Waterside Stress Assisted Corrosion (SAC) of Boiler Tubes

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Boiler Areas Susceptible to SAC

- Generally SAC initiates near weld joints on cold side of tubes
- SAC cracks are difficult to detect inaccessibility
- Failures Detected at Various Locations in Boilers
  - Floor
  - Waterwalls
  - Screens
  - Roof
  - Economizers
  - Floor-to Sidewall Seals
  - Smelt Box Attachments
  - Port Attachments
Waterside Cracks in Waterwall Tube Near Attachment Weld

Stress Assisted Corrosion Under Welded Joints on Inner Surface of Waterwall Tubes

Stress Assisted Corrosion in Waterwall Tubes
Magnetite Film Formation on Boiler Tubes

\[ 3 \text{Fe} + 4 \text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 4 \text{H}_2 \]

Above ~ 230°C, Magnetite Film Forms on Carbon Steel in Slightly Alkaline Oxygen-free Water

XRD of SA 210 Carbon Steel - Unexposed

SA 210 Carbon Steel - Unexposed

SA 210 Carbon Steel Surface Exposed to Pure Water at 250°C for 24 Hours
Oxide Scale on Failed Tubes

Oxide Scale on Water-Touched Tube Surface

Stress Assisted Corrosion Cracks and Oxide Scale Morphology
Microstructure of Carbon Steel Tubes With SAC

Decarburization and Grain Growth is Not Necessary for SAC but may facilitate easier Initiation

Decarburized and Large Grained Layer
Inner Tube Surface

Normal Boiler Tube Microstructure
Middle of Tube

C-Steel Waterwall Tubes in Area with SAC – Tube#5
Role of C-Steel Microstructure on SAC initiation

Microhardness of Boiler Tubes
Microstructure of Composite Tubes Removed from Front Wall (near smelt spouts) of Recovery Boilers
No SAC in these Tubes

Modeling of recovery boiler wall panel to investigate the effect of attachment plate

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Oak Ridge National Laboratory
Attachment plate places constraint on the free expansion of tubes at operating conditions

- Magnified (10x) view of the deformed mesh at operating temperature shows effect of attachment plate
- Constraint from attachment plate influences the stresses in the tubes containing the attachment weld

Constraint due to Welded Attachment Plate

- Attachment plate causes significant change in stress state in the immediate vicinity of the weld
  - Stresses are high on either side over a distance of about 4 elements, which is about 16 mm (5/8 in.)
Strain Measurements on Operating Boiler Tubes

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- Identified a boiler
  - heaviest available attachments around manway opening

- Installed gages during major outage *(just prior to restart)*
  - 19 strain gages and 7 TCs in area of interest
  - data every 30 seconds for ~7 months

- Use data to support finite element model
  - examine strain range during operation/shut-downs
  - use data as bounding conditions for FEM calculations
Original Start-Up Excursions
- largest $\Delta \varepsilon$ during experiment
- “steady state” within about 40 h

Example of a serious process upset (ESP)
- boiler tube temperature drops to ambient
- hydrotest prior to restart
- generates large relative strain
So What Causes SAC?

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Test Autoclave with Recirculation Loop

- Test Capabilities
  - Temperature up to 350°C, Pressure up to 3500 psi
  - Electrochemical Tests
    - AC Impedance
  - Stressed Samples for SAC
  - Special Fixture for Constant Extension Rate Tests
Autoclave with Recirculation Loop

- 100 Liter Makeup Tank
- Heat Exchangers to Conserve Heat and Achieve Steady State Easily
- High Pressure Pump for Recirculation
- Continuous Water Chemistry Monitoring

Equipments and Test Procedures for Crack Initiation Tests in Boiler Water

- Slow Strain Rate Tests for SAC Initiation
- Constant Strain Rate for Slow Strain Rate Test
Effect of Dissolved \( \text{O}_2 \) on SAC Cracking

SSRT tests @ 300 °C

Effect of Temperature on Crack Growth & Density

Effect of Temperature on Crack Growth & Density

Threshold Temperature: ~ 110°C
Effect of Temperature on Crack Length

@ 110 °C
@ 250 °C
@ 270 °C
@ 300 °C
@ 300 °C
@ 320 °C

Effect of Dissolved Oxygen on SAC Cracking

Threshold DO: < 20 ppb
Effect of Grain Size on SAC Cracking

![Graph showing the effect of grain size on SAC cracking. The graph includes a line graph that plots stress (MPa) on the y-axis against strain (%) on the x-axis. The graph also shows the relationship between crack velocity (mm/s) and grain size (μm) with the equation y = 2.21E-7x + 1.51E-6 and R² = 0.985. Another line graph shows the relationship between crack density (1/mm) and grain size (μm) with the equation y = 0.0456x + 9.5965 and R² = 0.868.]

1100 °C for 7 days
1100 °C for 3 days
1100 °C for 1 hour
As Received

![Images showing different conditions: 1100 °C for 7 days, 1100 °C for 3 days, 1100 °C for 1 hour, and As Received sample.]
Proposed Mechanism of SAC Initiation

Anode/Cathode area ratio change

Oxygenated Water 3ppm
Mechanical Strain
Compact magnetite Film
Carbon Steel

Oxygenated Water
Small Anode
Large Cathode
Carbon Steel

Oxygenated Water
Porous Film
Carbon Steel

Oxygenated Water
Corrosion Pits
Carbon Steel

How do SAC Cracks Initiate and Grow?

Boiler Temperature
Time (hrs)
Stress
Yield Stress
30% YS

Mechanical Strain
Magnetite Film
Carbon Steel

Oxygenated Boiler Water
Carbon Steel

Pits
Carbon Steel

Proposed Mechanism
Lab Results
Proposed Mechanism of SAC Propagation

Effects of Boiler Shutdown Conditions on Crack Morphology

*Sharp corrosion fatigue cracks and blunt SAC cracks have the similar initiation and growth mechanism*
SAC Cracks in Laboratory vs Boiler Tubes

SAC Cracks from Service Conditions

SAC Cracks from Simulated Lab Conditions

**Stress Assisted Corrosion**

- **Results Summary**

- Results indicate that SAC initiates and grows in the presence of oxygen

- If O₂ levels during shutdown are kept under control, then SAC are not expected to grow due to environmental effect
  - (unless the crack is already above a critical length where they can grow due to mechanical stresses alone)

- Strain measurements and FEM model show that the crack may grow during boiler shutdown and startup, when the strains are maximum and O₂ may also be available

- In presence of O₂, sharp fatigue crack or stress corrosion crack tips may corrode preferentially to make blunt, bulbous SAC cracks
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