Sour Service Corrosion Testing of Girth Welds

(Stress Corrosion Cracking of Welds)

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Testing
Advising
Assuring

ICorr Aberdeen Branch & The Welding and Joining Society Meeting
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Overview

- Sour Service Definitions & Cracking Mechanisms.
- Objectives.
- International Standards.
- Sour Service Testing of Carbon Steel Girth Welds.
- Sour Service Testing of CRA Girth Welds.
- Conclusions.

Objectives

- Summarize the Sour Service Cracking mechanisms.
- Provide guidance on the factors that need to be considered when specifying the Sour Service Testing of Girth Welds.
- Highlight recent and on-going developments in the test methods and standards for the Sour Service Testing of Girth Welds.

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Definitions and Cracking Mechanisms

HIC (SWC, HPIC), SSC, SCC, SOHIC, SZC,
HSC (HISC, GHSC).

Sour Service Definitions

A **WET** HYDROGEN SULPHIDE CONTAINING ENVIRONMENT

EFC16
'Sour environment for carbon steels based on the pH v pH_2S domain diagram'.

ISO 15156 / NACE MR0175-1 (3.19):2009
'Exposure to oilfield environments that contain H_2S and can cause cracking of materials by the mechanisms addressed by this part of the standard.'

Hydrogen Entry Mechanism

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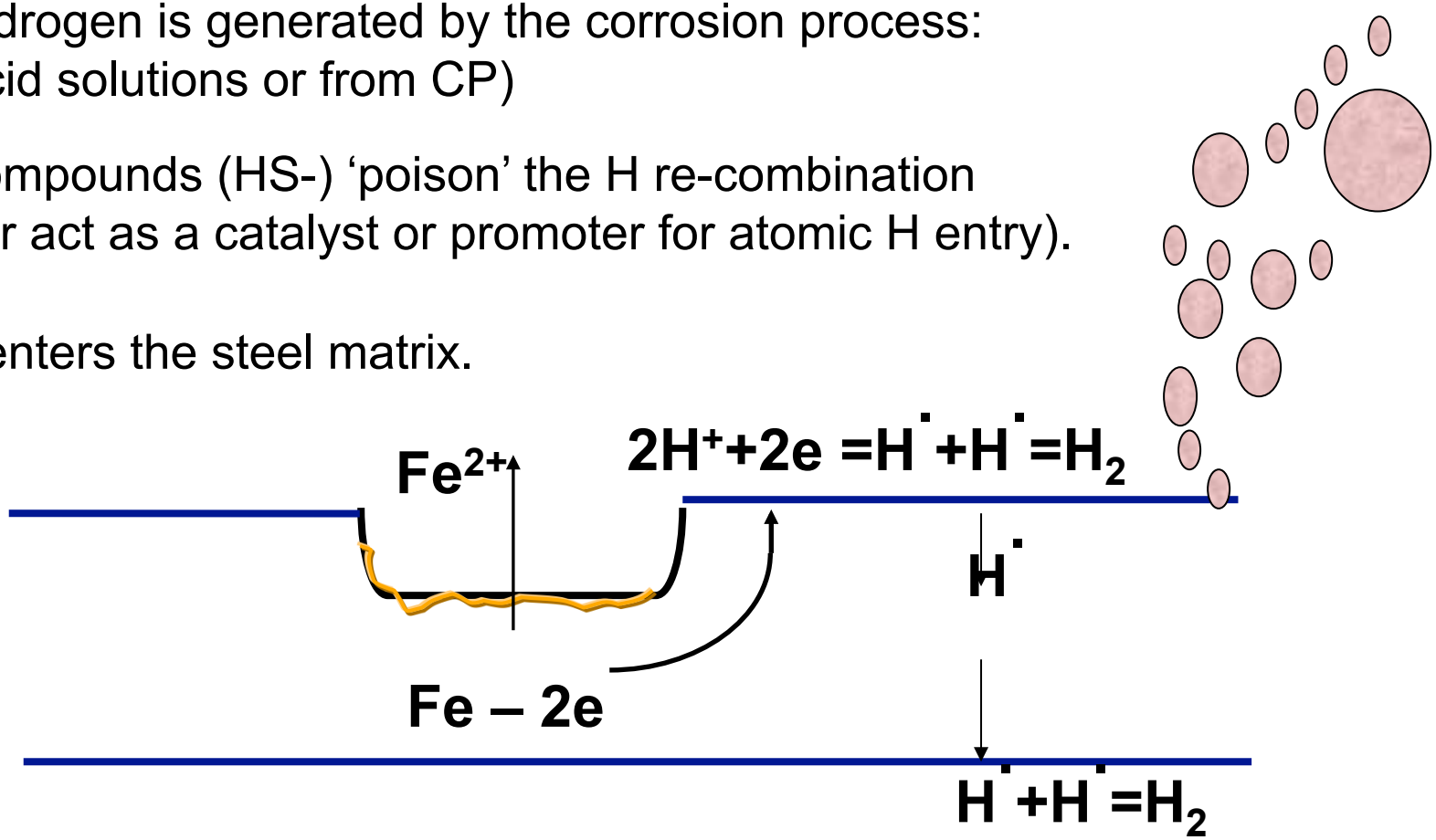
Atomic Hydrogen is generated by the corrosion process:
(or from acid solutions or from CP)

Sulphur compounds (HS-) ‘poison’ the H re-combination reaction (or act as a catalyst or promoter for atomic H entry).

Atomic H enters the steel matrix.



Hydrogen Entry Environmental Factors

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Partial pressure of H_2S (pH_2S)
Presence of H ‘poisons’ or flux promoters

Temperature

pH

Protective scale formation (Carbon Steels)

Chloride concentration (main influence on CRA’s)

Presence of elemental sulphur
Presence of processing contaminants such as oxygen

Sulphide Stress Cracking (SSC)

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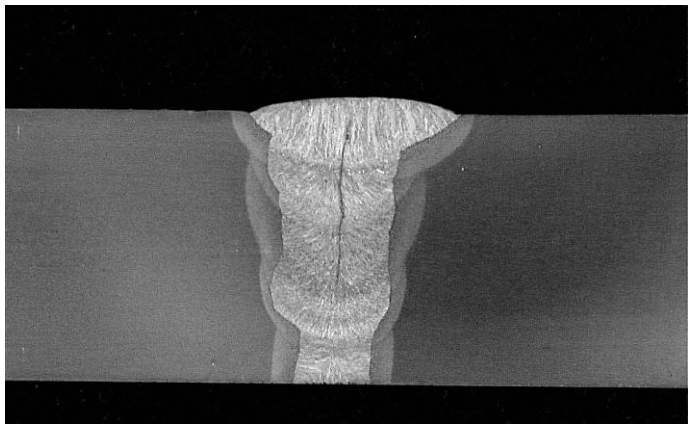
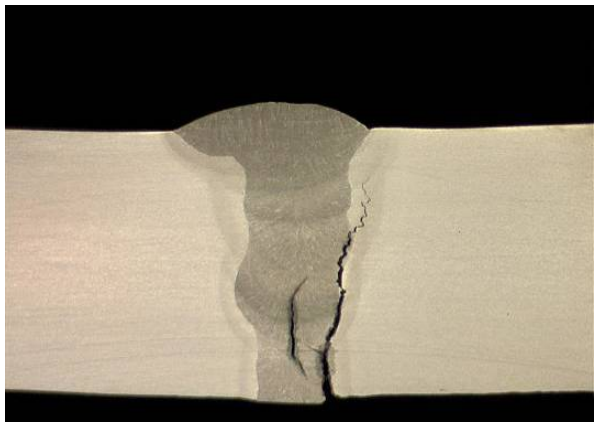
Cracking involving corrosion and tensile stress in the presence of water and H_2S

Low temperature (<60degC) hydrogen embrittlement (HE) mechanism.

High strength metal and hard zones of welds are prone to SSC





Stress Corrosion Cracking (SCC)

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Cracking involving corrosion and tensile stress in the presence of water and H_2S

Elevated temperature cracking mechanism for CRA's

Often associated with initial pitting in CRA's

Hydrogen Induced Cracking (HIC)

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- Can also be referred to as stepwise cracking (SWC) or hydrogen pressure induced cracking (HPIC).
- Cracking that occurs when atomic hydrogen diffuses into steel and combines to form molecular hydrogen at discontinuities.
- Influenced by; inclusions, microstructure, residual and applied stress.
- Confined to carbon steels
- **Can occur in girth welds.**

Hydrogen Induced Cracking (HIC)

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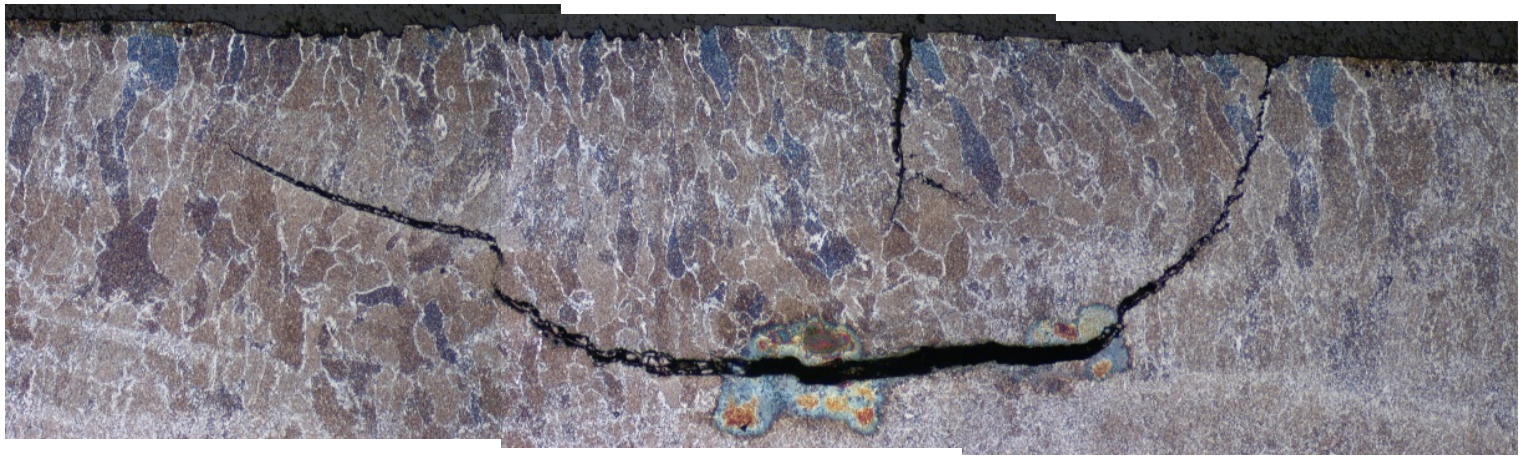

Example of HIC and associated SSC in girth weld cap

Stress Orientated HIC (SOHIC)

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Cracks form perpendicular to the principal stress resulting in a ladder-like array linking pre-existing HIC cracks.

Related to tri-axial stress distribution.

Can occur at the edge of the visible HAZ of girth welds due to localised low hardness regions.

May also be associated with the presence of sulphur and oxygen in the service environment.

Confined to carbon steels.

Stress Orientated HIC (SOHIC)

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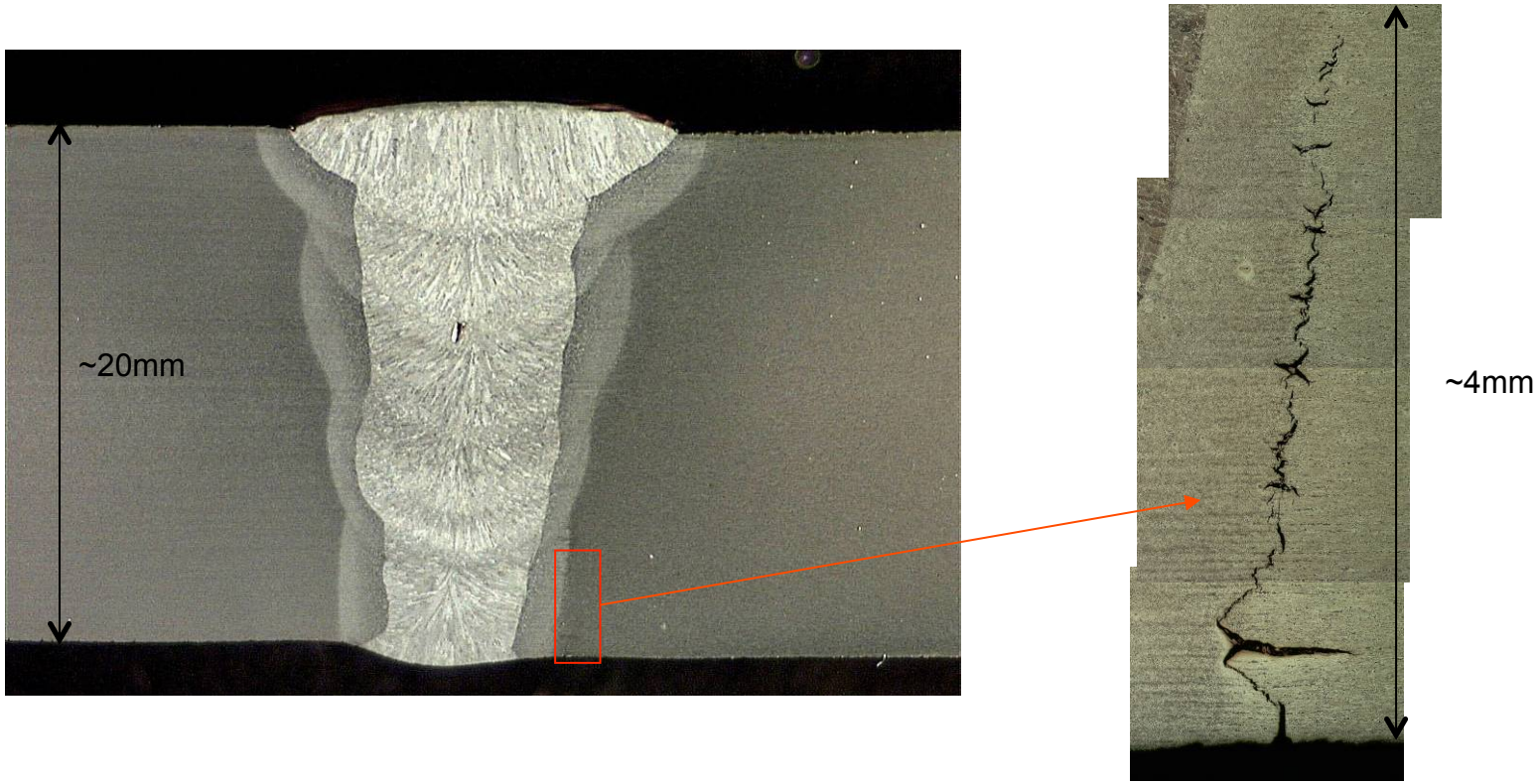

Soft Zone Cracking (SZC)

Soft zone cracking (SZC) is a form of SSC where hydrogen cracking can result, due to local yielding, associated with welds.

Similar mechanism to SOHIC

Hydrogen Stress Cracking (HSC)

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Also referred to as:

Hydrogen Induced Stress Cracking (HISC)
Galvanically Induced Hydrogen Stress Cracking (GHSC)

Cracking resulting due to presence of H and tensile stresses.

High strength steels subjected to Cathodic Protection (CP)

External pipe cracking of CRA's from CP

Cracking of galvanically coupled CRA's

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International Standards

ISO 15156 / NACE MR0175, EFC16, EFC 17,
DNV OS F101.

International Standards

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Carbon Steels:

ISO 15156 / NACE MR0175 – Part 2
DNV OS F101 (refers to ISO 15156)
EFC 16 (Guidance document)

CRA's:

ISO 15156 / NACE MR0175 – Part 3
DNV OS F101 (refers to ISO 15156)
EFC 17 (Guidance document)

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Sour Service Testing of Carbon Steel Girth Welds

ISO 15156 / NACE MR0175 General Requirements

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Covered by NACE ISO 15156 / NACE MR0175 - Part 2 & EFC 16

250Hv max (275Hv max in cap) for all combinations of pH / pH_2S

1% Ni max for weld consumables

SSC testing at Room temperature

Susceptibility to SZC and SOHIC may need to be considered.

HIC testing only required for flat rolled products or items manufactured from flat rolled products (NACE MR0175 / ISO 15156).

ISO 15156 / NACE MR0175 Domain Diagram

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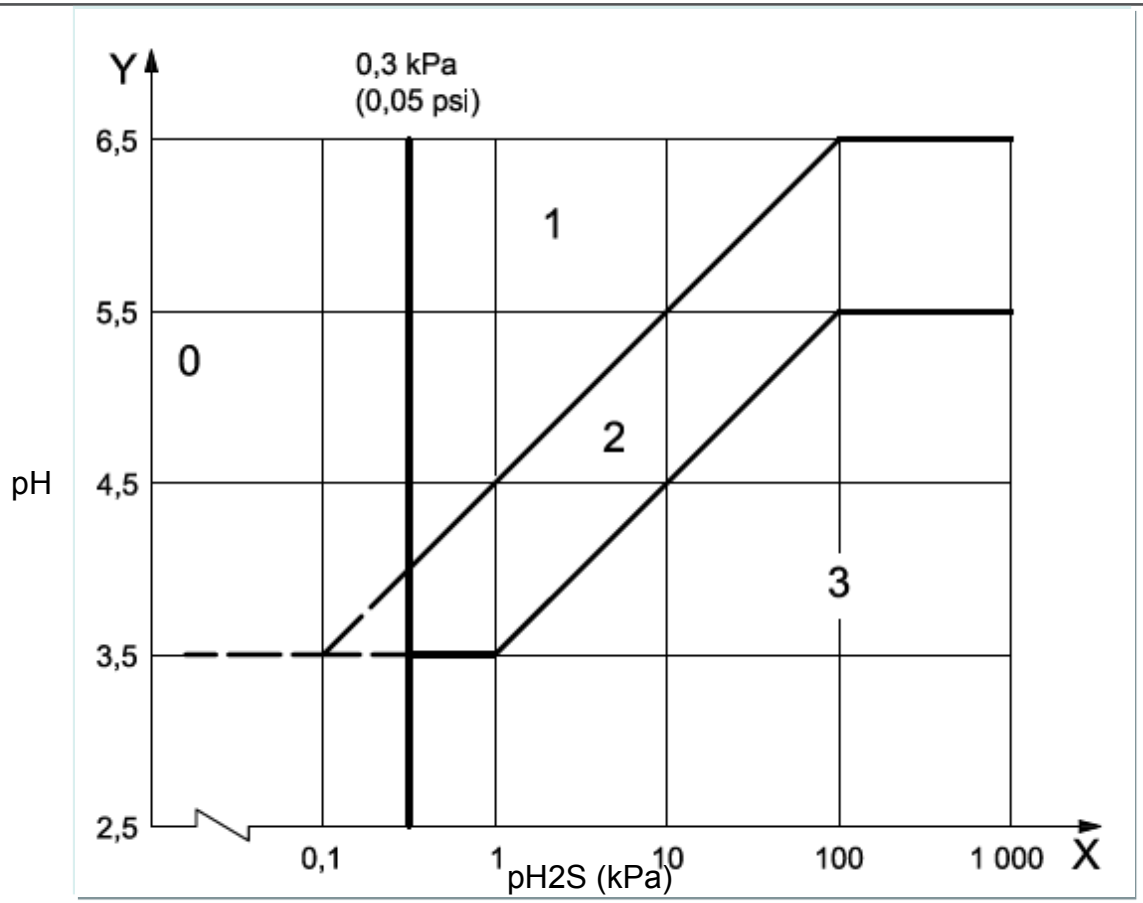

ISO 15156 / NACE MR0175 Domain Diagram

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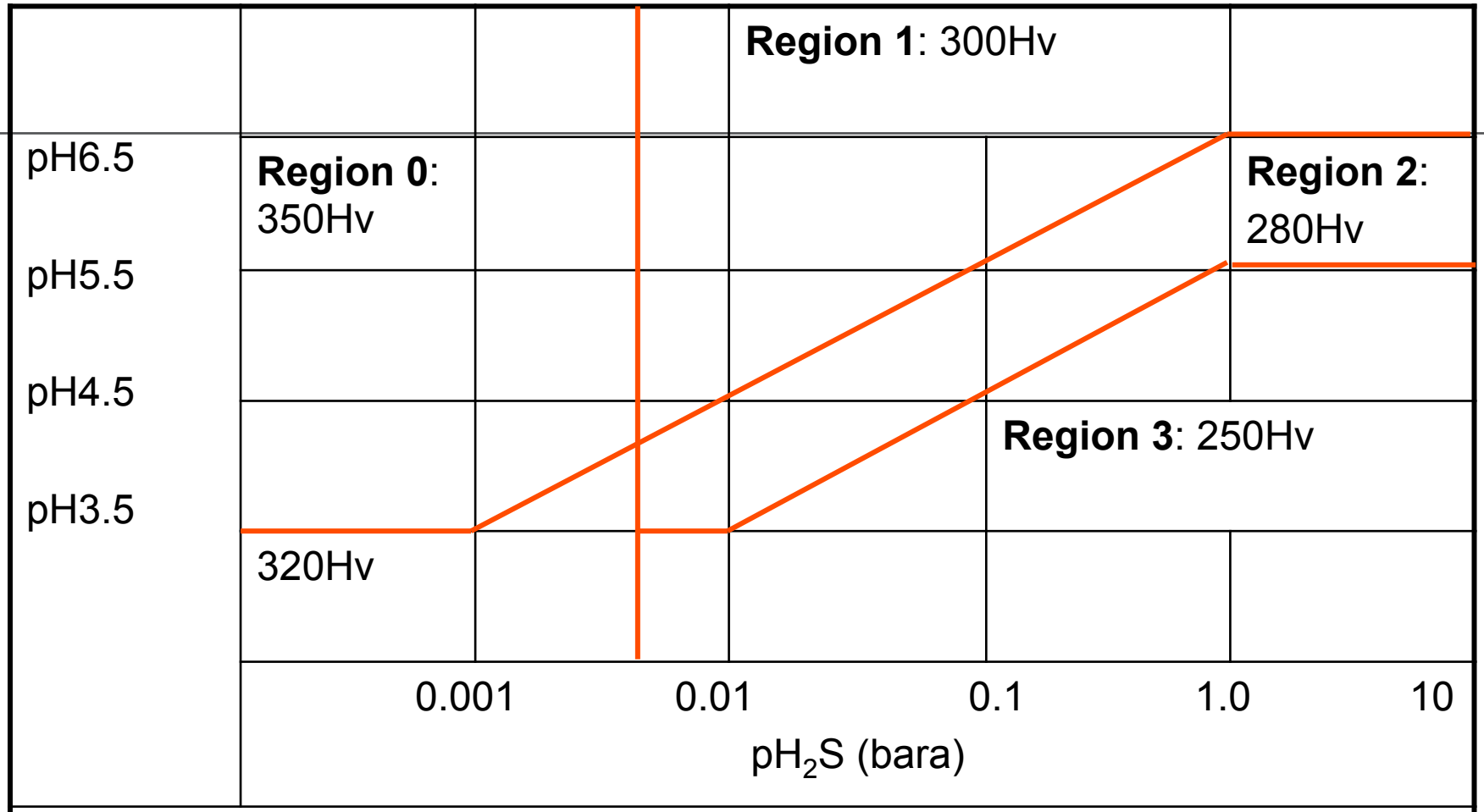
Region 0 – For pH2S <0.3kPa (0.05 psi):
No special precautions are normally required for the selection of steels under these conditions, although the following factors should be considered:

i) Steels that are highly susceptible to SSC and HSC.
ii) The steels inherent physical and metallurgical properties.
iii) Very high strength steels can suffer HSC in aqueous environments, without H2S, above 965 MPa.

Regions 1 & 2:
For steels with >250Hv testing is required under fitness for purpose conditions.

Region 3 (Also qualifies regions 0, 1 & 2):
For steels with >250Hv testing is required under NACE TM0177 - Solution A conditions at 1 bara pH2S.

Hardness Limits



Ref: Kermani, Boucher, Crolet, Enerhaug, Fassina, Howard, Jansen, Linne & Popperling, "Limits of linepipe weld hardness for domains of sour service in oil & gas production", NACE Paper 00157.

Hardness Testing

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Vickers hardness surveys required for girth welds.
(Ref: ISO 15156 / NACE MR0175 & DNV OS F101).

Beware!!! - Standard Hv surveys may not detect areas of maximum hardness.

Micro-hardness measurement may be required.

H_2S is the best 'hardness tester'!!!.

Influence of Hardness on SSC - Case Study

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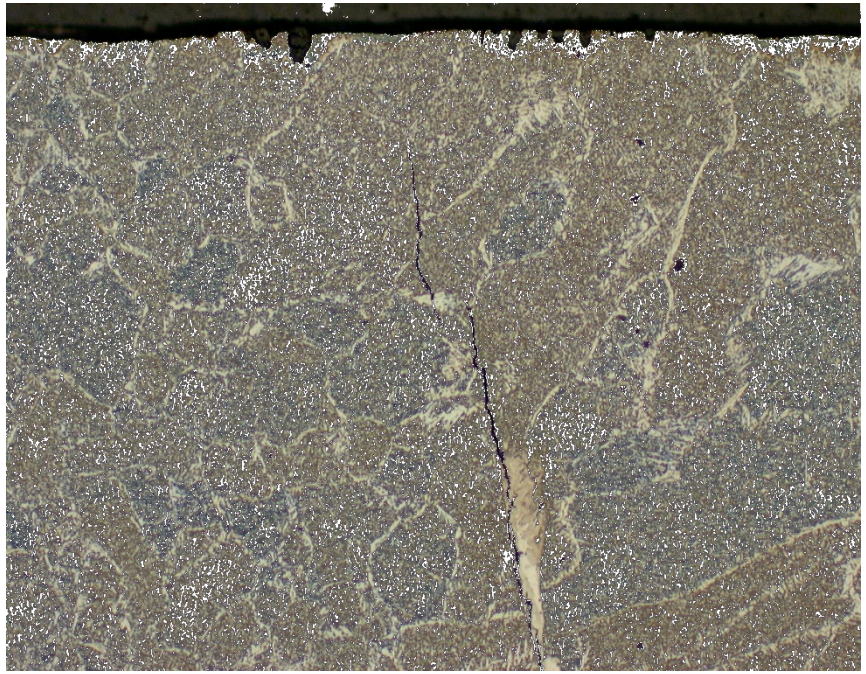
Sub-surface hydrogen crack in HAZ due to high local hardness



Sub-surface hydrogen crack at area of segregation (high hardness)

Girth Weld Qualification

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Set of three transverse weld specimens (FPB or C-ring) or FRT.

Normally Root in tension (Environment on inside).

Applied stress taken from parent tensile test, using lowest value based on 80% or 90% of AYS (0.2%PS).

Test duration – 720hr in ISO 15156 / NACE MR0175.

Evaluation to NACE TM0177 / EFC16 / ISO 15156 / NACE MR0175 or Client Agreed Procedure.

Test Parameters

All regions

1 bara pH_2S
NACE TM0177-Solution A
pH 2.7 – 4.0
720hr
80% AYS

Specific application for Regions 0, 1 & 2

pH_2S appropriate for application or region (Table B2)
EFC 16-Solution A
pH as appropriate for application or region
720hr
90% AYS

Test Parameters - Specific Application or Region

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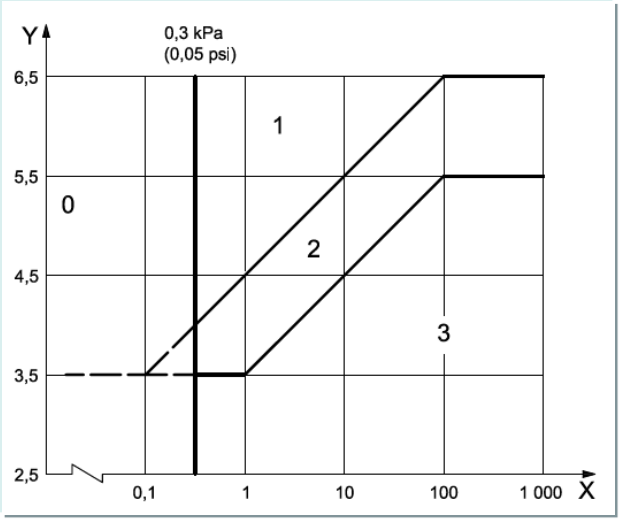
Options:
i)Test for specific field conditions using worst case pH and pH2S…or
ii)Test to cover specific region of domain diagram (see below)

pH	Required H_2S partial pressures for tests kPa	
	Set of conditions for SSC region 1	Set of conditions for SSC region 2
3.5	—	1
4.0	0.3	—
4.5	1	10
5.5	10	100
6.5	100	—



Reference: Table B2 of ISO 15156 / NACE MR0175-Part 2

Laboratory Testing
Tensile Method

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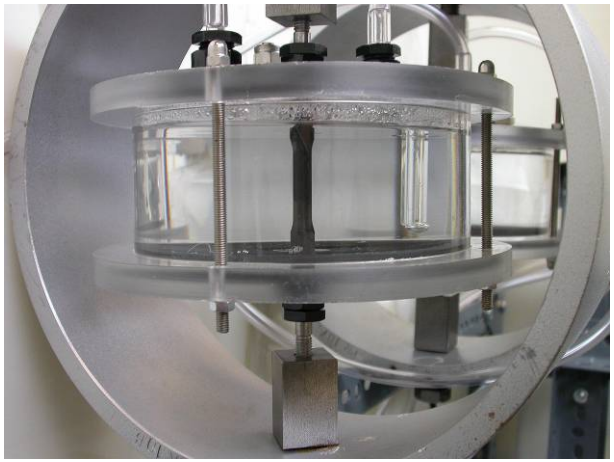
Fully machined specimen.

Difficult to sample weld root region.

Not commonly used for weld qualification tests.

Could be used to qualify weld consumables.



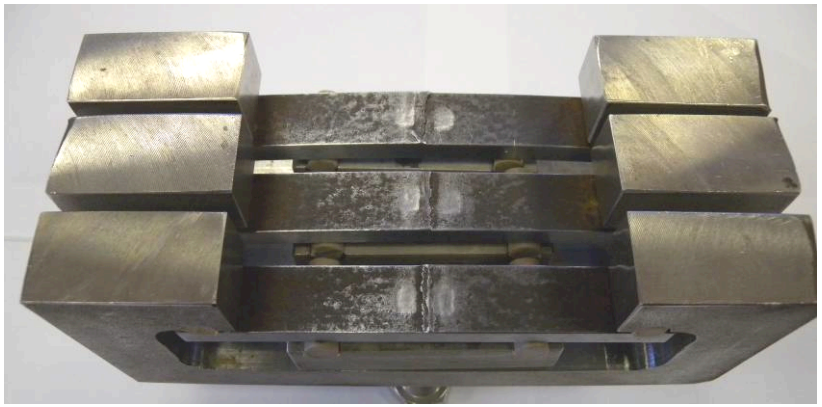
Laboratory Testing
Four Point Bend Method

Exova

EFC 16 – 3rd edition / ASTM G39 / ISO 7539-2

A separate test method for 4PB SSC / SCC is currently being developed by NACE Task Group 494.

Most common geometry for weld qualification tests



Four Point Bend Method Specimen Geometry

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Root intact:

- Test surface representative of service conditions.
- Stress concentration at weld toe regions can lead to localised plastic straining and cracking.
- Exposure of root run always guaranteed.
- ‘Hard-skin’ on parent pipe retained.

Root machined:

- Test surface not representative of service conditions
- ‘Uniform’ stress distribution
- Hot pass may be exposed following machining
- ‘Susceptible’ regions may be removed or exposed
- Influence of minor weld ‘defects’ may be exaggerated.

Four Point Bent Method Stress Considerations

Exova

Loss of residual stresses.

Applied stress 80% AYS (or 90%AYS) for NACE MR0175 or 90% AYS for EFC 16.

Direction of applied tensile stresses perpendicular to girth weld.

Applied stress based on AYS (May be reduced to <80% where low service stresses are guaranteed, ref: ISO 15156-Table B.1-clause c).

Increased stress at corner of specimens (up to 15%).

Strain gauging required.

Four Point Bent Method Specimen Evaluation

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ISO 15156 / NACE MR0175 – No cracks in accordance with NACE TM0177-96 assessment method.

NACE TM0177-Visual 10x for Uniaxial Tension specimens, followed by metallography, SEM or mechanical testing – **No reference to 4PB**.

EFC 16-3rd Ed – Sectioning following visual examination and NDT.

ASTM G39 – Visual @ 5 – 10x, supplemented by metallographic examination.

Sectioning is considered to be essential for girth welds.

Four Point Bent Method Recommendations

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Use root intact specimens where possible or skimmed specimens to eliminate stress concentrations.

Use full thickness specimens where practical.

Determine AYS either side of weld .

Strain gauge all specimens.

Consider stress concentrations and stress distribution.

Evaluate by: Visual @ 10x
MPI
Metallographic sections at mid-width

Laboratory Testing
C-Ring Method

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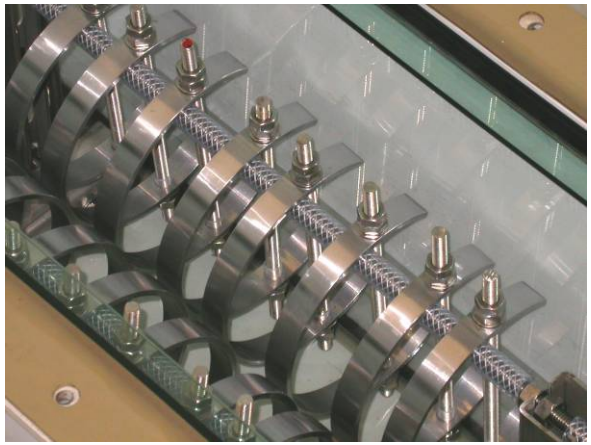
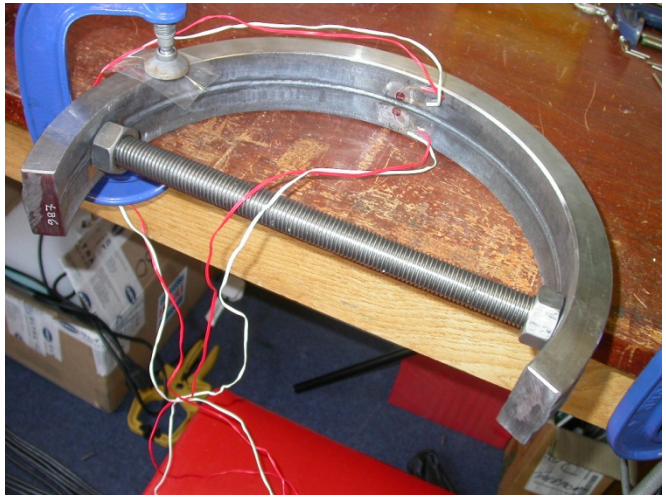
NACE TM0177 – Method C

Not commonly used for girth welds due to large specimen size and high number of welds required.

Mainly applied to seam welded pipe of relatively small diameter (i.e <200mm)





Full Ring Test (OTI 95 635)

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Versatile test allowing assessment of girth welded line-pipe for SSC, HIC and SOHIC (SZC).

Included as option in ISO 15156 / NACE MR0175.

Applied stress = 72% SMYS - Residual stresses associated with manufacture, welding and reeling are retained in the test ring.

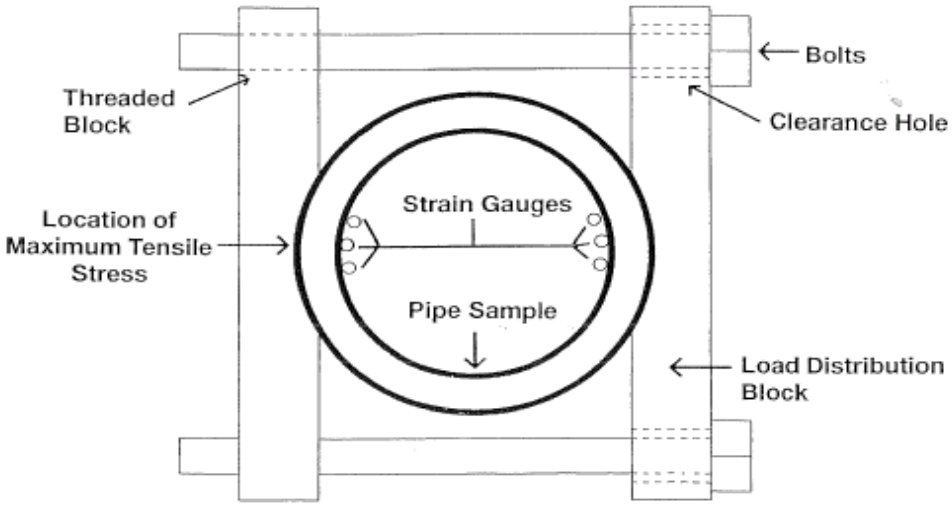
In-situ ultrasonic inspection for cracking can be undertaken.

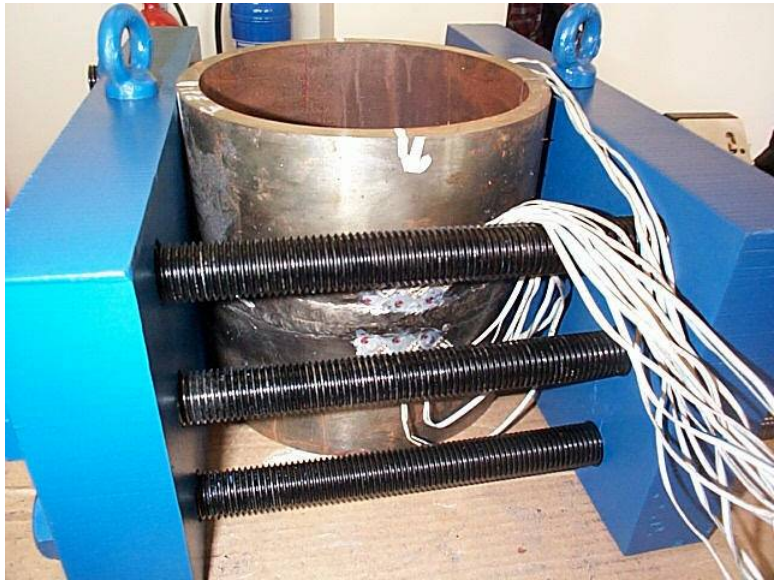
Hydrogen permeation can be undertaken to correlate extent of cracking with flux measurements.

Realistic test, ideally suited to the testing of reeled pipe.

Full Ring Test Externally Loaded

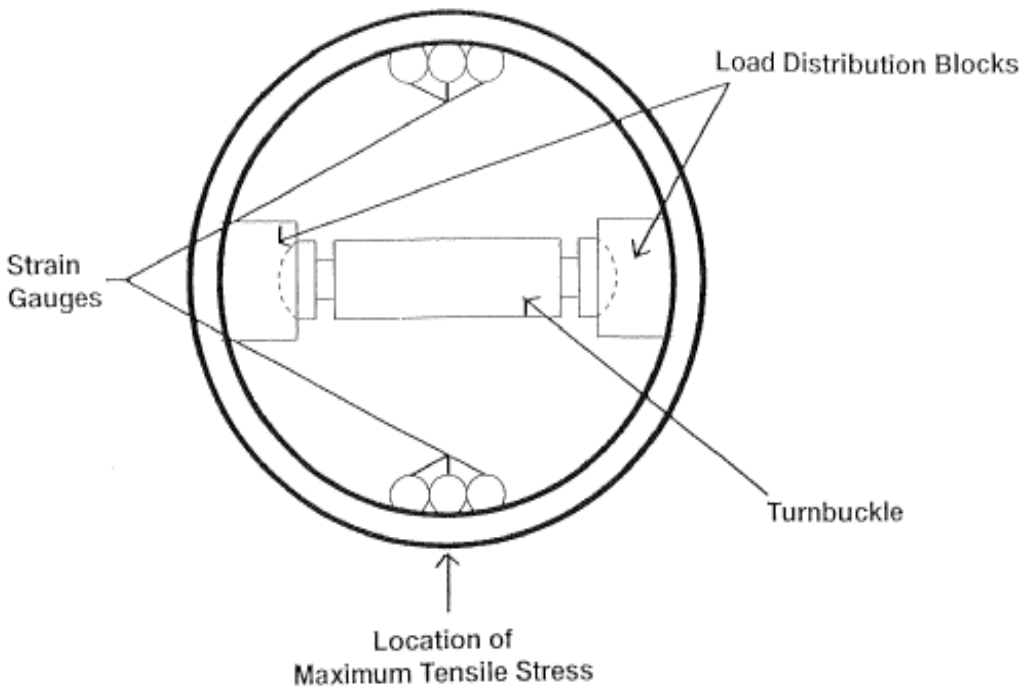
Exova





Full Ring Test Internally Loaded

Exova



SSC Case History
SSC in Full Ring Test

Exova

Weld metal SSC – Note crack orientation (Hoop stress)

Laboratory Testing Summary

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Uniaxial tensile (UT)

- Generally not applicable for weld qualification testing

Four Point Bend (FPB)

- Most common method for weld qualification testing
- Root in-tact, full thickness specimens preferable
- Stress limitations need to be considered
- Evaluation / acceptance criteria needs to be agreed.

C-Ring

- Not commonly used for weld qualification due to size restrictions
- Appropriate for seam welds on small pipe sizes (i.e <200mm).

Full Ring

- Residual stresses from pipe manufacture and welding and reeling (if applicable) are retained
- Realistic stress orientation
- SSC, HIC & SOHIC (SZC) can be evaluated in one test
- Full butt weld required

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Sour Service Testing of CRA Girth Welds

Qualification of CRA's General Requirements

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SSC evaluation at ambient temperature.

SCC at maximum operating temperature or at intermediate temperature at which maximum susceptibility is known (i.e. in the case of duplex stainless steels @ ~90ºC).

Pitting / crevice testing is often required at the maximum operating temperature.

Galvanically coupled (GHSC) testing may also be required.

Qualification of CRA's Stress Considerations

Exova

FPB Test conducted at 100% AYS to take into account creep / relaxation.

Required strain must be obtained from tensile testing.

Strain gauges must be used for girth weld testing.

Creep may need to be considered.

Qualification of CRA's Surface Considerations

Exova

Important to retain the as-welded surface

Strain gauges to be applied to as-welded surface without preparation

Care must be taken to avoid iron contamination during preparation or subsequent handling

Surface finish may have an influence on results

Qualification of CRA's Reeled Pipe–Girth Welds

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Simulated reeling using full size pipe or using strip samples to DNV RP-F108.

Inspect before testing.

High-Low regions and weld 'intrusions' need to be considered (see photo).

Surface condition is critical when testing 13%Cr Stainless Steels & CRA's.

Local changes in microstructure need to be considered.

Full Ring Testing would be the preferred method.

Qualification of CRA's Clad Pipe

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Specimen preparation is a critical step:

i) Avoid marking test face
ii) Inspect before test
ii) Minimise stress concentrations

Check for any significant increase in surface hardness above the ISO 15156 limits

Remove carbon steel and ensure absence of dilution on back face (check using Nital, copper sulphate, ferroxyl test or PMI)

Qualification of CRA's Clad Pipe

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ISO 15156 / NACE MR0175 requires the user to ensure the hardness of the base material is ≤250Hv.

Or

Demonstrate the long term in-service integrity of the cladding or overlay as a protective layer.

When using alloy 625 or duplex consumables for the girth weld this can be difficult to achieve, due to formation of an 'alloy diffusion zone'.

Therefore the options are:

i) Testing under fitness for purpose conditions.

ii) Ensuring the long-term in-service integrity is maintained.

Qualification of CRA's Clad Pipe

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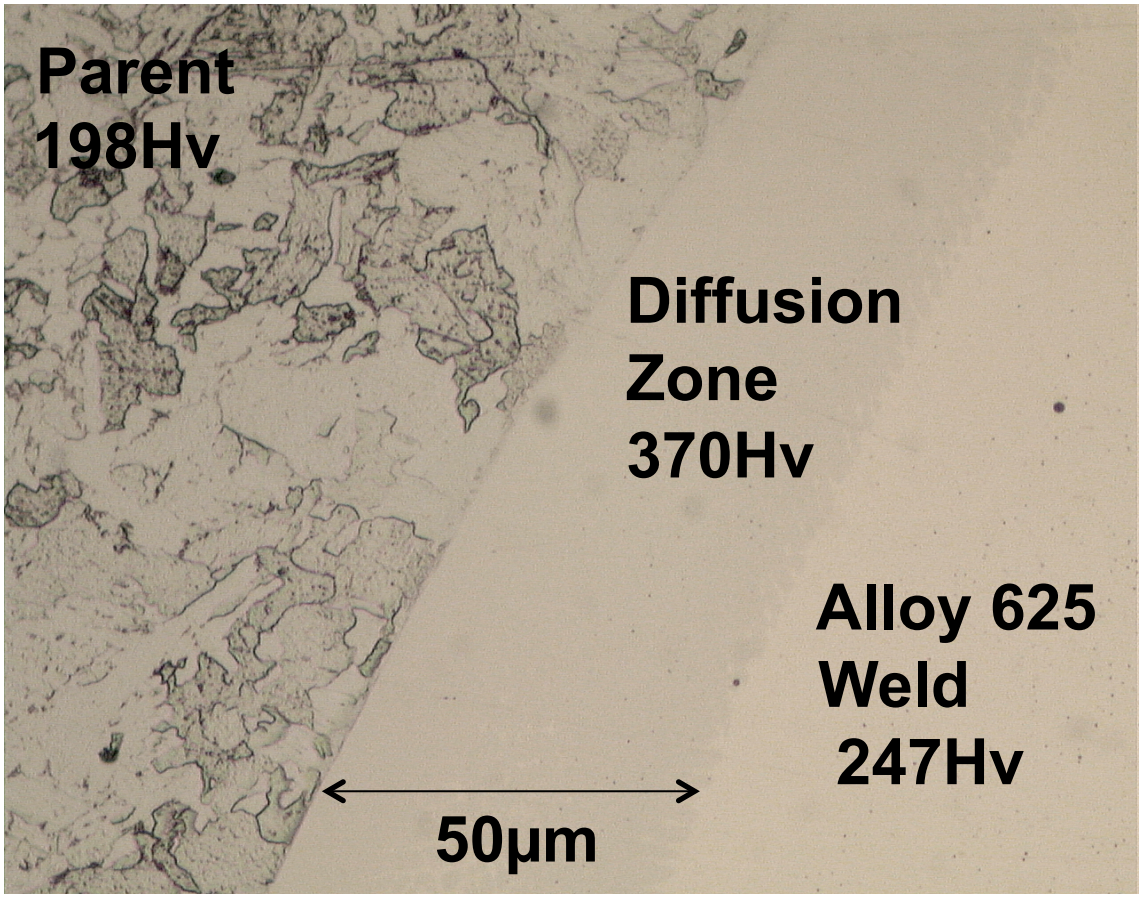

Qualification of CRA's 13% Cr Stainless Steels

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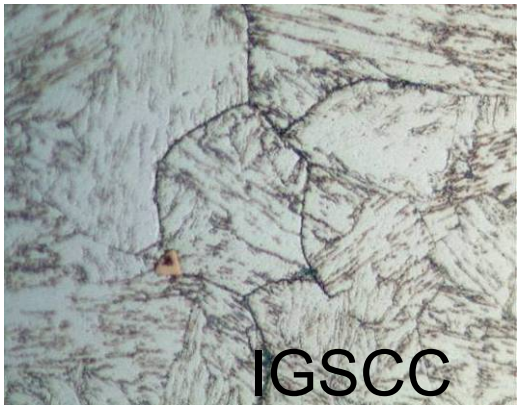
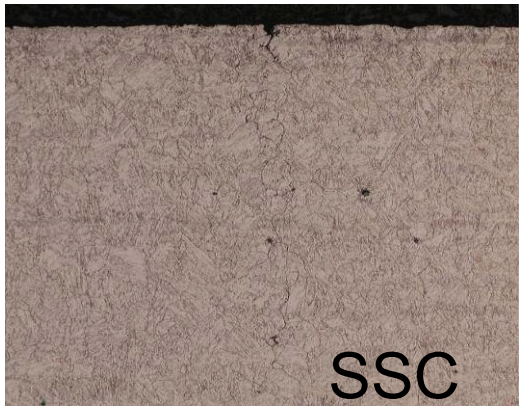
Weldable 13%Cr Stainless Steels can be susceptible to:

i) Low temperature (<60degC) SSC*
ii) High temperature SCC
iii) High temperature IGSCC
iv) High temperature pitting



Therefore test programs would normally include:

i) Room temperature SSC*
ii) Elevated temperature SCC
iii) Pitting at maximum service temperature



***The SSC susceptibility may be higher at sub-ambient temperatures**

Qualification of CRA's 13% Cr Stainless Steels

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The SSC susceptibility may be higher at sub-ambient temperatures*.

This could be a significant factor to consider under shut-in conditions where the pipe is subject to the environment at sea-bed temperatures (i.e. 4 - 5degC) .

Further work is required in this area to evaluate the risk.

SSC test results in Produced Water environment: 35 mbar H_2S

pH	Test temp (°C)	Specimen reference	Surface finish	Total no. of cracks	Max. crack length (µm)	Max crack Depth (µm)	Cracking & locations		
							edge	middle	rollers
4.5	24	P9	As received*	2	890	923	Y	N	N
		P10	As received*	4	1000	1474	Y	N	N
		P11	As received	0	0	0	N	N	N
		P12	Fully machined*	0	0	0	N	N	N
		P13	Fully machined*	0	0	0	N	N	N
	5	P14	As received	37	500	1175	Y	N	N
		P15	As received	3	500	525	Y	N	N
		P16	Fully machined	60	1500	160	Y	Y	Y
		P17	Fully machined	79	1400	44	Y	Y	Y

*Note: all specimens were prepared with 45° edge chamfers except P9, P10, P12 & P13 where the edges were left 'as-machined'.

*Ref NACE Paper 51313-02589-SG

Qualification of CRA's 13% Cr Stainless Steels

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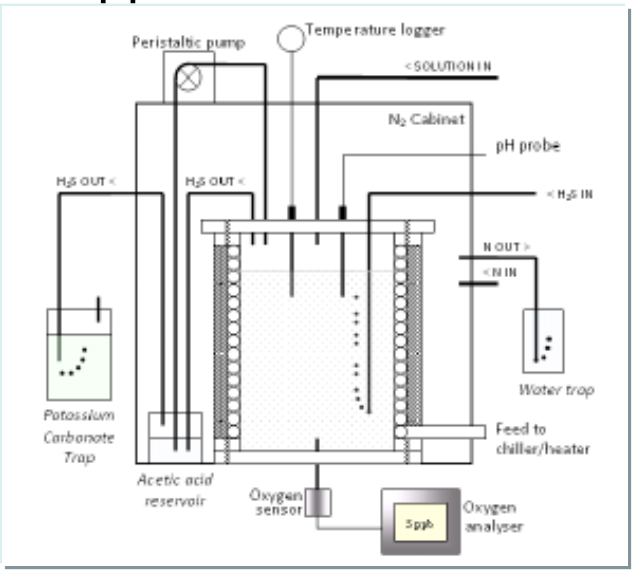
When testing 13%CrStainless Steels the following factors need to be considered:

i) Retention of bore surface following welding.
ii) Control of oxygen during testing to levels <10ppb.
iii) Control of pH during testing, particularly for low pH CW solutions.
iv) Careful examination and sectioning of all specimens



Ambient pressure / ambient temperature SSC tests need to be conducted in nitrogen cabinets to ensure adequate oxygen control.

Conclusions

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- A number of cracking mechanisms exist for carbon steel and CRA girth welds and therefore the appropriate test program needs to be selected.

- The current international standards for Sour Service Testing do not specify all of the critical parameters and consequently the actual test procedures adopted can influence the results obtained.

- The implementation of a successful Sour Service test program requires collaboration between:
  - i) The end user
  - ii) The welding contractor
  - iii) The test laboratory

Thank you for your attention

Any Questions?

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