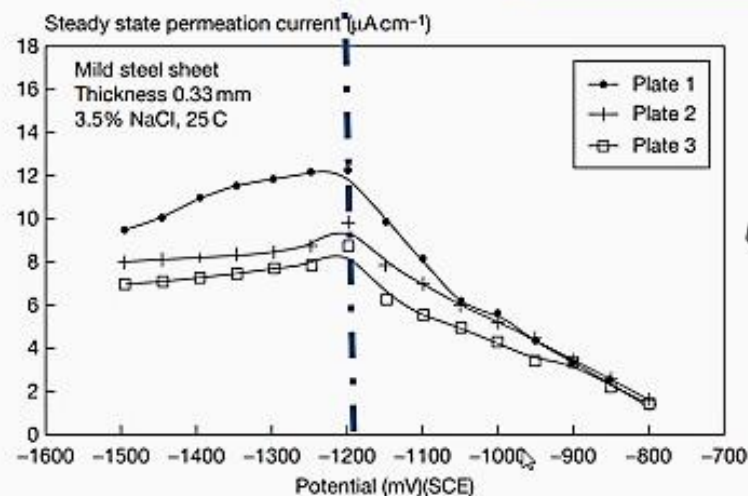


Permeation falls / remains constant
At large overpotentials
And in very alkaline solutions

Electrochemical desorption takes over

Membrane Permeation
 $\propto \sqrt{ic}$

*Assumes H Permeation current
< H₂ evolution*



Umist, Obuzor, PhD1989

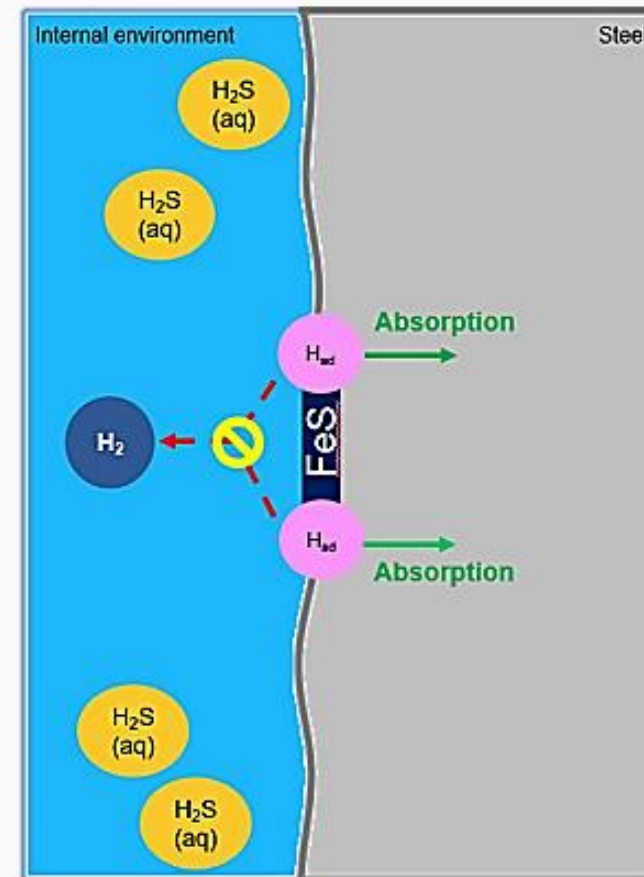
Atomic H abs... H₂S

- Steel materials
- H₂S environment

- $H_{2S(g)} + H_2O \rightarrow H_{2S(aq)}$
- $Fe_{(s)} + H_{2S(aq)} \rightarrow FeS_{(s)} + 2H_{(ad)}$
- $2 H_{(ad)} \rightarrow H_{2(g)}$

Kinetically very slow
H₂S poisons recombination

Adsorbed concentration of atomic H increases
More Atomic H enters Metal



HE... Definitions

Material degradation caused by the presence of atomic hydrogen under load. It is manifested in:

- ✓ Strain hardening rate
- ✓ Tensile strength
- ✓ Reduction in area
- ✓ Fracture toughness
- ✓ Elongation to failure
- ✓ Crack propagation rate

Degraded material often fail **prematurely** and sometimes **catastrophically** by cracking

HE... Mechanisms

- ✓ The effect of hydrogen on the plastic behavior of metallic materials is somewhat **complex**
- ✓ To the non-specialist, theories of hydrogen effects seem very **confusing** and mutually **contradictory**

Embrittlement theories

- ✓ Decohesion ... Vs Localised Plasticity !
- ✓ Hardening Vs Local Softening !

Viable Mechanisms usually quoted

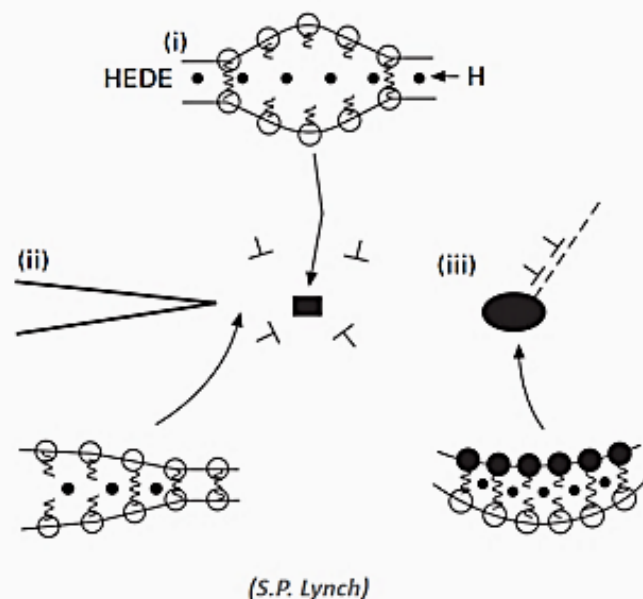
- Stress Induced Hydride formation and cleavage
... *Metals with stable hydrides (Group Vb metals, Ti, Mg, Zr and alloys)*
- Hydrogen-Induced Decohesion (HEDE)
- Hydrogen-Enhanced localised Plasticity (HELP)
- Adsorption-Induced Dislocation Emission (AIDE)

Dependent on
microstructure, yield strength, number and structure
of slip systems, specific material/environment system

Likely to be driven by a synergistic combination of
aspects of the different theories

... **Strong Personal views...**

HE Mechanisms... HEDE



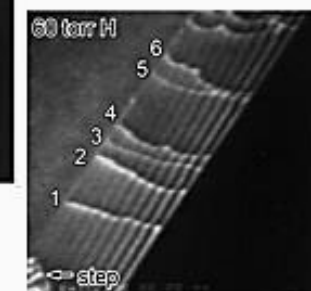
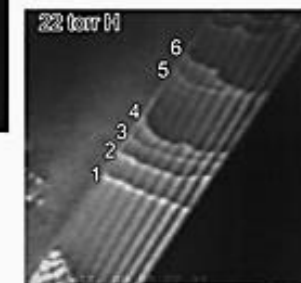
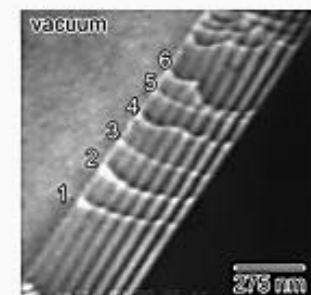
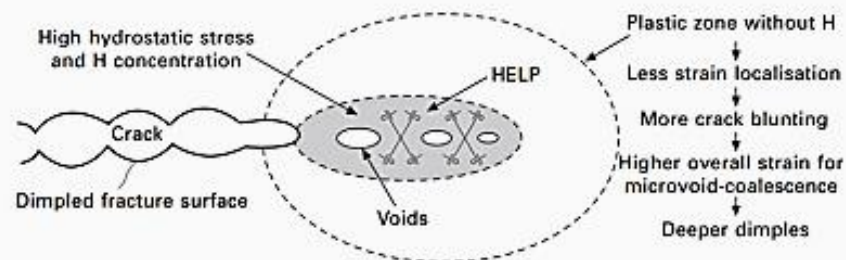
1960s -1970 s ... Oriani, Troiano...

*Role of hydrogen is to weaken the interatomic bonds (...)
facilitating GB separation or cleavage crack growth*

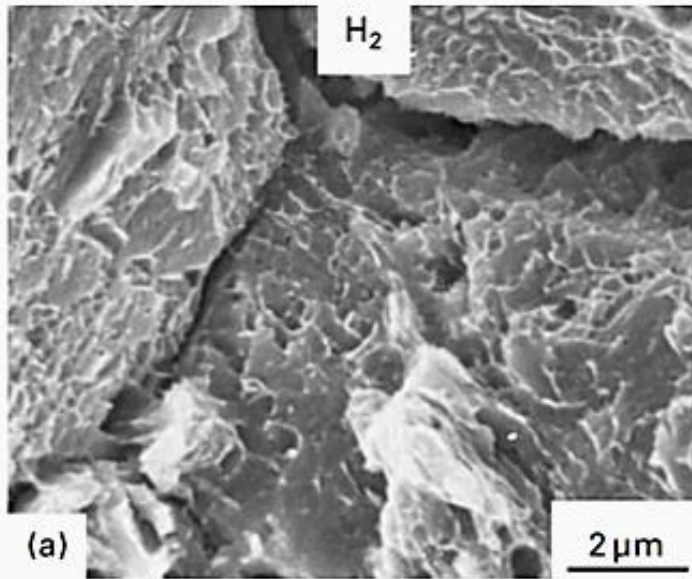
- ✓ Supported by Quantum-mechanical Calculations
- ✓ High H concentrations observed at GB and particle/matrix interfaces
- ✓ Direct fractographic evidence is lacking...
Featureless Fracture surface? ... Shallow dimples? ... SEM resolution?
- ✓ How to explain T.g. cracking?.. *H concentration at triaxial tensile stress?*

HE Mechanisms... HELP

- ✓ Hydrogen-induced shielding of the Interactions between microstructural defects, dislocations
- ✓ ...hydrogen acts by reducing the stress required for dislocation motion....
- ✓ ...crack propagation occurs by highly localized slip due to local softening by hydrogen at the crack tip.. .
- ✓ Failure is by localized shear processes occurring along slip planes: **shear localization**

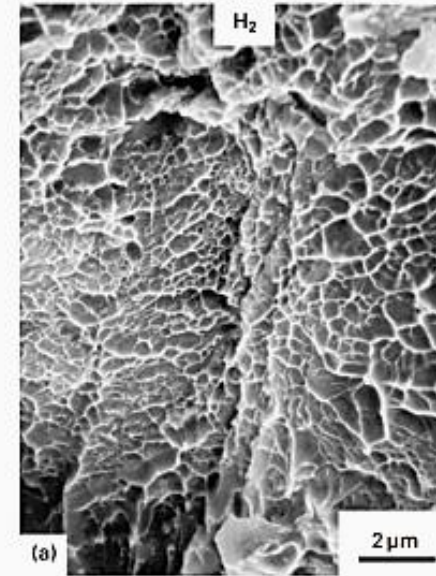


HE Mechanisms... HELP



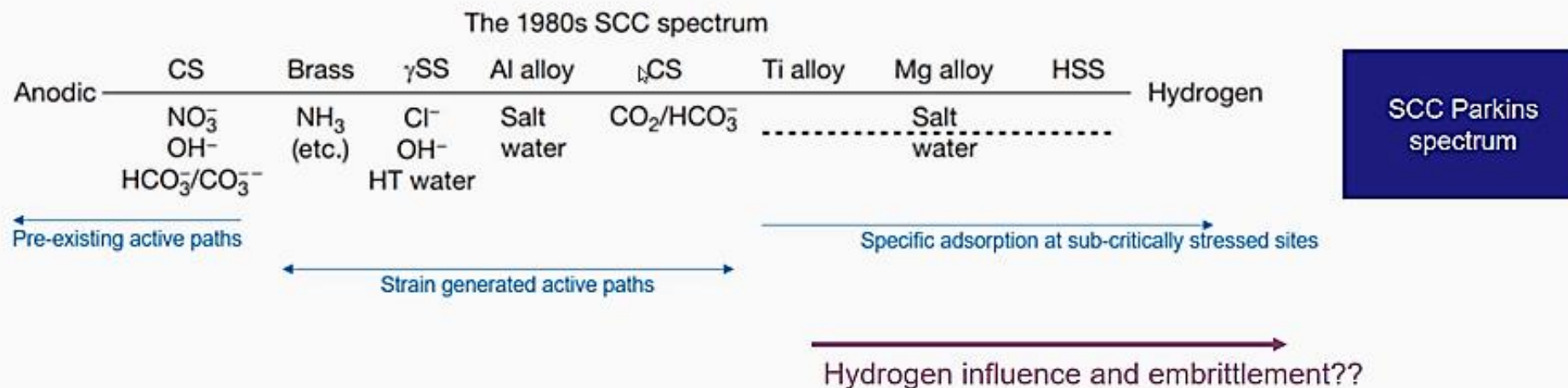
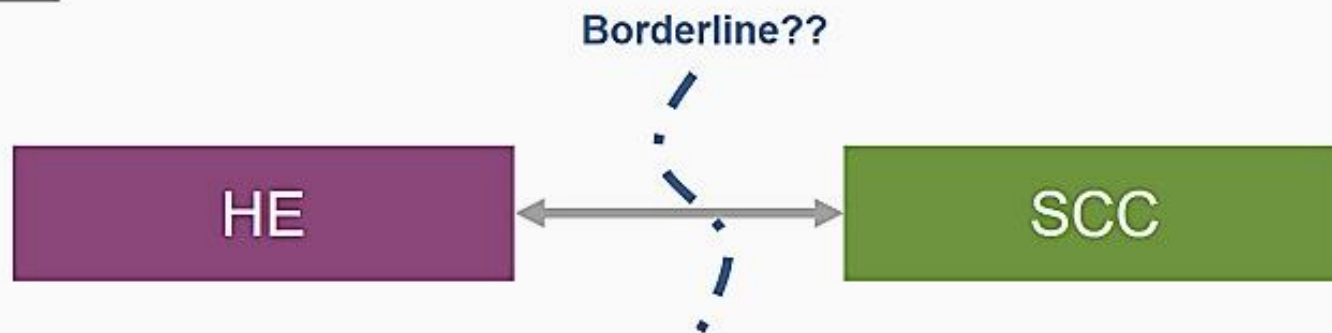
- ✓ Intergranular fracture occurs by localized ductility in the region adjacent to the grain boundaries

(S.P. Lynch)



- ✓ Transgranular fracture surfaces are highly deformed **despite the fact macroscopic ductility is reduced** (localized shear processes occurring along slip planes)

HE vs SCC borderline



HISC in onshore PLs... Morphology



HIC



HISC



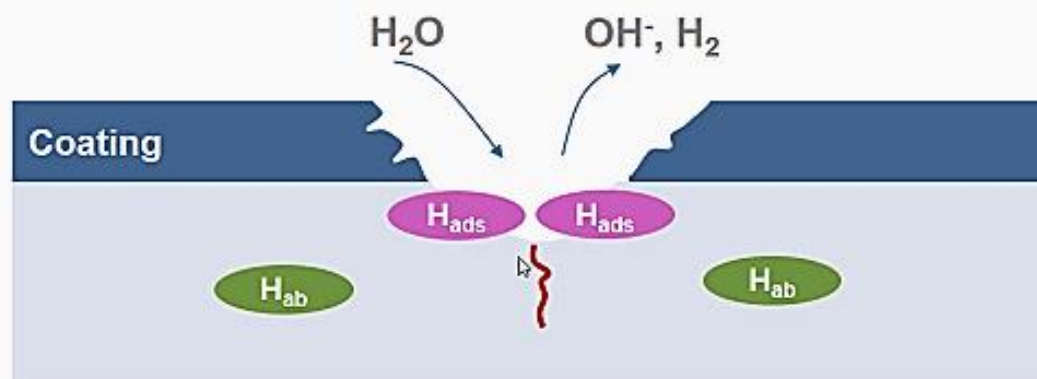
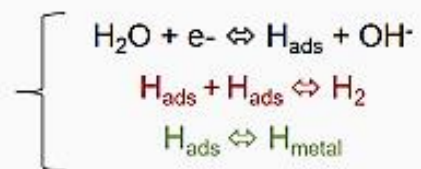
HISC in onshore PLs... Occurrence

Precursor event



HISC in onshore PLs... Occurrence

HISC



HISC in onshore PLs... Occurrence



...CP overprotection... < -1.2 V OFF CSE

...AND Presence of substantial plastic deformation...

Micro & Macro

...Presence of hard spots... HV >400

Steel materials with high YS >550 N/mm²
(X80)

HISC in onshore PLs... Some cases...

- ✓ 1967... X52 crude
- ✓ 1987... SNAM...24" X60 (1968) gas
- ✓ 1988...Rotterdam-Anvers... 34" X60 crude
- ✓ 1995... 12" X60 gas
- ✓ 2017... X52 (1967)

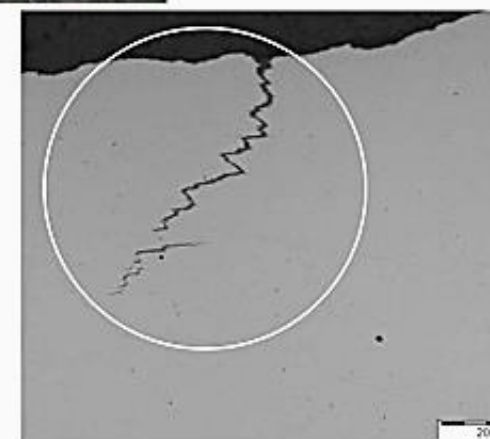
✓ Etc?.

✓ Detailed RCA? Expertise? Public domain?

✓ Other considerations?
Calcareous protective layers



10" X52 (1967)



HISC in onshore PLs... Management considerations

Why is my pipeline overprotected?

HVAC interference issues
(onshore)

$J_{ac}/J_{DC} < 5$ & $J_{DC} > 10 \text{ A/m}^2$

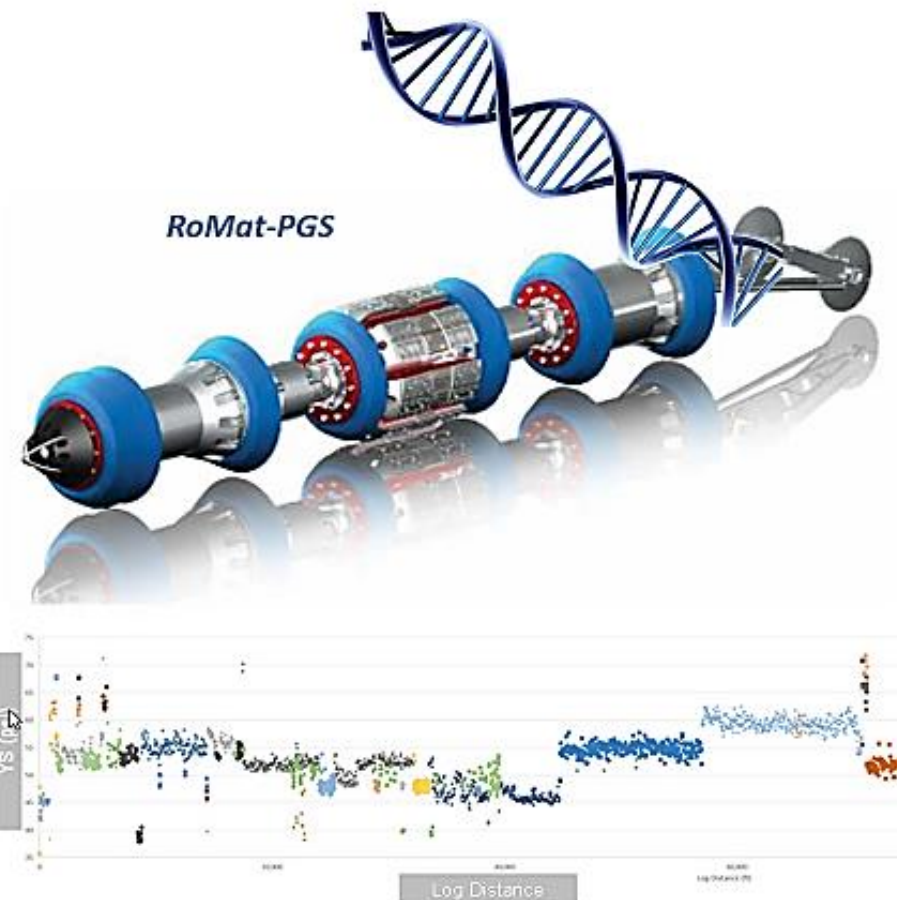
...Long transmission pipeline corrosion...
(onshore)

Underprotection issues

HISC in onshore PLs... Management considerations

Understand your materials

...Design vs actual...



HISC in onshore PLs... Management considerations



RoMat-DMG

HISC in onshore PLs... Management considerations

ID geometric anomalies

...Dents, gouges...

ID high bending strain areas

...geohazards...



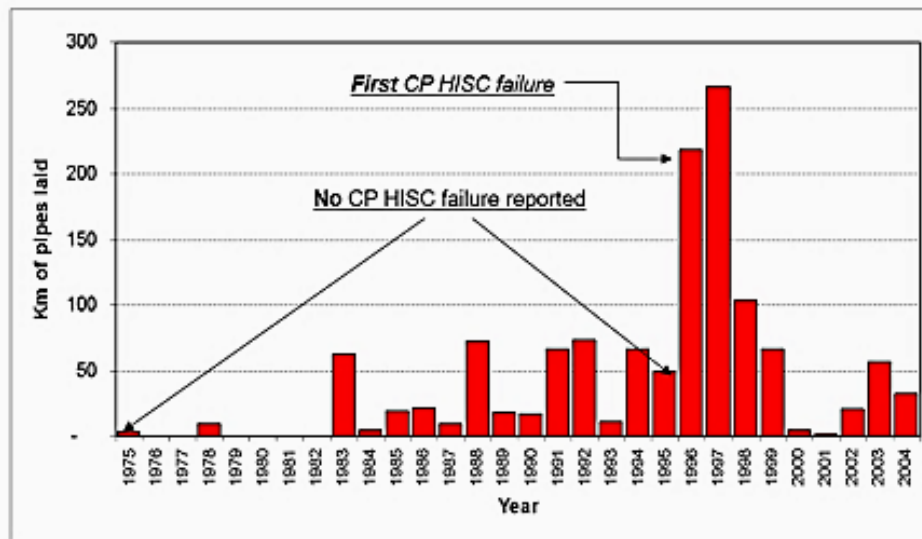
HISC in onshore PLs... Look ahead...



Hydrogen transport ... CP criteria?

4

CRAs offshore



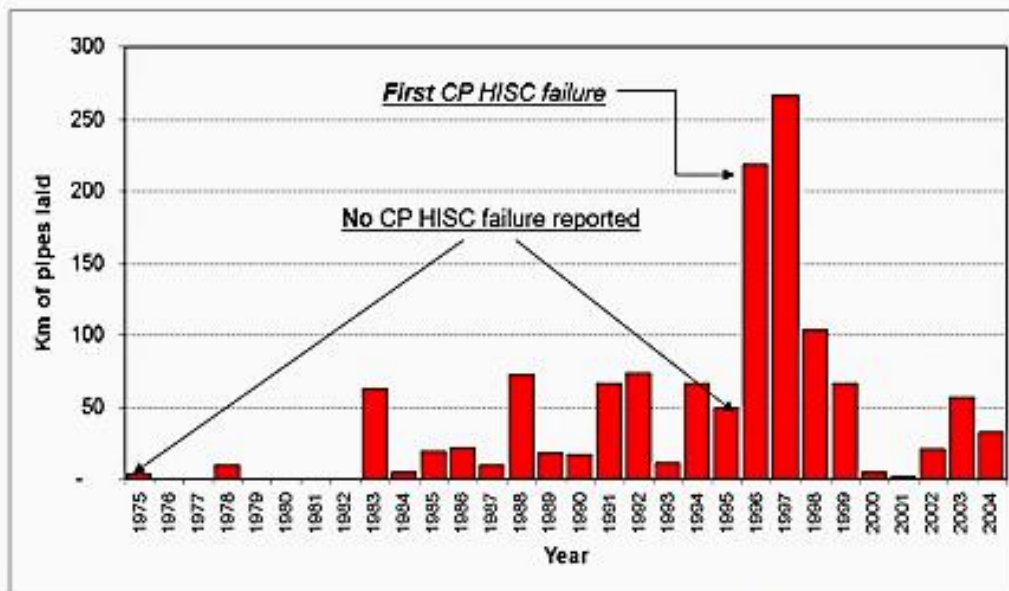
Overview of duplex stainless steel in subsea pipes from 1975 to 2004

Jumpers, manifolds, tie-in spools, bolts, fasteners

EU... multiphase pipelines / corrosive env.
...Rigid or clad/lined...
Rigid risers...22Cr / 25Cr

... field gathering pipelines to manifold...

SS vs. CP (offshore)



Overview of duplex stainless steel in subsea pipes from 1975 to 2004

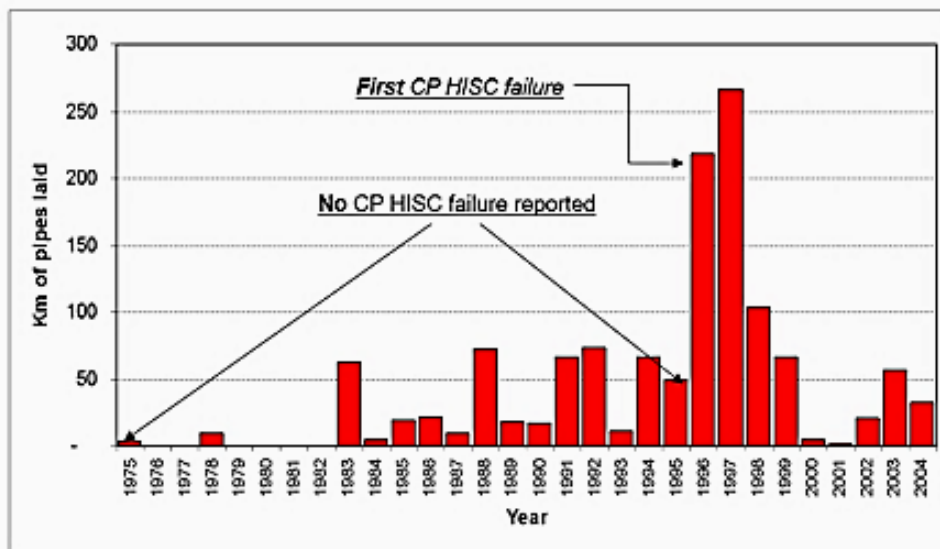
OFF CP CS pipelines / structures
as low as -1100 mV Ag/AgCl

...CRA CP criteria... Pitting...
CP as high as -700 to -500 mV

... Duplex SS OFF CP criteria...
 -500 to -800 mV Ag/AgCl

ISO 15589-2

SS vs. CP (offshore)



Overview of duplex stainless steel in subsea pipes from 1975 to 2004

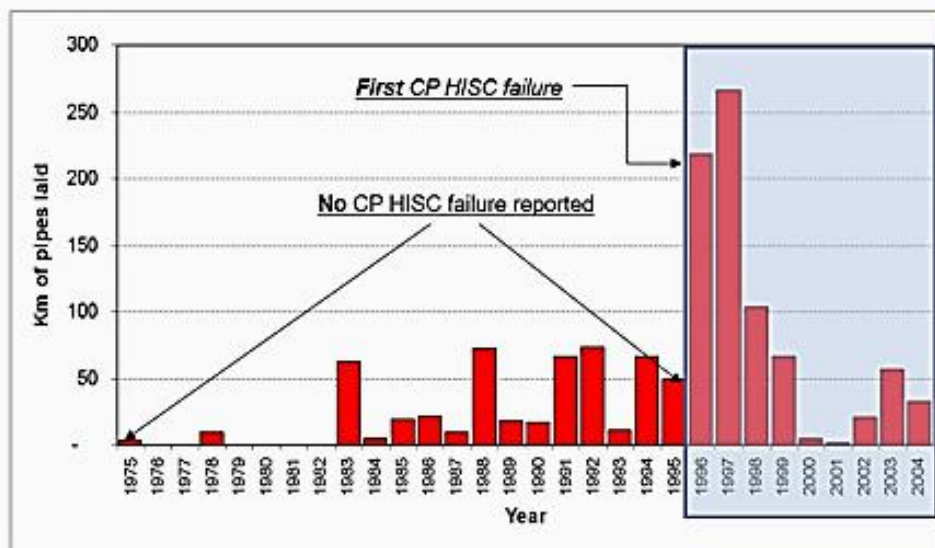
Duplex SS vs HISC
...Lab test as early as the 1980s....

...lab test...
HISC issue for YS>750 MPa

... weldable 22Cr or 25Cr (subsea)...
SMYS 450 to 550 MPa

...HISC not a problem?....

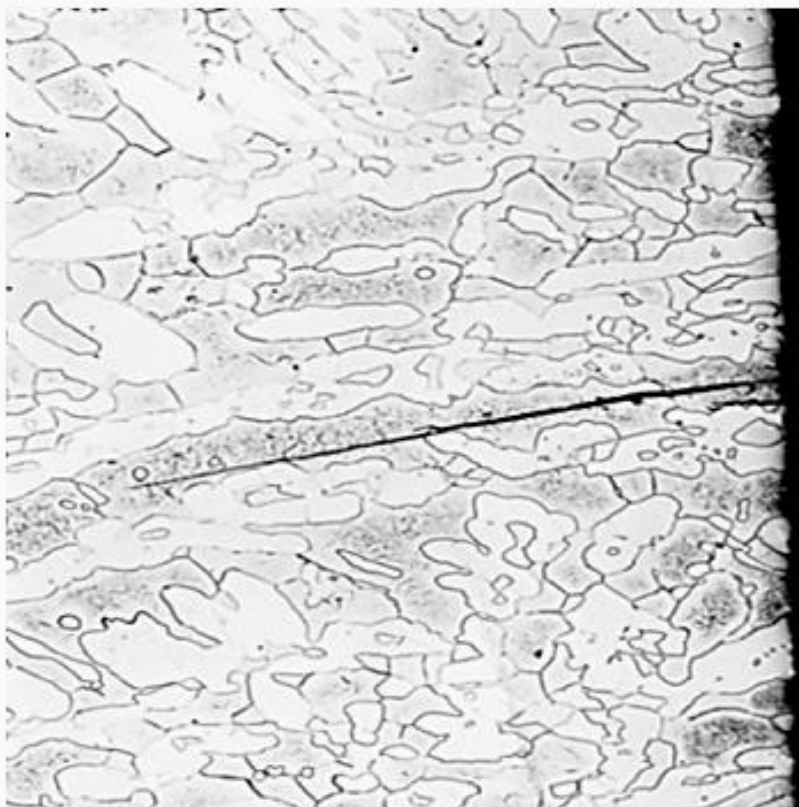
HISC on DSS... Incident Cases



Overview of duplex stainless steel in subsea pipes from 1975 to 2004

Incident	Op/Field	%Cr	Subsea Failure location
1996	Foinaven BP	25Cr	Hub - Parent (non-painted)
1997	Amerada Hess	22Cr	Tie-in spool - Weld Toe (to anode) (Blistered coating)
1998	Britannia	22Cr	Flowlines - parent (Rock dump - disb. coating)
2003	Shell Garn West	25Cr	Hub - Girth Weld (non-painted)
2003/4	Chevron	25Cr	Tee connections - Fillet Weld
2013	Statoil	22Cr / 25Cr	Flanges - Girth Weld

HISC on DSS... occurrence...

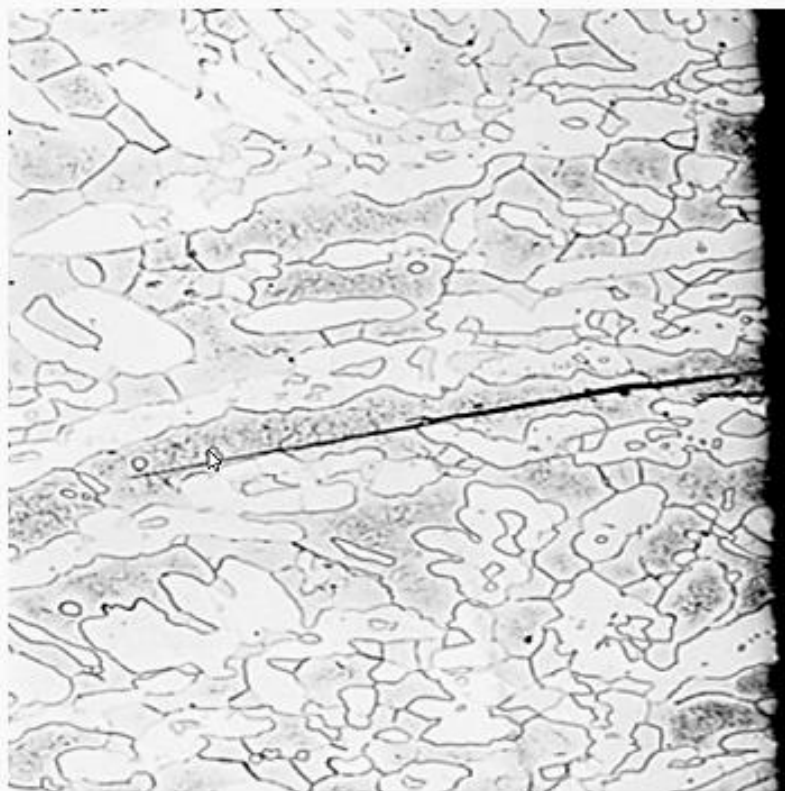


HE of Duplex (22Cr) or SDSS (25Cr)

...CP overprotection ...
< -0.8/-0.85 V OFF Ag/AgCl

... AND Presence of
substantial plastic straining...

HISC on DSS... occurrence...



Ferrite content > 50%

...Large grain size...
> 100 – up to 180 μm ...

.... Large austenite spacing....

HISC on DSS... DNV-RP-F112



RECOMMENDED PRACTICE

DNVGL-RP-F112

Edition July 2017

Design of duplex stainless steel subsea equipment exposed to cathodic protection

Austenite spacing $<30\mu\text{m}$

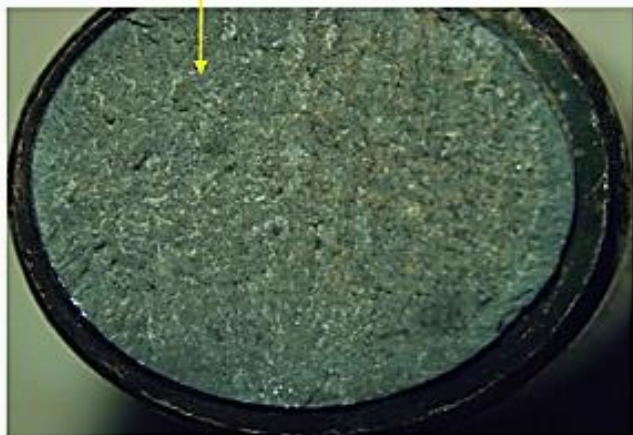
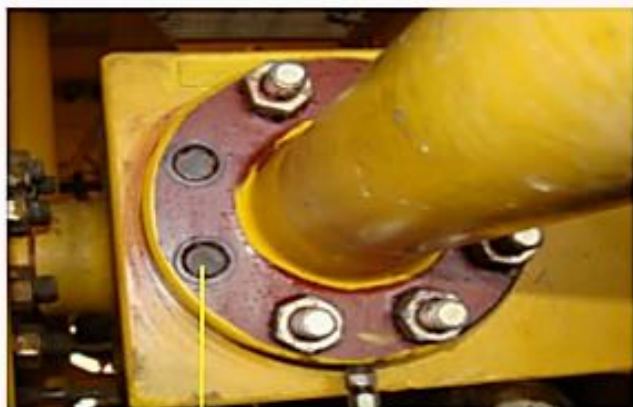
Balanced Austenite/Ferrite microstructure

Minimise direct CP contact ... use of diodes?

Coating... **Not ultimate mitigation**

- Existing CP bonded designs?
- Manuf. Efforts to improve HISC resistance & increase F112 utilisation thresholds?

HISC offshore... other!...



High strength Carbon steel bolts

ASTM A193 B7 - > HRC 35

LAS fasteners

ASTM 320 (bolts)/ASTM194 nuts

...Super martensitic SS pipes...

Conclusion

Complexity

Challenges

Understand your mechanism

Refine your *puzzle*



Conclusion



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Thank you for joining

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