R-TECH MATERIALS

# Failure Analysis – An Insight Into Forensic Investigation, Failure Mechanisms & Prevention

26th November 2024

Sarah Bagnall

WWW.R-TECHMATERIALS.COM

R-TECH MATERIALS

*Assured testing and materials expertise when safety, quality & integrity are the only option*

# Our services

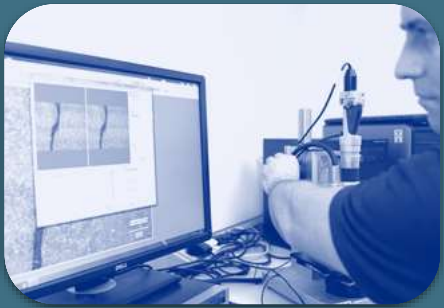
Testing of steel products for structural concrete

Failure Analysis Consultancy

Polymer & Composites Testing

Onsite services

Training Courses



Metallurgical services

Weld assessment

Testing of components for water industry

R-TECH MATERIALS

# Failure Analysis

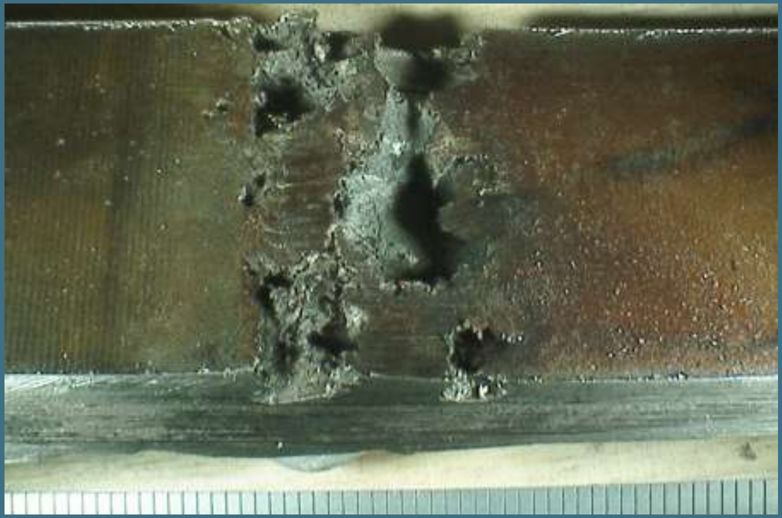
R-TECH MATERIALS

# Failure Analysis

- Failure analysis is critical to industrial applications
- When a material fails, it leaves behind a trail of evidence which when pieced together can lead to the cause of failure
- This information can be implemented to prevent failure from reoccurring
- Materials failures can lead to
  - fatality/injury
  - unplanned costly maintenance
  - uneconomical production
  - environmental issues
  - political issues

# Failure Analysis

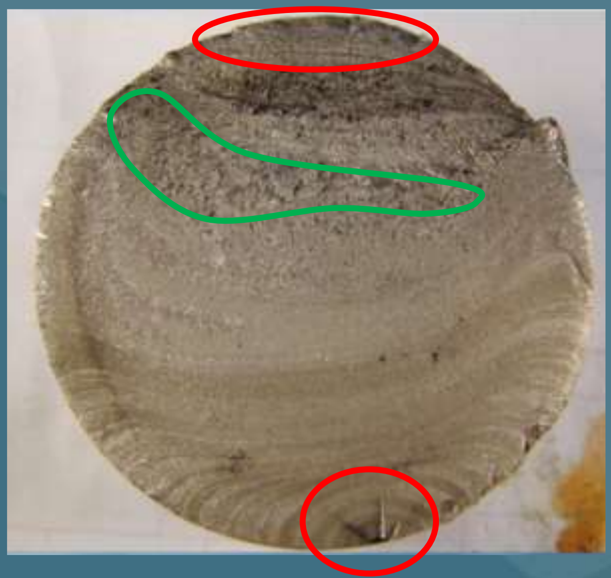
- A metallurgical failure analysis forms part of an overall root cause analysis
- The root cause can sometimes be determined from the metallurgical analysis, though in the majority of cases this forms only one part of a bigger picture

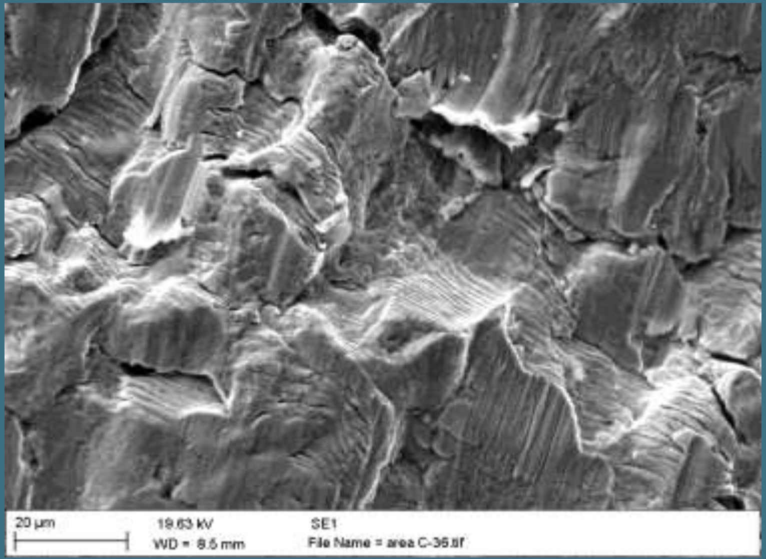


- A root cause analysis can include the following additional elements:
  - Design review
  - Review of operating history
  - Detailed account of events before and after
  - Review of witness statements
  - Examination of associated components
  - Stress analysis

# Gathering the Evidence

- Visual Examination
  - Site Visit
  - NDT
  - Dimensional checks
  - Photography






- Fractography:
  - Single/multiple fracture modes
  - Fracture initiation point
    - Any defects, machining marks, pitting?
  - Secondary cracks

# Gathering the Evidence

- Metal loss failure:
  - Examine morphology; localised, general, directional?
  - Associated corrosion product (if present)

- Analysis of corrosion deposits:
  - SEM/EDX analysis
  - XRD analysis

R-TECH MATERIALS

# Gathering the Evidence

- Metallographic examination:
  - Crack morphology
  - Metal loss morphology
  - Material & welding defects
  - Sub-surface cracking/voids



- Microstructure - conformity to standard
- Microstructural degradation
- Inclusion concentration
- Grain size
- Surface treatments

# Gathering the Evidence

- Materials testing:
  - Chemical analysis
  - Hardness testing
  - Tensile testing
  - Impact testing

  - In certain situations it may be necessary to carry out other tests such as:
    - Corrosion testing
    - Bend testing
    - Fatigue testing
- Literature review

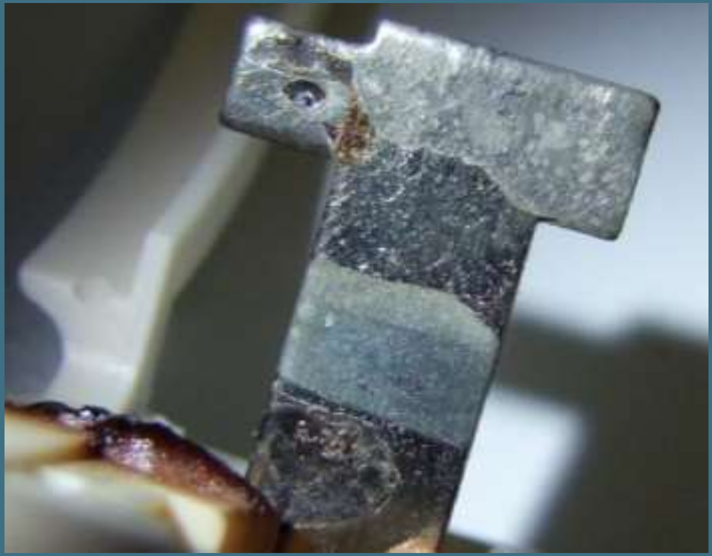
R-TECH MATERIALS

# Gathering the Evidence

- A significant part of a failure analysis is determined/limited by the background information provided:
  - Type of plant
  - Material grade
  - Process conditions (pressure, temp, process fluid)
  - Circumstances surrounding failure
  - Inspection intervals
  - Service length of component compared to expected

# Materials Failure Mechanisms

- Metal loss (corrosion, erosion, oxidation etc.)
- Fatigue



- Overloading
- Embrittlement
- Creep

- Material/welding defect
- A combination of these mechanisms

R-TECH MATERIALS

# Common Root Causes

- Misuse/abuse
- Improper maintenance
- Inadequate environmental protection/control

- Design errors
- Manufacturing defects
- Assembly errors

- Improper material
- Unexpected operating conditions
- Improper heat treatment

R-TECH MATERIALS

# Failure Cases

- Defence – Failure of an 800 mm propeller shaft from an Aircraft Carrier
- Automotive – Fatigue failure of an exhaust valve

- Petrochemical – exploded pipe which scattered 20+ pieces across the refinery
- Manufacturing – rail failure causing a torpedo carrying molten metal to de-rail leading to an explosion.

- Power generation – Creep failure of a reconditioned turbine blade
- Public – Stress Corrosion Cracking of bolts used within the roof of a swimming pool.

R-TECH MATERIALS

# Case Study 1

# Case Study 1

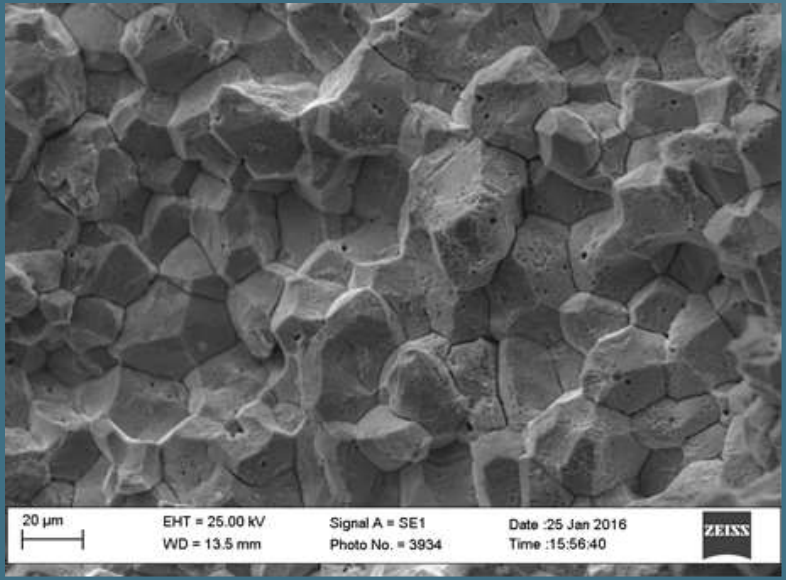
- Client experienced an oil leak from the main cargo line of an oil tanker used to transfer gas oil, gasoline, diesel and oil.
- The bolts used to secure the flange had fractured. The bolts had been in service for 6 months
- 304 stainless steel

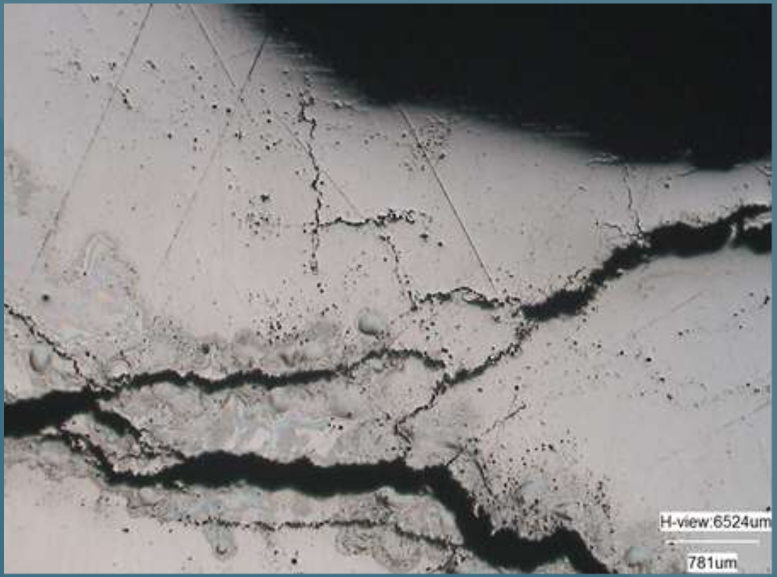
R-TECH MATERIALS

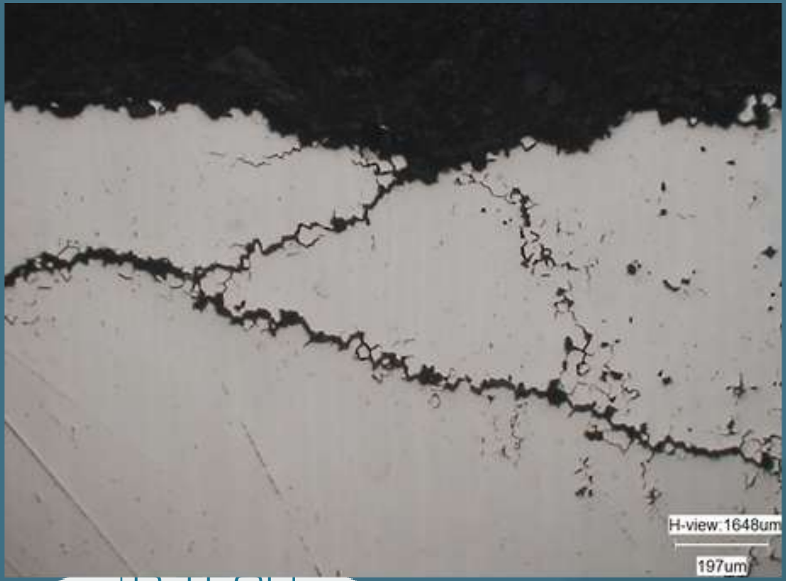
# Case Study 1

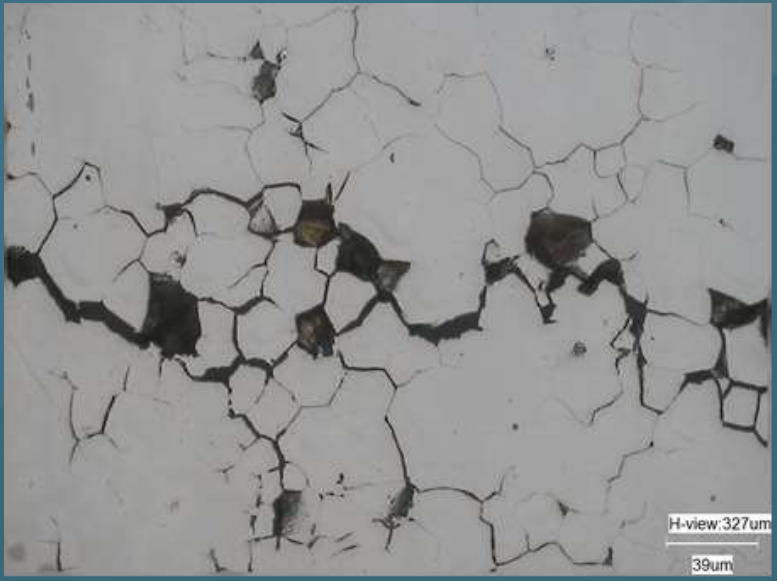
R-TECH MATERIALS

# Case Study 1

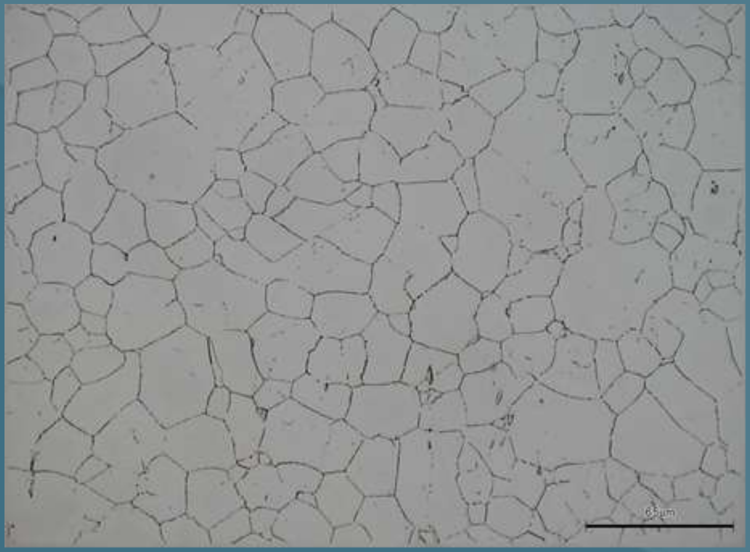

20 µm
EHT = 25.00 kV
WD = 13.5 mm
Signal A = SE1
Photo No. = 3934
Date :25 Jan 2016
Time :15:56:40
ZEISS


H-view:6524um
781um


H-view:1648um
197um


H-view:327um
39um

# Case Study 1


- Deposit contained significant levels of chlorine and sulphur.
- Microstructure was heavily sensitised

R-TECH MATERIALS

# Case Study 1

Mechanism was **Polythionic Acid Stress Corrosion Cracking.**

- Occurs due to the formation of sulphide scales in the presence of sulphur compounds, which then react with air and moisture during start-up/shutdown to form sulphur acids (polythionic acid).
- Sulphide is thought to have formed due to exposure to an environment containing hydrogen sulphide.
- In the presence of a tensile stress (residual or applied), polythionic acid attacks sensitised austenitic stainless steels adjacent to the chromium depleted grain boundaries, producing intergranular cracking.

R-TECH MATERIALS

# Case Study 2

R-TECH MATERIALS

# Case Study 2

- Super duplex stainless steel pipework from a seawater injection system
- The maximum operating temperature of the outlet was 35°C.

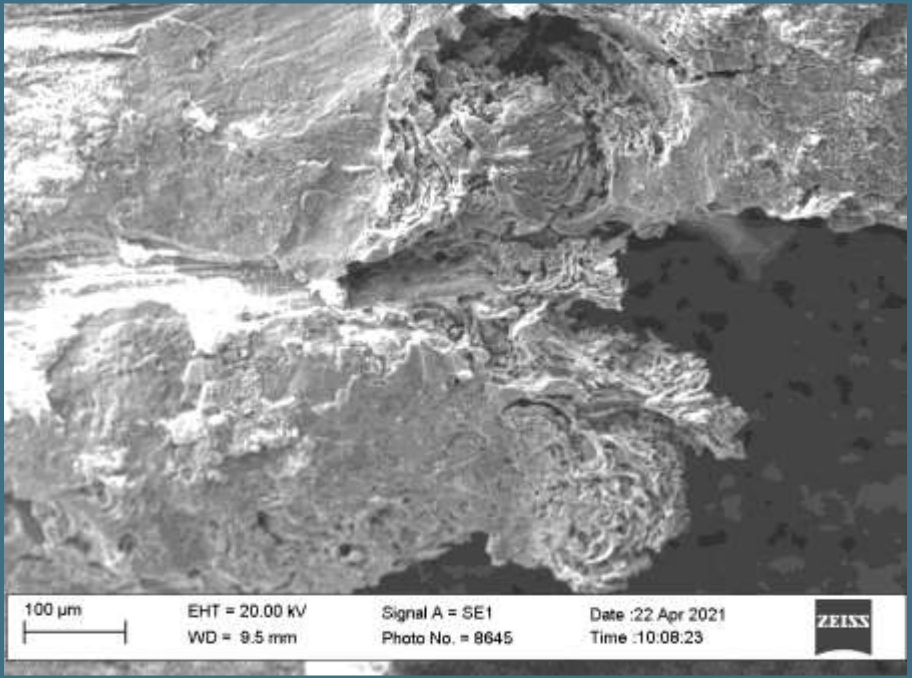
R-TECH MATERIALS

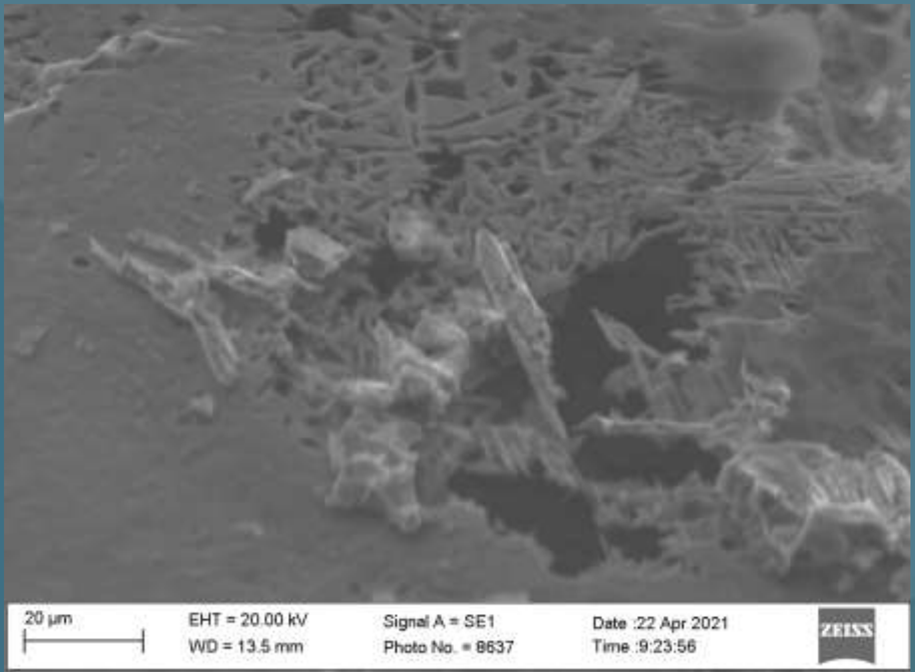
# Case Study 2

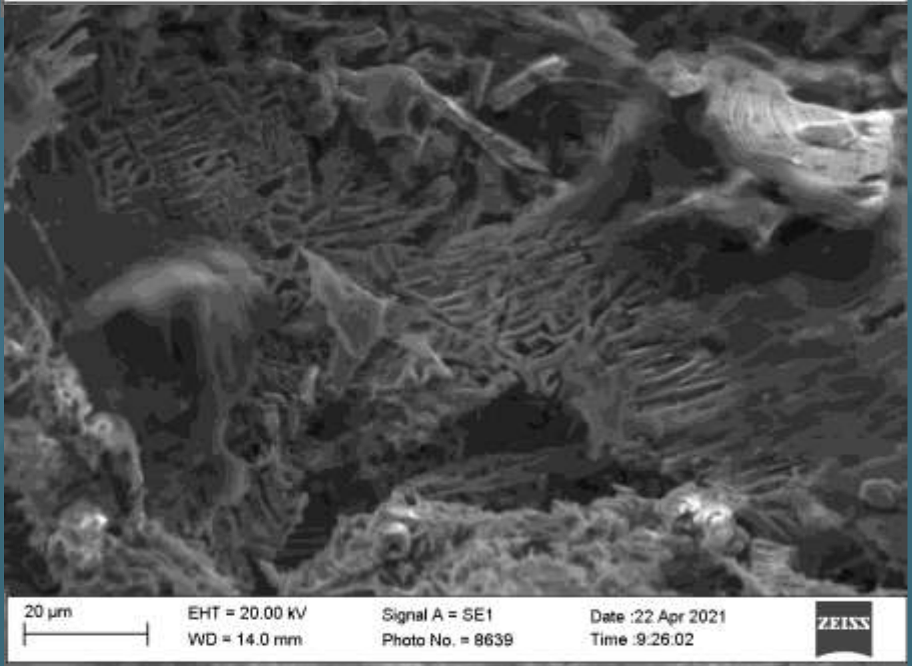
- Area of perforation evident within the weld
- At internal surface – significant metal loss was apparent below seemingly intact surface


# Case Study 2

- SEM showed areas of selective attack in the vicinity of the hole
- Deposit contained significant levels of chlorine and sulphur




R-TECH MATERIALS

# Case Study 2

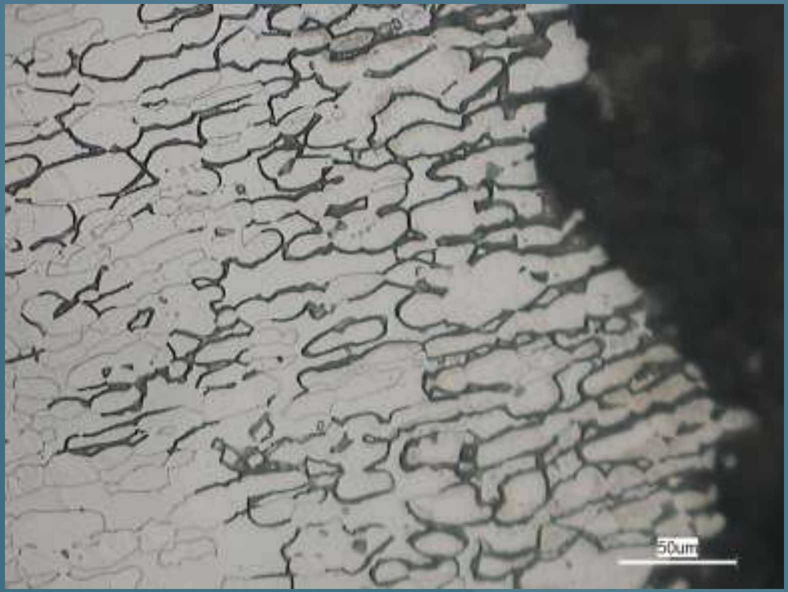
- Significant undercutting and hemispherical pitting evident within the weld metal



R-TECH MATERIALS

# Case Study 2

- Sigma phase & carbide was evident along the austenite/delta ferrite phase boundary
- Chemical analysis of the weld and parent materials were compliant with the specification






R-TECH MATERIALS

## Case Study 2

- Mechanism was deduced to be Microbial induced corrosion

- The presence of sulphur and the morphology of the pitting may indicate the presence of sulphate reducing bacteria. No sample was available to confirm this.

- The presence of carbides/nitrides along phase boundaries increases the likelihood of corrosion

# Case Study 2 - Recommendations

- Water quenching after heat treatment.
    - It is important to keep the time between exiting the furnace and water quenching as short as possible.

- During welding, the heat input should be optimised so that the cooling rate will be quick enough to avoid detrimental phases, though not so fast that there remains excessive ferrite in the vicinity of the fusion line.

- To maintain operational usage of the unit as far as possible in order to ensure continued flow through the elbow.
- If downtime for long periods is expected, adequate drainage and drying is necessary

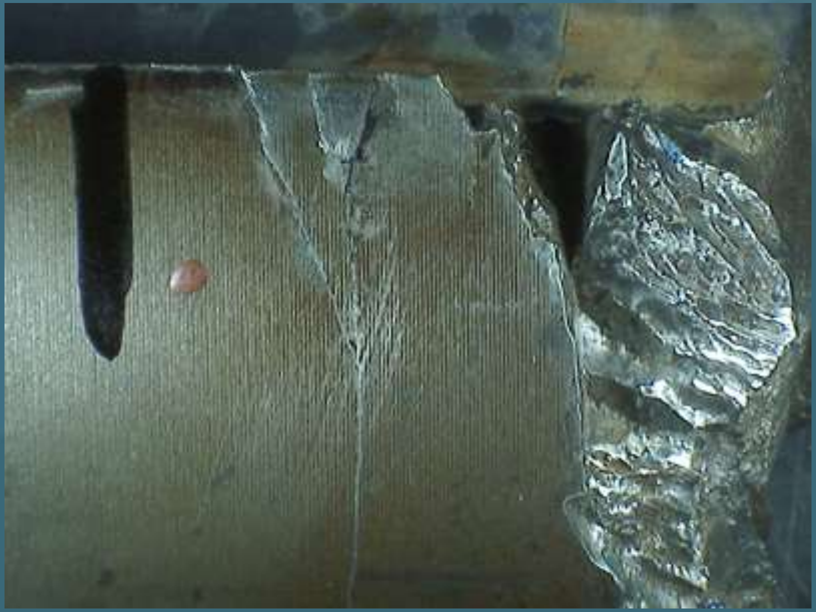
# Case Study 3

# Case Study 3

- Propeller shaft from a pilot vessel
- Duplex stainless steel
- Impressed current cathodic protection had been utilised.

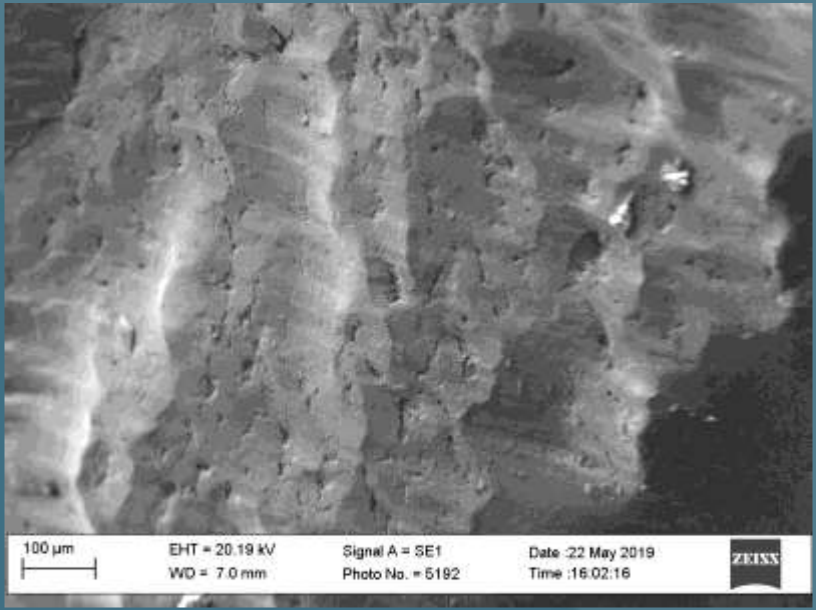
# Case Study 3

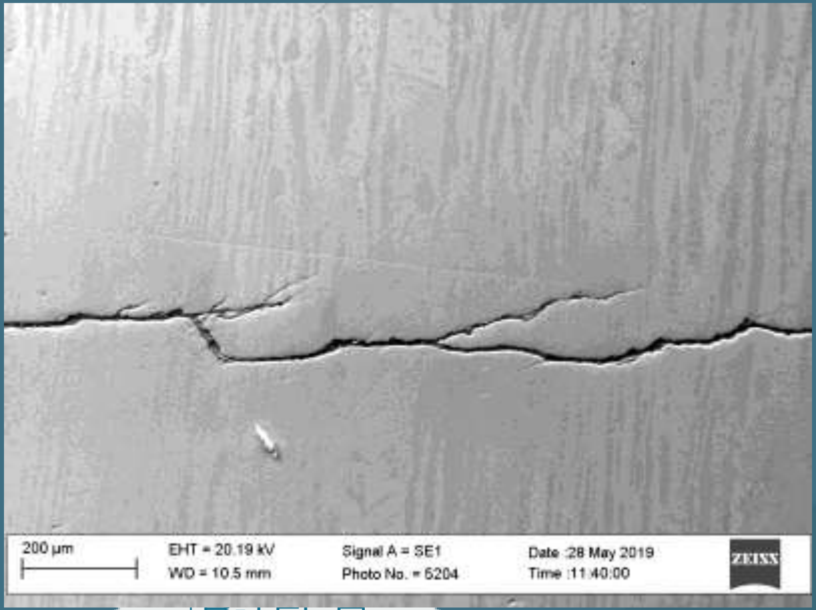
- River lines radiating from the keyway
- Brittle fracture mechanism
- Multiple secondary cracks initiating from the keyway

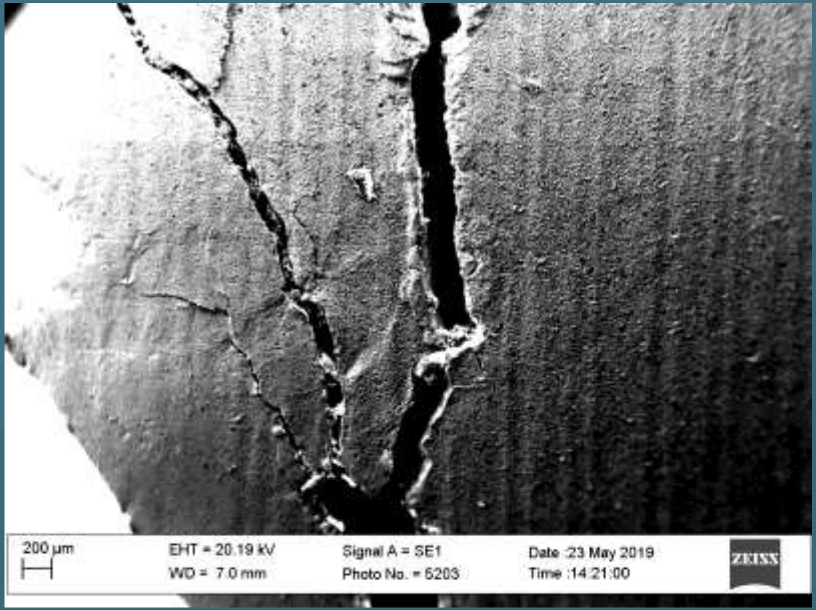


# Case Study 3

- Fracture surface on a micro scale exhibited significant damage



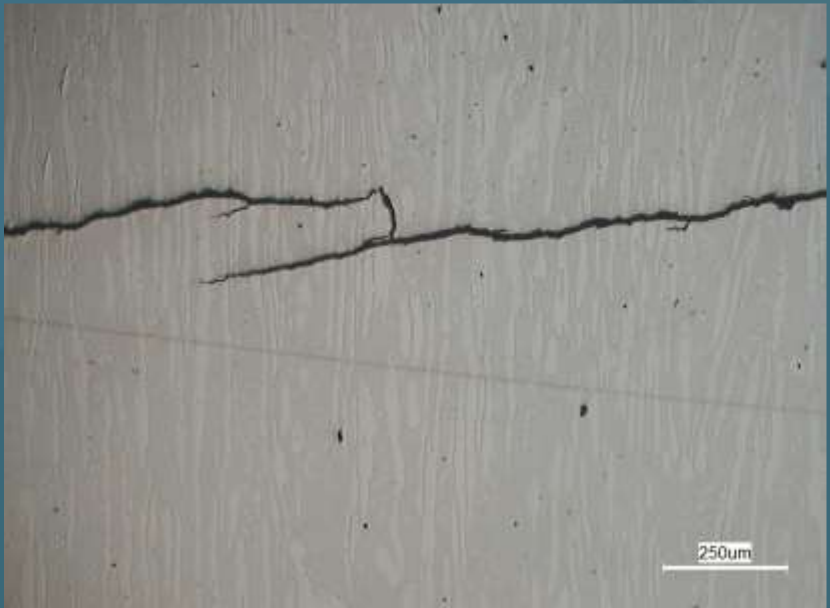




R-TECH MATERIALS

# Case Study 3



- The deposit within the cracking contained significant levels of chlorine and sulphur.

# Case Study 3

- Mechanism was deduced to be **Hydrogen Induced Stress Cracking (HISC)**
  - Hydrogen atoms form as a consequence of the cathodic protection.
  - Hydrogen atoms can either combine to form molecular hydrogen or become absorbed in the metal matrix.
  - For a susceptible material, this can lead to hydrogen cracking.
- The vessel adopted zinc anodes which were mounted directly on to the propeller shaft

- The vessel spent 80% of its time within freshwater and 20% at sea. Zinc anodes are typically employed for seawater environments, magnesium for freshwater.

# Case Study 3 - Recommendations

- Review design of the CP system relative to the operating waters. Aluminium can be used in both seawater and freshwater.

- Ensure that the appropriate potential is used for the material grade.

- Inspection to be carried out periodically i.e. DPI


R-TECH MATERIALS

# Case Study 4

R-TECH MATERIALS

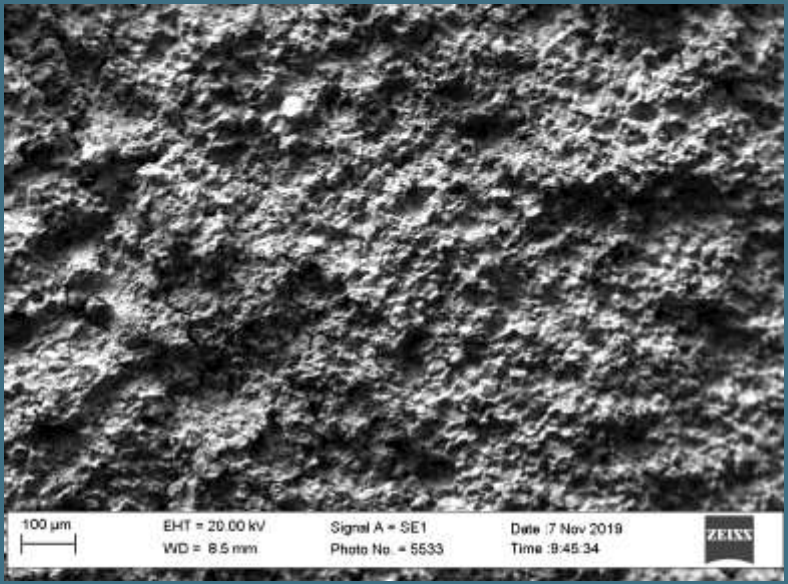
# Case Study 4

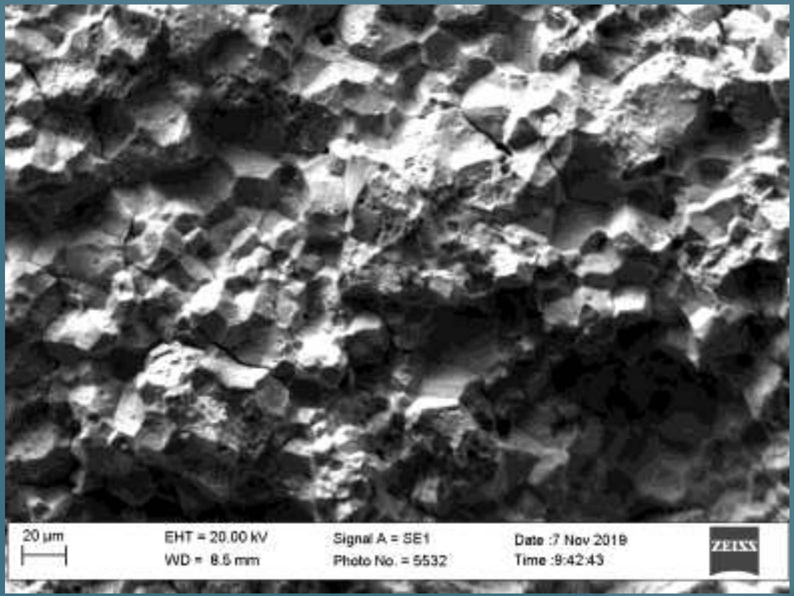
- 5" Heavy weight drill pipe threaded connection
- Mud temperature was approximately 38 degC.
- 4140 alloy steel
- Failed after 247 hours of drilling

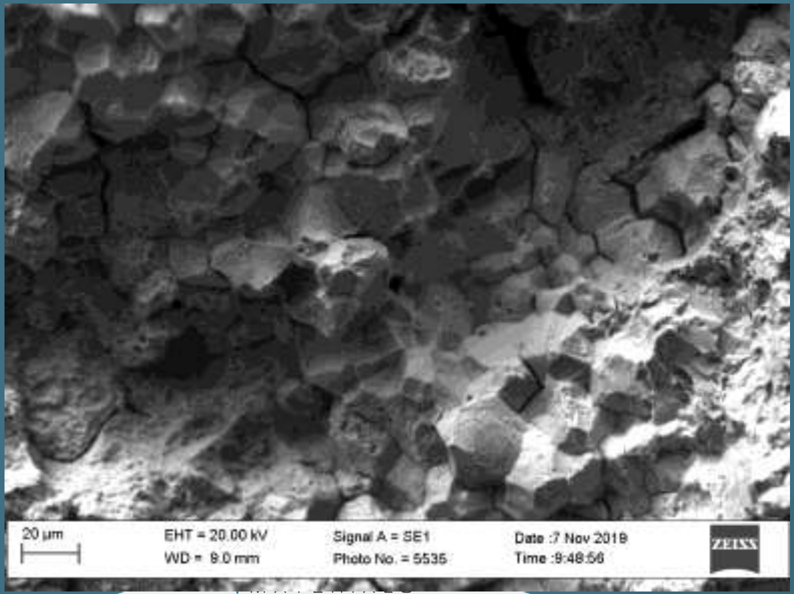
R-TECH MATERIALS

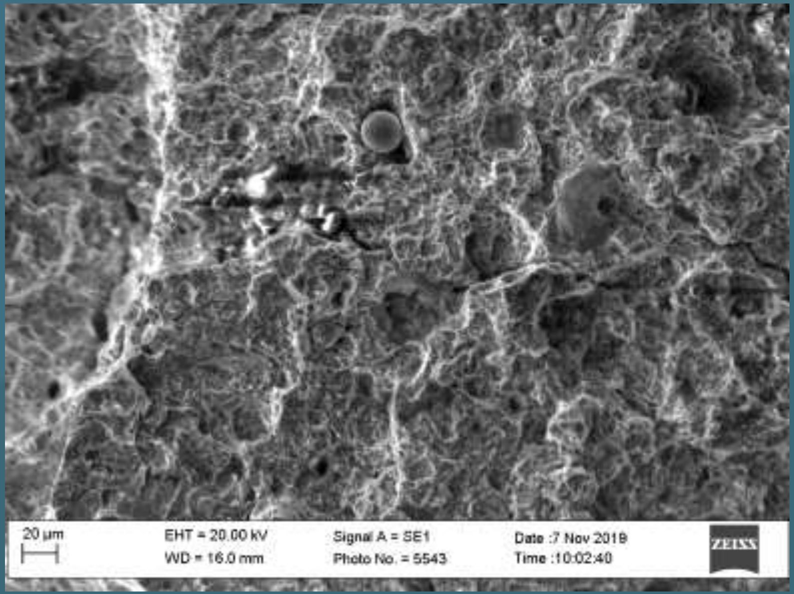
# Case Study 4


# Case Study 4


100 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = SE1
Photo No. = 5533
Date :7 Nov 2019
Time :9:45:34
ZEISS


20 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = SE1
Photo No. = 5532
Date :7 Nov 2019
Time :9:42:43
ZEISS


20 µm
EHT = 20.00 kV
WD = 9.0 mm
Signal A = SE1
Photo No. = 5535
Date :7 Nov 2019
Time :9:48:56
ZEISS


20 µm
EHT = 20.00 kV
WD = 16.0 mm
Signal A = SE1
Photo No. = 5543
Date :7 Nov 2019
Time :10:02:40
ZEISS

# Case Study 4




# Case Study 4

- Selective attack along internal surface
- Deposit contained significant levels of sulphur (up to 30%).
- Hardness levels were up to 520 Vickers. Material grade specifies a range of 302-362 Vickers. Light etching layer was 630 Vickers.



# Case Study 4

- Failure was attributable to sulphide stress corrosion cracking.
  - Occurs under the combined influence of a tensile stress and corrosion in the presence of water and hydrogen sulphide.
  - Tends to occur at temperatures below 82$^{o}$C.
  - Susceptibility is primarily dictated by a material's hardness. 200 HV is generally used as the safe limit for carbon and low alloy steels.
  - The hardness levels for the pin were exceptionally higher than this level and the maximum specified for the material specification. Therefore, the pin would be considered highly susceptible to sulphide stress corrosion cracking.


R-TECH MATERIALS

# Case Study 4 - Recommendations

- Controlling corrosive quantities of sulphur trioxide in the flue gas
  - Operate the boiler at or below 5% excess air to the burners
  - Minimise air infiltration
  - Specify fuels with low sulphur content

- Controlling the level of moisture in the flue gas
  - Specify fuel with low moisture content
  - Prevent tube leaks
  - Reduce amount of soot blowing

# Case Study 5

# Case Study 5

- Rear waterwall tubes extracted from the main boiler of an LNG carrier.
- The crew experienced limitations in steam production when attempting to operate the main turbine at high load.
- Inspection found evidence of significant water ingress about the manipulated tube immediate to the retractable soot blower lance sleeve
- Carbon steel
- The design pressure was in the region of 76 – 78 bar, which facilitates a saturated steam temperature of approx. 300oC.

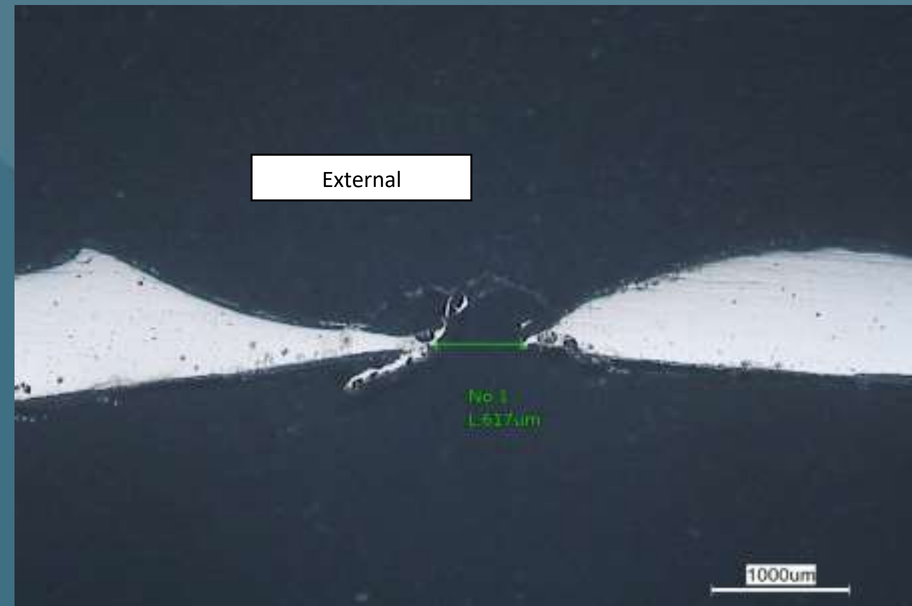
R-TECH MATERIALS

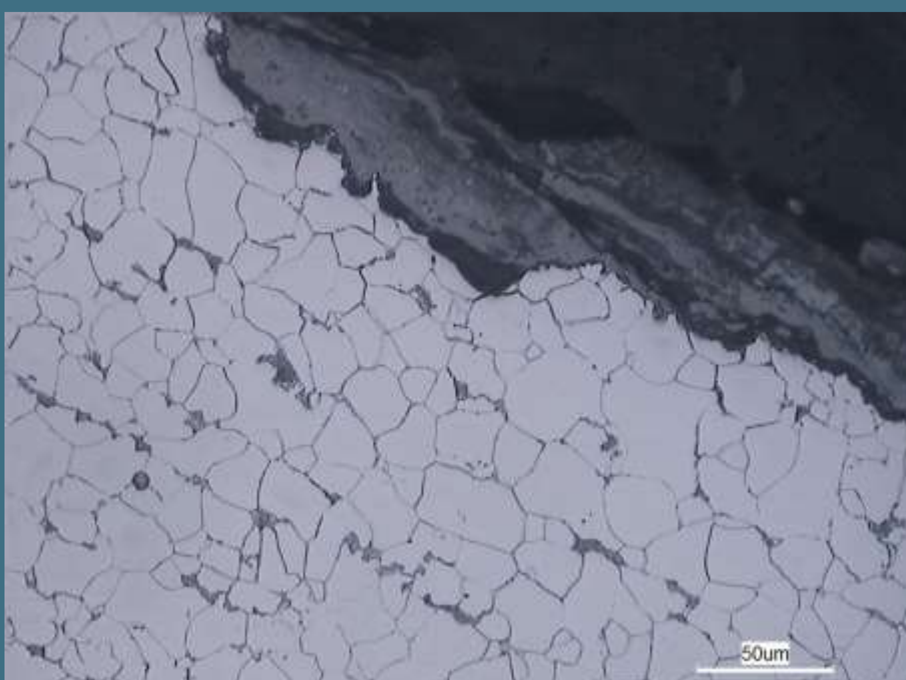
# Case Study 5

- Scale evident at the external surface was brown, yellow and white in colour.
- 3 pinholes were present
- Smooth undulating surface, almost scalloped in nature.
- Areas of the surface were pockmarked in appearance

# Case Study 5

- Microstructure was as expected
- Pinhole was associated with a shallow gradient of wall loss
- Pockmarks/pits were evident along the external surface




# Case Study 5

- Corrosion deposit consisted of iron sulphate hydrate, calcium phosphate & hematite
  - Iron sulphate hydrate is produced when concentrated sulphuric acid forms on steel surfaces and reacts with the underlying steel.
  - Calcium phosphate is one of the more common components of boiler deposits, and forms when phosphate salts used to treat boiler water preferentially precipitate with calcium.
  - Hematite is a non-protective iron-oxide formed in oxygen-rich concentrations and can act as binder species; allowing for other phases to accumulate within the deposit.


R-TECH MATERIALS

# Case Study 5

- Mechanism was identified as **Sulphuric Acid Dewpoint Corrosion:**
  - Occurs when metal temperatures fall below the sulphuric acid dew point of the flue gas. Generally termed "cold-end corrosion" since it generally affects the cooler regions.

  - Sulphur is present in heavy oil and during combustion, sulphur oxides are generated, a small portion of which becomes $SO_3$.
    - As the exhaust gas temperature reaches the dew point or lower, vapour-phase sulphuric acid forms.
    - If this contacts the lower-temperature metal surface it can condense as liquid sulphuric acid, attacking the underlying metal.

  - Temperature at which sulphuric acid condenses varies between 116 -166°C or higher
    - Depends on the $SO_3$ and water vapour concentrations in the exhaust gas.
    - The dew point increases with $SO_3$ content and moisture content.

R-TECH MATERIALS

# Case Study 5 - Recommendations

- Controlling corrosive quantities of sulphur trioxide in the flue gas
  - Operate the boiler at or below 5% excess air to the burners
  - Minimise air infiltration
  - Specify fuels with low sulphur content

- Controlling the level of moisture in the flue gas
  - Specify fuel with low moisture content
  - Prevent tube leaks
  - Reduce amount of soot blowing

R-TECH MATERIALS

# Case Study 5 - Recommendations

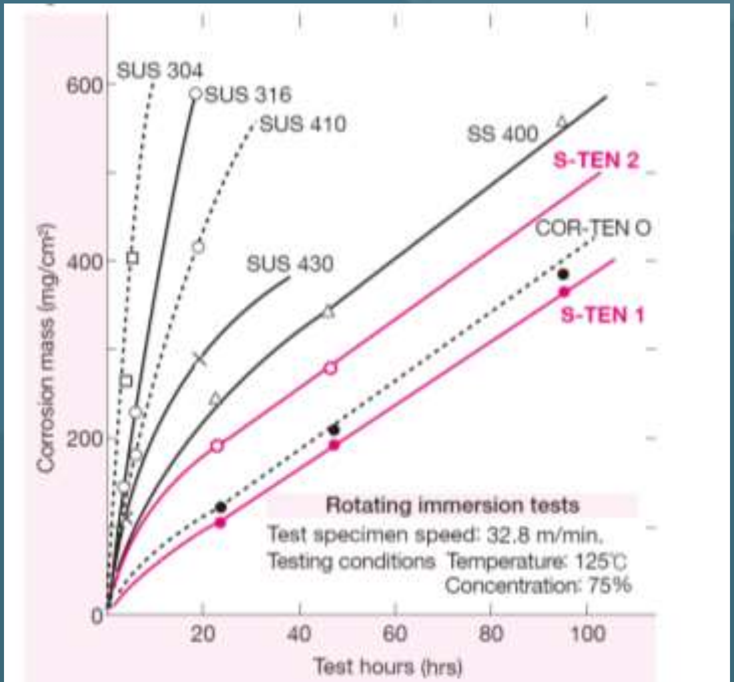
- Controlling metal surface temperatures
    - Requires substantial design changes

- Feeding of fuel additives and/or cold end additives i.e. MgO

- Periodic removal of ash deposits

- Application of a corrosion inhibitor following cleaning and drying during shutdown. Humidity control can also be implemented.

- Weathering steels, such as COR-TEN and S-TEN, have been reported to be highly resistant to sulphuric acid dew point corrosion in comparison to low carbon steels and the majority of stainless steels.



R-TECH MATERIALS

# Any Questions?

+44 (0)1656 748 000
sarah.bagnall@R-TECHMATERIALS.COM

WWW.R-TECHMATERIALS.COM