Power Generation Industry Experience

Stress Relaxation Cracking (SRxC) and Strain Induced Precipitation Hardening (SIPH) Failures

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DOE sCO₂ Cross-Cutting Team Workshop: Evaluation of Welding Issues in High Nickel and Stainless Steel Alloys for Advanced Energy Systems
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Introduction and background
SRxC/SIPH cracking – not a new problem

1950s
- Increasing steam outlet temperature exceeded limits for conventional steels
  - In the UK, and to a lesser extent in the USA, 347H or similar variants were used to fabricate complex components
  - Variable experience, and in the UK experience thousands of repairs were required
- In the USA, challenges were observed at Eddystone, but robust R&D program and an overall philosophy of ‘well-engineered’ enabled two units to run for ~50 years with extensive amounts of 316H

1990s
- Policy statement from one major OEM, “As a result of the numerous failures that occurred throughout the industry in the 1950’s in tubular and other components, [OEM] together with a number of other equipment manufacturers and utilities, adopted a requirement that all cold-formed bends and certain welds be solution annealed prior to service installation. The immediate and complete elimination of all failures due to this condition following a properly applied solution anneal was a testament to the efficacy of the heat treatment requirement.”

2000s
- New wave of (ultra) supercritical plant installations
- Recurring issues in widely installed Ni-base (alloy 617) or stainless steels (347H, HR3C) including cracking at:
  - Tube to tube butt welds including dissimilar metal welds between alloy 617 and stainless steel
  - Attachment welds
  - Bends

Today
- Documented challenges in fabricating 740H (although issues do not appear to be ‘widespread’)
- Significant concerns regarding the view of Codes and Standards as ‘THE’ and not a ‘MINIMUM’ requirement
- 50+ years of research, still no widely accepted screening or robust testing methodologies to support best practice

Industry has done a poor job implementing lessons of the past!
<table>
<thead>
<tr>
<th>Plant</th>
<th>Material</th>
<th>Component</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>347H</td>
<td>Superheater support lug</td>
<td>SRxC</td>
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<td>Superheater tube</td>
<td>SIPH</td>
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<tr>
<td>2</td>
<td>347H</td>
<td>Superheater bend</td>
<td>SIPH</td>
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<td>3</td>
<td>321H</td>
<td>Superheater bend</td>
<td>SIPH</td>
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<tr>
<td>4</td>
<td>304H</td>
<td>Superheater dutchman repair</td>
<td>Combination of deformed surface, high stress due to thinned wall and possible propagation of damage due to SIPH</td>
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<tr>
<td>5</td>
<td>304H</td>
<td>Superheater bend</td>
<td>Long-term overheat</td>
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<tr>
<td>6</td>
<td>347H</td>
<td>Reheater bend</td>
<td>SIPH</td>
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<tr>
<td></td>
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<td>Reheater support lug weld</td>
<td>SRxC</td>
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<tr>
<td>7</td>
<td>321H</td>
<td>Swages</td>
<td>SIPH</td>
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<tr>
<td>8</td>
<td>304H</td>
<td>Superheater bend</td>
<td>SIPH, other contributing factors possible</td>
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<tr>
<td>9</td>
<td>HR3C</td>
<td>Reheater swage</td>
<td>SIPH</td>
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<tr>
<td>10</td>
<td>347H</td>
<td>Swages</td>
<td>SIPH</td>
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Expert review from 2015…

Many theories have been put forth and testing methodologies have been developed to understand strain age cracking. Still, the underlying mechanism has yet to be determined. This is mainly due to the lack of a holistic testing methodology that gives a definitive evaluation of cracking susceptibility. Most of the current tests, such as Gleeble, stress to fracture, and the patch test, are not applicable since they do not simulate real conditions of stress development during cooling of the weld metal and stress relaxation subsequent to PWHT.
SAC or relaxation cracking is also a concern, but the complexity of the problem, lack of understanding of residual stresses, and lack of a standardized test method provides a challenge to the research community to further the science …perhaps through a combination of available computational methods to address fundamental material chemistry and precipitation kinetics, experimentation to validate models, and field testing to confirm.
Reaching ‘consensus’ is challenging…

“...In adopting rules restricting cold forming, the Code recognizes that a simplified treatment has been given to a complex subject, and that application of these rules is not an absolute guarantee that premature failures will be avoided in all situations. Likewise, violation of the limits defined in the rules will not inevitably result in premature failures... the rules represent a consensus achieved by parties representing disparate interests and are viewed as a step in the right direction [2].”

Contributing factors to observed cracking

Material
- Bulk composition
- Scrap or ore selection
- Tramp or impurity elements
- Local composition
- Melting practice
- Deoxidation
- Grain size
- Processing and heat treatment history

Thermal history
- Welding
- Filler metal selection, heat input and multi-pass welds
- PWHT (if applicable)
- Heating rate or profile and peak temperature
- Service exposure
- Temperature, time, precipitation

Stress
- Welding residual stress
- Phase transformations
- Deformation/working processes (e.g. cold bending)
- Constraint
- Section thickness, inherent versus external restraint, system flexibility, weld fit-up, weld profile, alignment, etc.
- Service-induced

At what temperature will welding residual stress(es) begin to relax? And what is the creep ductility of the material in this regime? And what is precipitating?

How much of this will be reported on a material cert?
How much of this will be documented for the end-user?
How much of this can be controlled?
**Little Consensus in Research Community**

<table>
<thead>
<tr>
<th>Testing Method Type</th>
<th>Lab/ Author/ Researcher and Year</th>
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</thead>
<tbody>
<tr>
<td>Weld mock-up tests to simulate weld residual stress</td>
<td>J. C. Borland, 1960 (Borland test)</td>
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<td>R. J. Dennis, 2008 (Ring weld method)</td>
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<tr>
<td>C- Ring Test</td>
<td>C. D. Lundin, 1990</td>
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<tr>
<td>Fracture mechanics, CTOD tests</td>
<td>R. J. Christoffel, 1962</td>
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<td>K. Purazrang, 1976</td>
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<tr>
<td>Gleeble based test methods</td>
<td>L. Li, 2000 (RPI - Notched test specimen)</td>
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<td>J. Dupont, 2003 (Lehigh - Notched test specimen)</td>
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<td>J. E. Ramirez, 2005 (OSU - Notched test specimen)</td>
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<td></td>
<td>R. Kant, 2019 (Lehigh - Notched test specimen)</td>
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<tr>
<td>Tensile test</td>
<td>A. Dhooge, 2004 (BWI - slow strain rate tensile)</td>
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<tr>
<td>Three-point bend testing</td>
<td>Van Wortel, 2007 (<a href="#">TNO Industrie</a>)</td>
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<tr>
<td>Notched bar creep testing</td>
<td>M. Spindler, 2009 (<a href="#">Électricité de France</a>)</td>
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<td>Four-point bend testing</td>
<td>B. Kuhn, 2013 (<a href="#">Jülich Research Center</a>)</td>
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<td>A. Shyam (ORNL), J. Shingledecker (EPRI), 2014</td>
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<tr>
<td>Lever-arm loading</td>
<td>E. S. Robitz, 2001 (<a href="#">B&amp;W test method</a>)</td>
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Various test methods with differing test geometries explored to recreate this phenomenon in a laboratory. 60 yrs of R&D, still no standard screening test
An Illustration of the General Challenges

- Failures measured in the tens to hundreds of thousands
- Susceptibility
  - “Global”, as assessed across the stainless steel family
  - “Local”, as assessed on a heat-to-heat basis for a single grade
  - “Micro”, as individual locations (i.e., weldments, attachments, bends)
  - “Nano”, electron-microscopy to define susceptible precipitates, phases or other characteristics in the microstructure which contribute to failure
- Prevention versus elimination
- Management of issues – Repair / replacement guidelines

The first step to prevention and informed research studies is to fully understand and appreciate the failure mechanism
Case Studies: Stainless Steel
Failures in Stainless Steels

Many instances of attachment and tube-to-tube failures

Indication at the weld toe
Through wall damage
Longitudinal section along attachment
Through wall failure

Program 87 Webcast Series: An Update on EPRI Research for Stainless Steel Cracking Issues: 05 Oct, 2017
### Key concern: poorly established susceptibility in new alloys

Advanced alloys are more complex, and may include additional processing or heat treatment steps. There is substantial evidence that the current conventional grade composition does not control sufficient elements.

<table>
<thead>
<tr>
<th>Conv. SS Grade</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
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**Up to 7 more elements**
Case Study: Failures At SH/ RH Tube Attachment Welds

- Multiple utilities have reported cracking issues at attachment welds on 347H SH/ RH tubes
- Cracks appear at toe of fillet weld, in the HAZ
Case Study: Analysis of Cracking at Attachment Welds

347H SH tube with extensive damage (initiation at weld toe attachment)

Site for TEM Analysis

TEM sample taken from ahead of crack tip showing a creep cavity at grain boundary

Grain Boundary

Cavity
Case Study: STEM-EDS Cr Distribution Map

Cr denuded zone at the grain boundary

Cr rich Carbide

~1µm

(Next slide)
Case Study: STEM-EDS Nb Distribution map at GB

Very fine (~20 nm) Nb-rich precipitates forming within grains and a narrow PFZ at the grain boundary.
Case Studies: Nickel-base alloys
In-Service SRxC in Alloy 617

In-Service SRxC in European Comtes Facility (alloy 617B)

- A-USC Component Test Facility
  - Goal: demonstration of full-size components operating ~700°C
  - From 2005-09 ➔ ~22,000 hours
  - 13,000hrs >680°C

<table>
<thead>
<tr>
<th>Component</th>
<th>Time</th>
<th>Description of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-pressure bypass valve</td>
<td>22,000 hrs</td>
<td>Cracking found propagating from thread roots during inspection after service</td>
</tr>
<tr>
<td>Superheater transition piece</td>
<td>&lt;10,000 hrs</td>
<td>Relaxation crack in cold deformed and welded region of tube</td>
</tr>
<tr>
<td>Spray attemperators</td>
<td>&lt;10,000 hrs</td>
<td>Multiple cracks attributed to thermal cycling in multiple locations in three components</td>
</tr>
<tr>
<td>Girth weld near attemperation</td>
<td>&lt;1 year</td>
<td>Fitting was installed during a repair and not PWHT; relaxation cracking susceptible material</td>
</tr>
<tr>
<td>Girth weld repair</td>
<td>~9 months</td>
<td>Fatigue in highly stressed weld at turbine valve</td>
</tr>
<tr>
<td>Main steam stub tubes</td>
<td>~2 years</td>
<td>Multiple indication in 2 stub tube welds to MS piping requiring remediation &amp; replacement</td>
</tr>
</tbody>
</table>

Intensive studies to remediate cracks via weld repair demonstrated the potential for a 980°C ‘stabilization’ heat-treatment to alleviate SRxC concerns, BUT “final repair concept could not be fully verified”
In-Service SRxC – Coal-fired 617 DMW experience

- Superheater and reheater sections, configuration:
  - HR3C (austenitic stainless steel) to alloy 617 transition piece (617 filler metal) to T92 steel
- SRxC observed in BOTH alloys after ~10,000hrs in service (steam temperature ~580-620°C)
  - ‘Leaks’ and ‘bursts’
  - Specialist field inspection techniques developed
  - Considered “Thin-section welds”

- Challenges for repair procedure development
  - Best heating method to minimize variability in field application (up to 980°C)
  - Potential for alternative ‘lower strength’ filler metal
  - Concerns for sensitization in stainless steel
    - SCC failures have also been observed
  - T92 cannot exceed 800°C; target = 720°C

In a single unit, 100s of affected joints (fleet = 1,000s)
Heat-Treatment (Fabrication) SRxC: 740H

- GTI/Optimus STEP Program fired heater
  - ~3% of tube-to-tube butt welds exhibited cracking after PWHT
  - No cracking in tube-to-header, end plates, drains, etc.

- Scope of EPRI Support
  - Failure analysis for tubes with leaks (6 tubes) + destructive evaluation of an additional 6 weld joints
    - Extensive study (>40 mounts for metallography)
  - Review of fabrication documents
  - NDE assessment (procedure, technique, and destructive evaluation to support method validation)

First large-scale application of 740H welding (>1,600 welds) including a range of weld geometries and thicknesses
Heat-Treatment (Fabrication) SRxC: 740H

Failure analysis confirmed SRxC

Outside diameter

#1

Weld

#2

Weld

#3

Weld

#4

Weld

1 mm

No damage

Initiation at weld toe on the ID, propagation through HAZ and into the weld

Initiation at weld toe on the ID, propagation through HAZ

Failure analysis confirmed SRxC
Heat-Treatment (Fabrication) SRxC: 740H - Morphology

R13, W4, #4

OD

ID

Image to the right

Intergranular, initiation at weld toe

0.5 mm

Isolated cavities ahead of crack tip
Heat-Treatment (Fabrication) SRxC: 740H - Morphology

Precipitate Free Zones (PFZs) identified at grain boundaries in limited HAZ/FL areas
Heat-Treatment (Fabrication) SRxC: 740H - Analysis

- Cracking mechanism: the location and characteristics of the cracking suggests SRxC during PWHT
  - I.D. initiation at weld toe, exclusively intergranular initiation and growth, and voids ahead of crack tips
- **Did not** appear to be contributing factors based on sample analyzed
  - No trend with grain size or composition found for limited range of grain sizes and heats utilized for the heater
  - Carbide stringers do not provide preferential cracking locations
  - No evidence of cold deformation (from hardness testing)
  - No evidence of welding defects (over 40 mounted cross-sections without any identification of a weld defect)

Opportunity to utilize data and leverage with future additional research to develop specs which go ‘beyond code’ for future 740H tube fabrication
Concluding Remarks
(Some) Question Power Generation Members Ask

- Are current code rules and/or material standards sufficient?
  - If not, how will improved specifications reduce the susceptibility to cracking?
- Should material suppliers be screened?
- Why did only X% of the tubes or welds fail? And is there a concern for the balance of the components?
  - What is the strategy for inspection (technology & implementation)?
  - What are the options for repair? What if solution annealing in the field is impossible?
- Will automated welding reduce variability?
- Can ‘lessons learned’ from some alloys be borrowed for others?
  - If 347H is susceptible, what about other alloyed advanced stainless steels like Super 304H or HR3C?

The obvious challenge for any industry is that excessive uncertainty becomes unmanageable
Conclusions for the researcher

Material
- Bulk composition
- Local composition
- Grain size
- Processing and heat treatment history

Scrap or ore selection
Melting practice
Deoxidation
Tramp or impurity elements

Thermal history
- Welding
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Stress
- Constraint
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Section thickness, inherent versus external restraint, system flexibility, weld fit-up, weld profile, alignment, etc.

EPRI advocates integrated research in materials characterization, testing, modeling, and practical fabrication processes

How much of this will be reported on a material cert?
How much of this will be documented for the end-user?
How much of this can be controlled?
Conclusions for the industry

- Variability in current component performance is not well-understood
  - For failed components, there is often insufficient documentation to support thorough root cause investigation
  - Inspection and repair strategies have generally been reactionary and not proactive/preventative
    - *We need to anticipate and/or expect challenges, especially in first-of-a-kind demonstration*

- Codes and standards will not protect the owner/operator
  - These are minimum requirements
  - Specifications are vital to reducing uncertainty in the final product or component

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Who will you go to for help? And will that entity have sufficient expertise to solve emerging challenges?
On the need for future work

- Current research is focused on specific aspects of the challenge
  - Without strong foundational knowledge and understanding of all the important variables, industry developed ‘solutions’ cannot be directly applied to other situations (materials, design, operating conditions, etc.)

- First-of-a-kind demonstrations
  - Materials support independent of project critical path working with project team can be very beneficial to addressing challenges and focusing future research

- Power generation (AUSC, sCO₂, CSP, Advanced Nuclear) and petrochemical industries share similar challenges, collaboration approaches:
  - Industry sharing of experience
  - (better) definition of potential contributing factors
  - outline future work and reduce fragmentation

Opportunity: Integration of efforts between researchers and industry with technology transfer via **Consortium Approach**
Together...Shaping the Future of Electricity