Power Generation Industry Experience

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

John Siefert, Ph.D.
John Shingledecker, Ph.D.
Tapasvi Lolla, Ph.D.
Electric Power Research Institute

DOE sCO_2 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

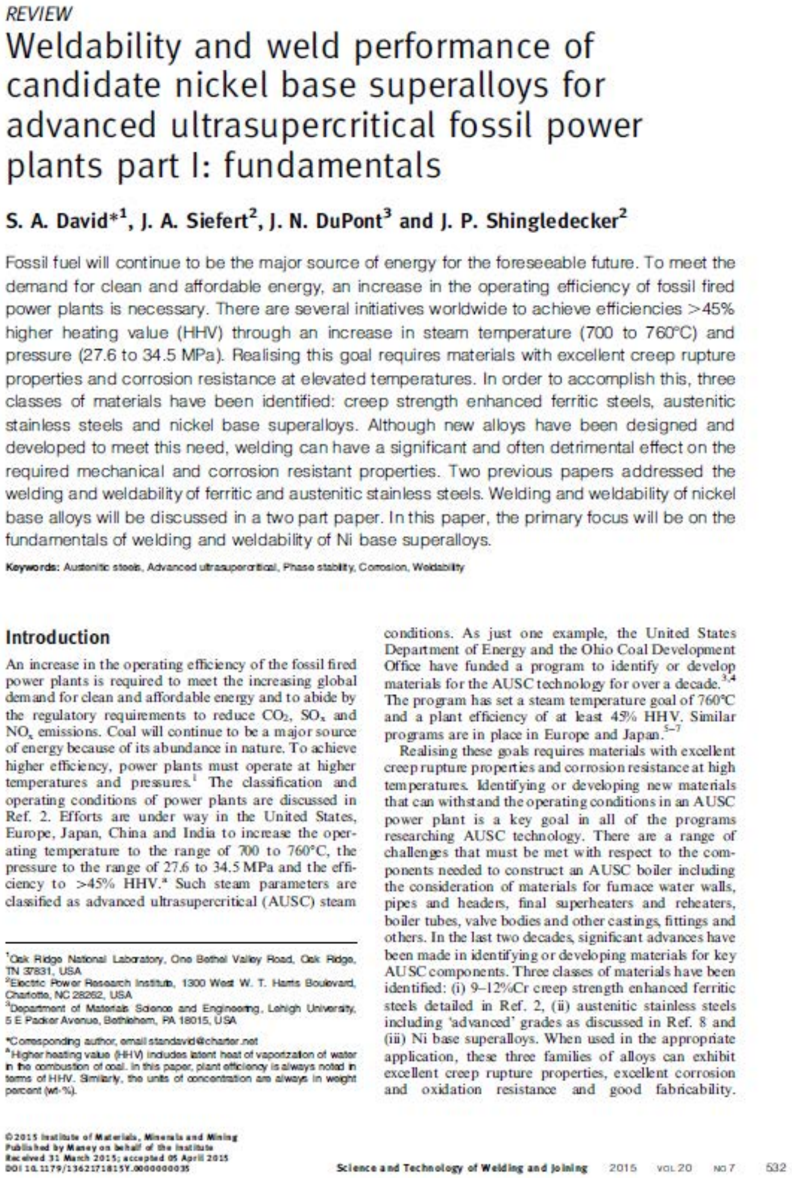
- Documented challenges in fabricating 740H (although issues do not appear to be ‘widespread’)
- Significant concerns regarding the view of Codes and Standards as ‘THE’ and not a ‘MINIMUM’ requirement
- 50+ years of research, still no widely accepted screening or robust testing methodologies to support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

Industry has done a poor job implementing lessons of the past!

Failures are not hard to find…EPRI, 2011 (1017607)

Plant	Material	Component	Mechanism
1	347H	Superheater support lug	SRxC
		Superheater tube	SIPH
2	347H	Superheater bend	SIPH
3	321H	Superheater bend	SIPH
4	304H	Superheater dutchman repair	Combination of deformed surface, high stress due to thinned wall and possible propagation of damage due to SIPH
5	304H	Superheater bend	Long-term overheat
6	347H	Reheater bend	SIPH
		Reheater support lug weld	SRxC
7	321H	Swages	SIPH
8	304H	Superheater bend	SIPH, other contributing factors possible
9	HR3C	Reheater swage	SIPH
10	347H	Swages	SIPH

Expert review from 2015…



REVIEW

Weldability and weld performance of candidate nickel base superalloys for advanced ultrasupercritical fossil power plants part I: fundamentals

S. A. David*[1], J. A. Siefert[2], J. N. DuPont[3] and J. P. Shingledecker[2]

Fossil fuel will continue to be the major source of energy for the foreseeable future. To meet the demand for clean and affordable energy, an increase in the operating efficiency of fossil fired power plants is necessary. There are several initiatives worldwide to achieve efficiencies >45% higher heating value (HHV) through an increase in steam temperature (700 to 760°C) and pressure (27.6 to 34.5 MPa). Realising this goal requires materials with excellent creep rupture properties and corrosion resistance at elevated temperatures. In order to accomplish this, three classes of materials have been identified: creep strength enhanced ferritic steels, austenitic stainless steels and nickel base superalloys. Although new alloys have been designed and developed to meet this need, welding can have a significant and often detrimental effect on the required mechanical and corrosion resistant properties. Two previous papers addressed the welding and weldability of ferritic and austenitic stainless steels. Welding and weldability of nickel base alloys will be discussed in a two part paper. In this paper, the primary focus will be on the fundamentals of welding and weldability of Ni base superalloys.

Keywords: Austenitic steels, Advanced ultrasupercritical, Phase stability, Corrosion, Weldability

Introduction

An increase in the operating efficiency of the fossil fired power plants is required to meet the increasing global demand for clean and affordable energy and to abide by the regulatory requirements to reduce CO_2, SO_x and NO_x emissions. Coal will continue to be a major source of energy because of its abundance in nature. To achieve higher efficiency, power plants must operate at higher temperatures and pressures.[1] The classification and operating conditions of power plants are discussed in Ref. 2. Efforts are under way in the United States, Europe, Japan, China and India to increase the operating temperature to the range of 700 to 760°C, the pressure to the range of 27.6 to 34.5 MPa and the efficiency to >45% HHV.[a] Such steam parameters are classified as advanced ultrasupercritical (AUSC) steam conditions. As just one example, the United States Department of Energy and the Ohio Coal Development Office have funded a program to identify or develop materials for the AUSC technology for over a decade.[3,4] The program has set a steam temperature goal of 760°C and a plant efficiency of at least 45% HHV. Similar programs are in place in Europe and Japan.[5–7]

Realising these goals requires materials with excellent creep rupture properties and corrosion resistance at high temperatures. Identifying or developing new materials that can withstand the operating conditions in an AUSC power plant is a key goal in all of the programs researching AUSC technology. There are a range of challenges that must be met with respect to the components needed to construct an AUSC boiler including the consideration of materials for furnace water walls, pipes and headers, final superheaters and reheaters, boiler tubes, valve bodies and other castings, fittings and others. In the last two decades, significant advances have been made in identifying or developing materials for key AUSC components. Three classes of materials have been identified: (i) 9–12%Cr creep strength enhanced ferritic steels detailed in Ref. 2, (ii) austenitic stainless steels including 'advanced' grades as discussed in Ref. 8 and (iii) Ni base superalloys. When used in the appropriate application, these three families of alloys can exhibit excellent creep rupture properties, excellent corrosion and oxidation resistance and good fabricability.

[1]Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN 37831, USA
[2]Electric Power Research Institute, 1300 West W. T. Harris Boulevard, Charlotte, NC 28262, USA
[3]Department of Materials Science and Engineering, Lehigh University, 5 E Packer Avenue, Bethlehem, PA 18015, USA

*Corresponding author, email standavid@charter.net

[a]Higher heating value (HHV) includes latent heat of vaporization of water in the combustion of coal. In this paper, plant efficiency is always noted in terms of HHV. Similarly, the units of concentration are always in weight percent (wt-%).

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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.

Expert review from 2018…

Age Hardenable Nickel-Based Alloy Developments and Research for New High Temperature Power Cycles

Check for updates

John P. Shingledecker and John A. Siefert

Abstract Advanced Ultrasupercritical (A-USC) steam Rankine cycles and Supercritical Carbon Dioxide (sCO_2) Brayton cycles are under intensive development to enable low carbon generation of electricity. These high-efficiency power cycles, aimed at fossil and in some cases renewable energy, require higher temperatures and pressures compared to traditional steam cycles for pressuring retaining components such as tubing, piping, heat exchangers, and turbine casings. Extensive research and development to produce and characterize age-hardenable nickel-based alloys containing Al, Ti, and Nb in judicious amounts have allowed designers to now consider supercritical fluid temperatures up to ~760 °C which is much greater than today's supercritical steam technology based on steel metallurgy up to ~610 °C. This paper will focus on the alloys developed around the world to enable these advanced power cycles, and a discussion on their key properties: long-term creep strength (100,000 h+), fabricability, and weldability/weld performance. Most of these alloys contain less than 25% gamma prime, such as alloy 740H, 263, and 282, due to the need for heavy section weldability, unique to these applications. While welding processes have now been developed for many of these alloys using a variety of filler metals and processes, key research questions remain on the applicability of processes to field power plant erection, the potential for cracking to occur during service, and the long-term weld creep and creep-fatigue performance.

Keywords Steam boilers · Steam turbines · Inconel® alloy® 740H Welding

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Age Hardenable Nickel-Based Alloy Developments & Research for New High Temperature Power Cycles

John Shingledecker, Ph.D.
co-author: **John Siefert**
Electric Power Research Institute

2018 Superalloy 718 & Derivatives: Energy Aerospace, and Industrial Applications
June 3, 2018: Pittsburg, PA USA

SUPERALLOY 718 and Derivatives | 2018 SUPERALLOY 718 & DERIVATIVES: ENERGY, AEROSPACE, AND INDUSTRIAL APPLICATIONS

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]*."*
  - 2007 ASME Boiler and Pressure Vessel Code. Section II – Materials, Part D, Appendix A. © 2007 The American Society of Mechanical Engineers.

The industry's overreliance on Codes or Standards as 'THE' requirement introduces considerable uncertainty in the final product

Contributing factors to observed cracking

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

How much of this will be reported on a material cert?

- **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

How much of this will be documented for the end-user?

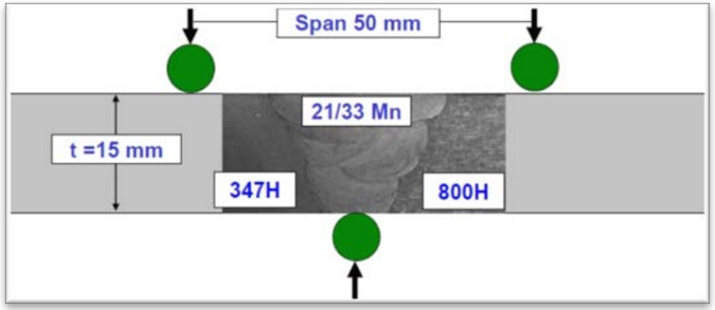
- **Stress**
  - Welding residual stress — Phase transformations
  - Deformation/working processes (e.g. cold bending)
  - Constraint — Section thickness, inherent versus external restraint, system flexibility, weld fit-up, weld profile, alignment, etc.
  - Service-induced

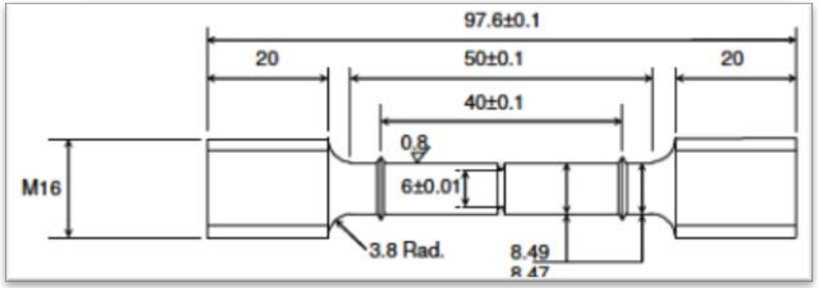
How much of this can be controlled ?

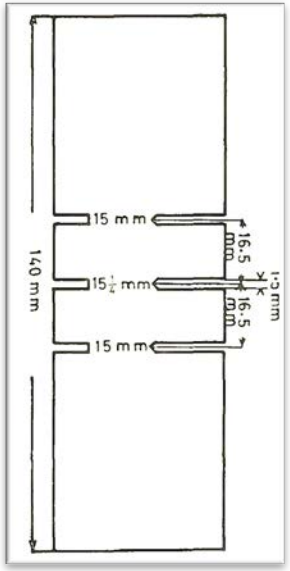
At what temperature will welding residual stress(es) begin to relax? And what is the creep ductility of the material in this regime? And what is precipitating?

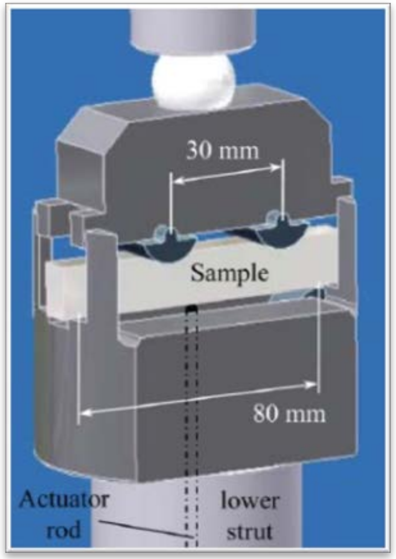
Little Consensus in Research Community

Testing Method Type	Lab/ Author/ Researcher and Year
Weld mock-up tests to simulate weld residual stress	J. C. Borland, 1960 (Borland test) R. J. Dennis, 2008 (Ring weld method)
C- Ring Test	C. D. Lundin, 1990
Fracture mechanics, CTOD tests	R. J. Christoffel, 1962 K. Purazrang, 1976
Gleeble based test methods	L. Li, 2000 (RPI - Notched test specimen) J. Dupont, 2003 (Lehigh - Notched test specimen) J. E. Ramirez, 2005 (OSU - Notched test specimen) R. Kant, 2019 (Lehigh - Notched test specimen)
Tensile test	A. Dhooge, 2004 (BWI - slow strain rate tensile)
Three-point bend testing	Van Wortel, 2007 *(**TNO** Industrie)*
Notched bar creep testing	M. Spindler, 2009 (Électricité de France)
Four-point bend testing	B. Kuhn, 2013 *(Jüelich Research Center)* A. Shyam (ORNL), J. Shingledecker (EPRI), 2014
Lever-arm loading	E. S. Robitz, 2001 (B&W test method)









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

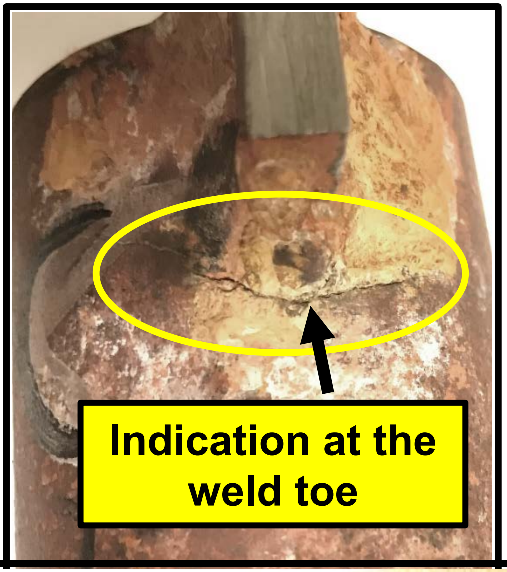
An Illustration of the General Challenges

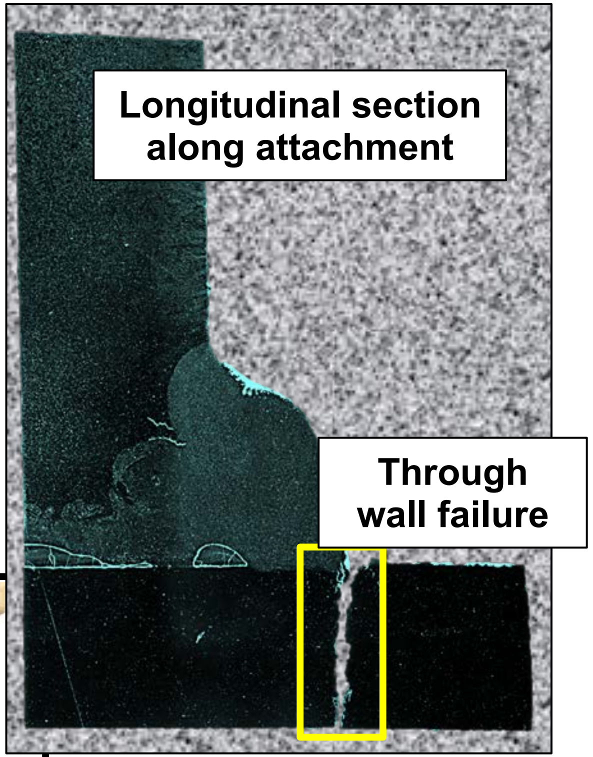
- Failures measured in the tens to hundreds of thousands
- Susceptibility
  - "Global", as assessed across the stainless steel family
  - "Local", as assessed on a heat-to-heat basis for a single grade
  - "Micro", as individual locations (i.e., weldments, attachments, bends)
  - "Nano", electron-microscopy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

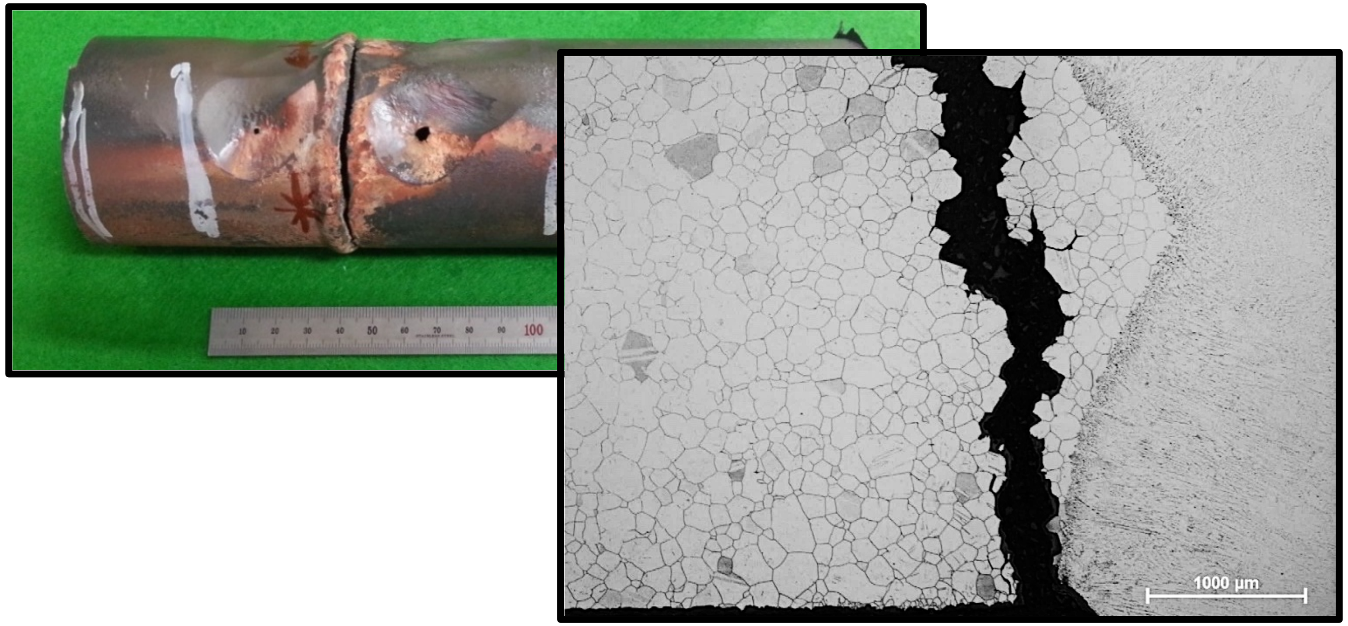
The first step to prevention and informed research studies is to fully understand and appreciate the failure mechanism

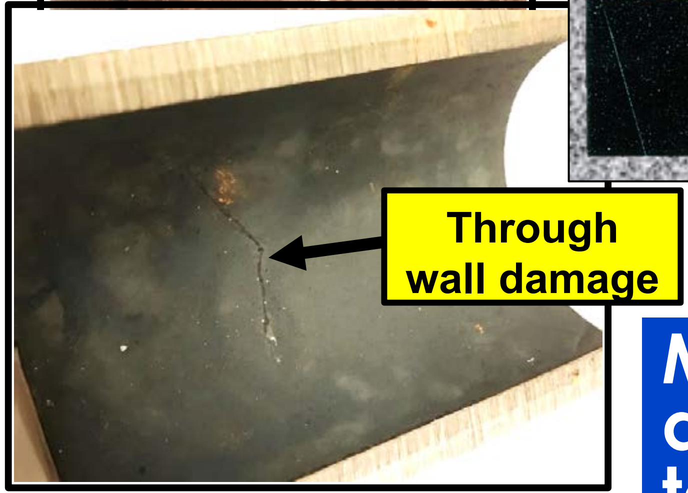
Case Studies: Stainless Steel

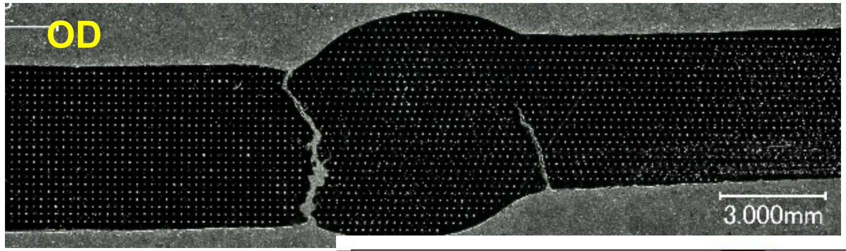
Failures in Stainless Steels



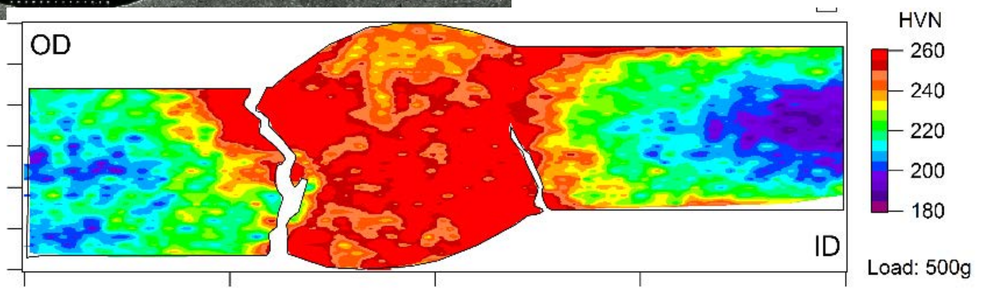








Many instances of attachment and tube-to-tube failures



[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

Conv. SS Grade	C	Mn	P	S	Si	Cr	Ni	Mo	Nb	Ti
TP304	■	■	■	■	■	■	■			
TP316	■	■	■	■	■	■	■	■		
TP321	■	■	■	■	■	■	■			■
TP347	■	■	■	■	■	■	■		■	

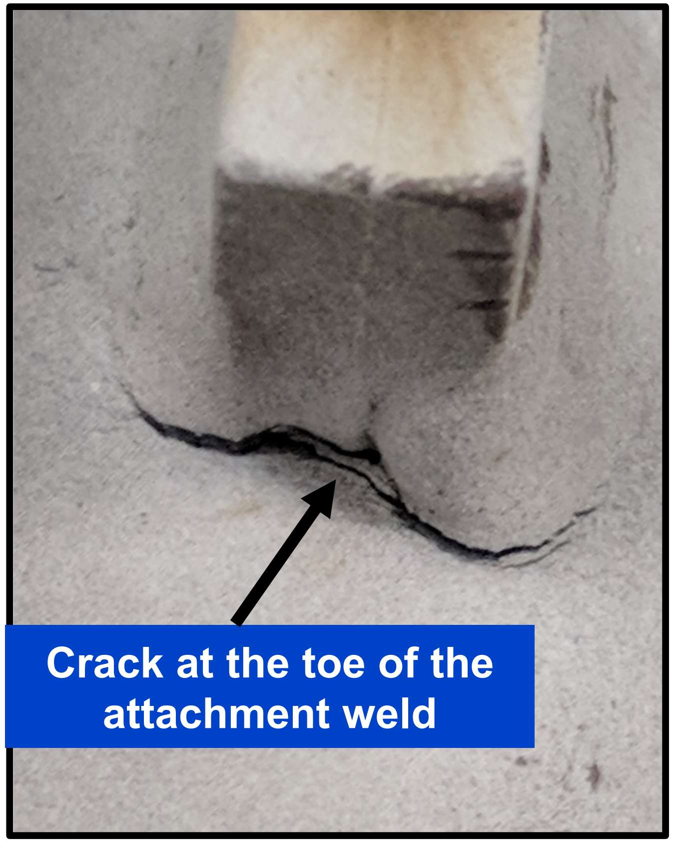
Advanced alloys are more complex, and may include additional processing or heat treatment steps. There is substantial evidence that the current conventional grade composition does not control sufficient elements.

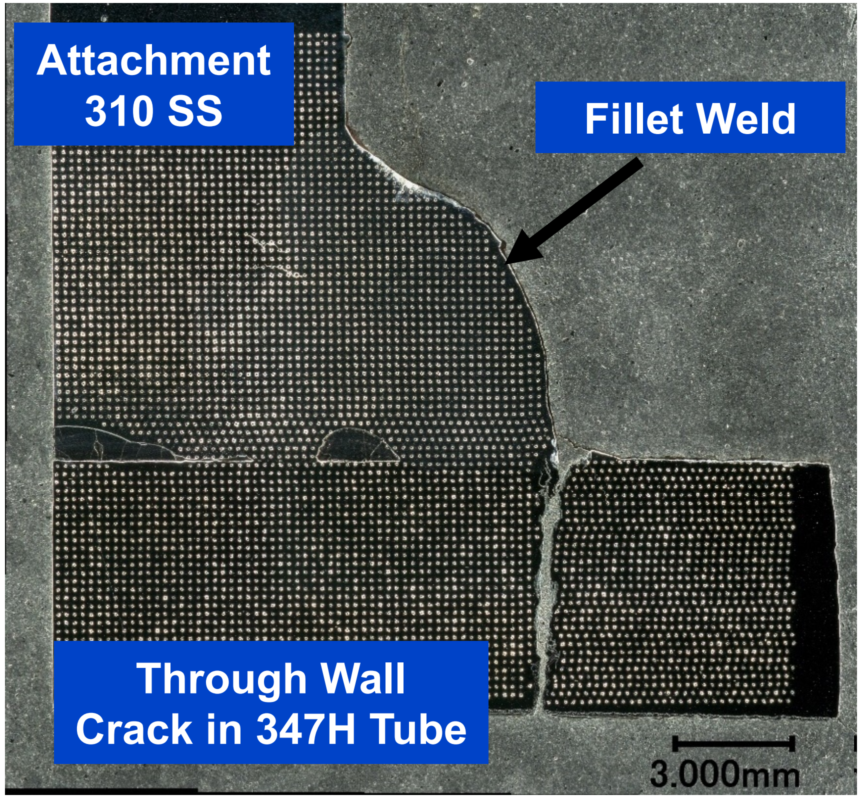
Adv. SS Grade	C	Mn	P	S	Si	Cr	Ni	Mo	Nb	Ti	V	N	B	Co	Cu	W	Al
HR3C	■	■	■	■	■	■	■		■		■	■					
347HFG	■	■	■	■	■	■	■		■								
SUPER304H	■	■	■	■	■	■	■		■			■	■		■		■
SANICRO® 25	■	■	■	■	■	■	■		■			■		■	■	■	
Tempaloy AA-1	■	■	■	■	■	■	■		■				■		■		
Tempaloy A-3	■	■	■	■	■	■	■		■			■	■				
XA704	■	■	■	■	■	■	■	■	■	■		■	■				
NF709	■	■	■	■	■	■	■		■		■	■				■	

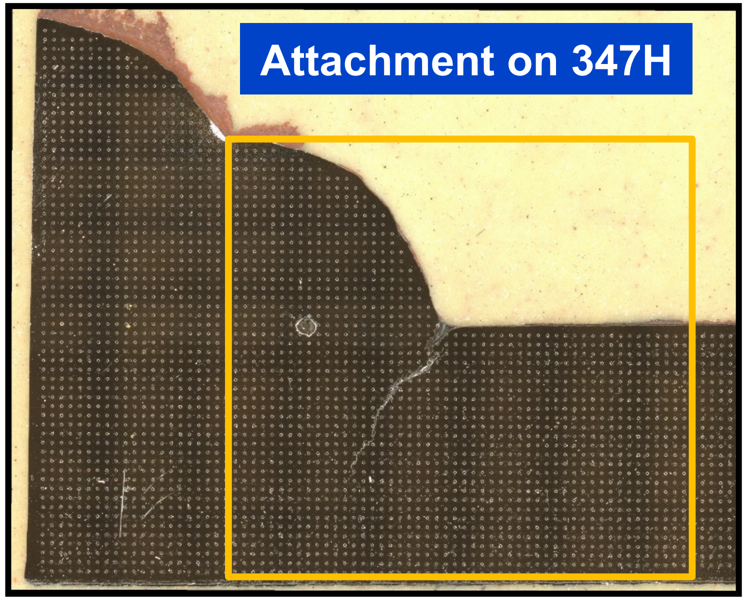
Up to 7 more elements

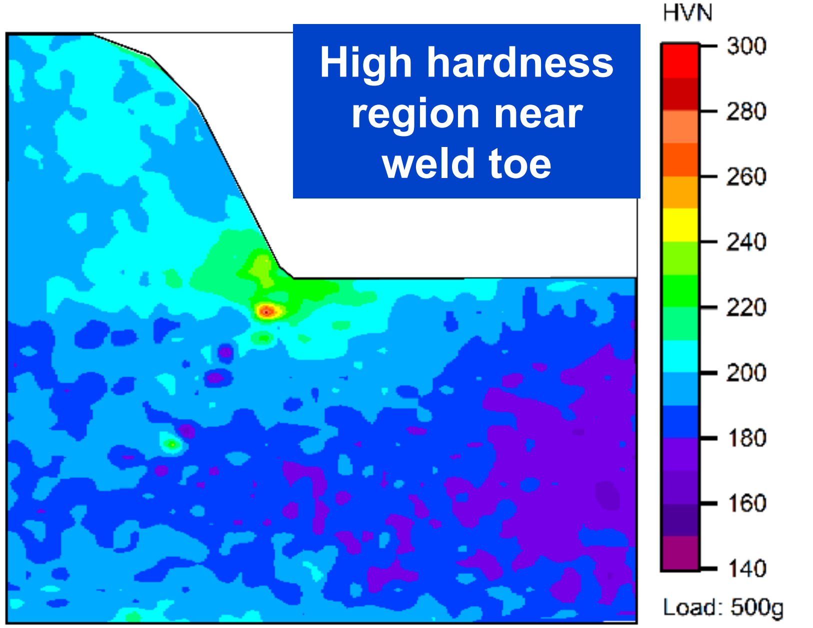
Case Study: Failures At SH/ RH Tube Attachment Welds

- Multiple utilities have reported cracking issues at attachment welds on 347H SH/ RH tubes
- Cracks appear at toe of fillet weld, in the HAZ

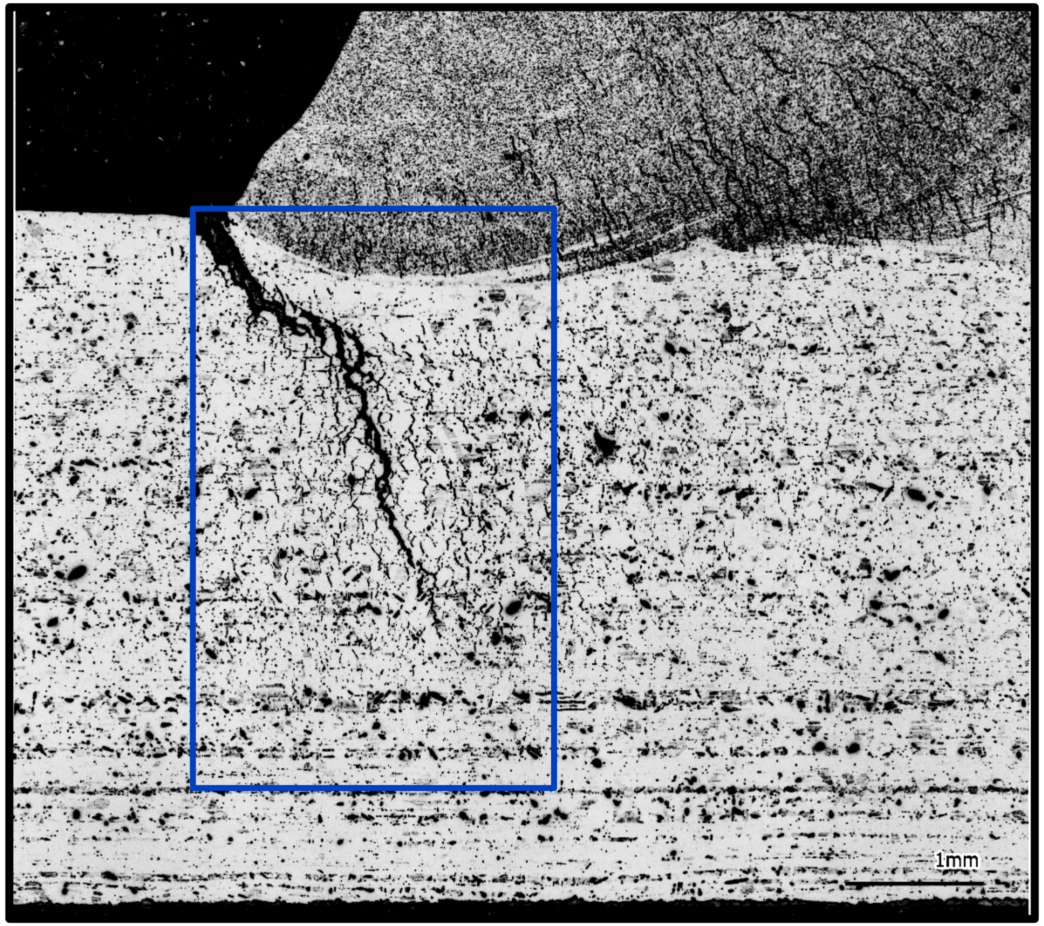


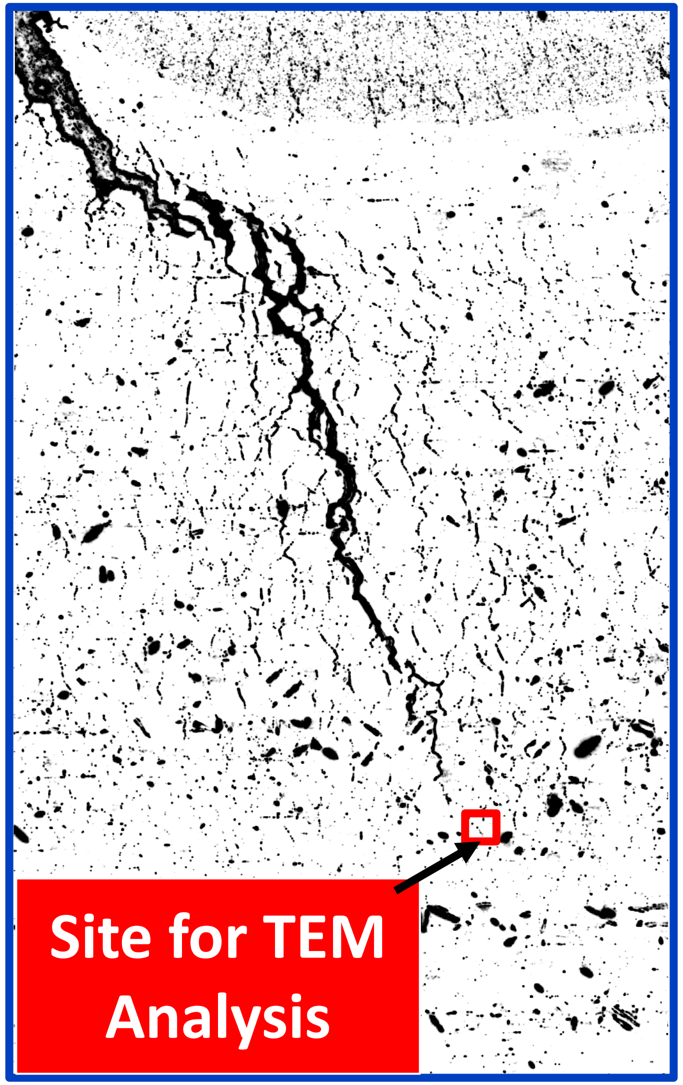




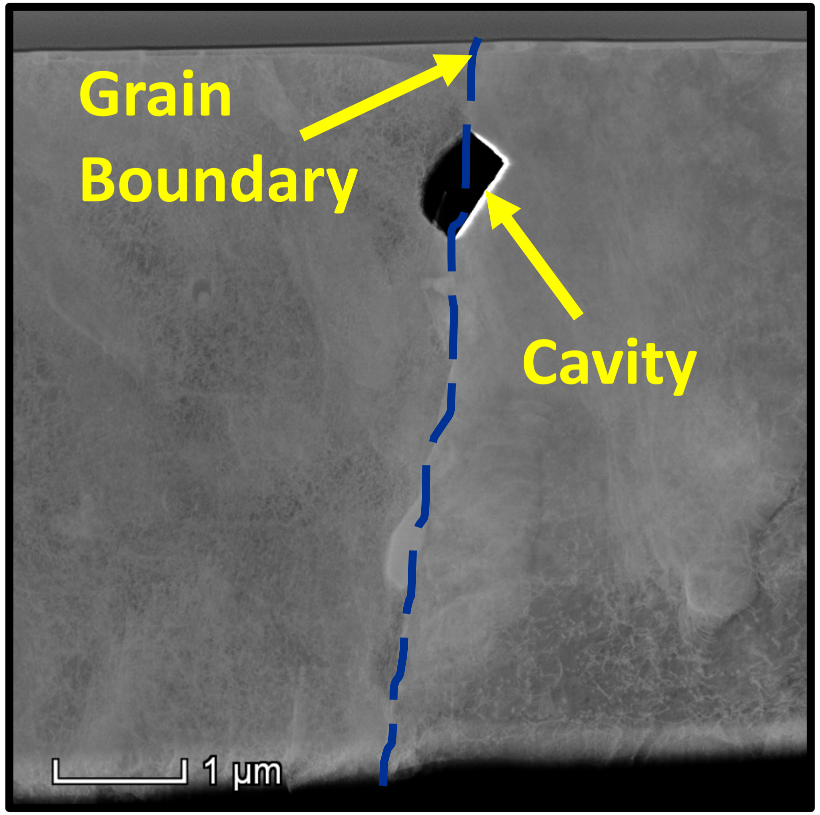


Case Study: Analysis of Cracking at Attachment Welds



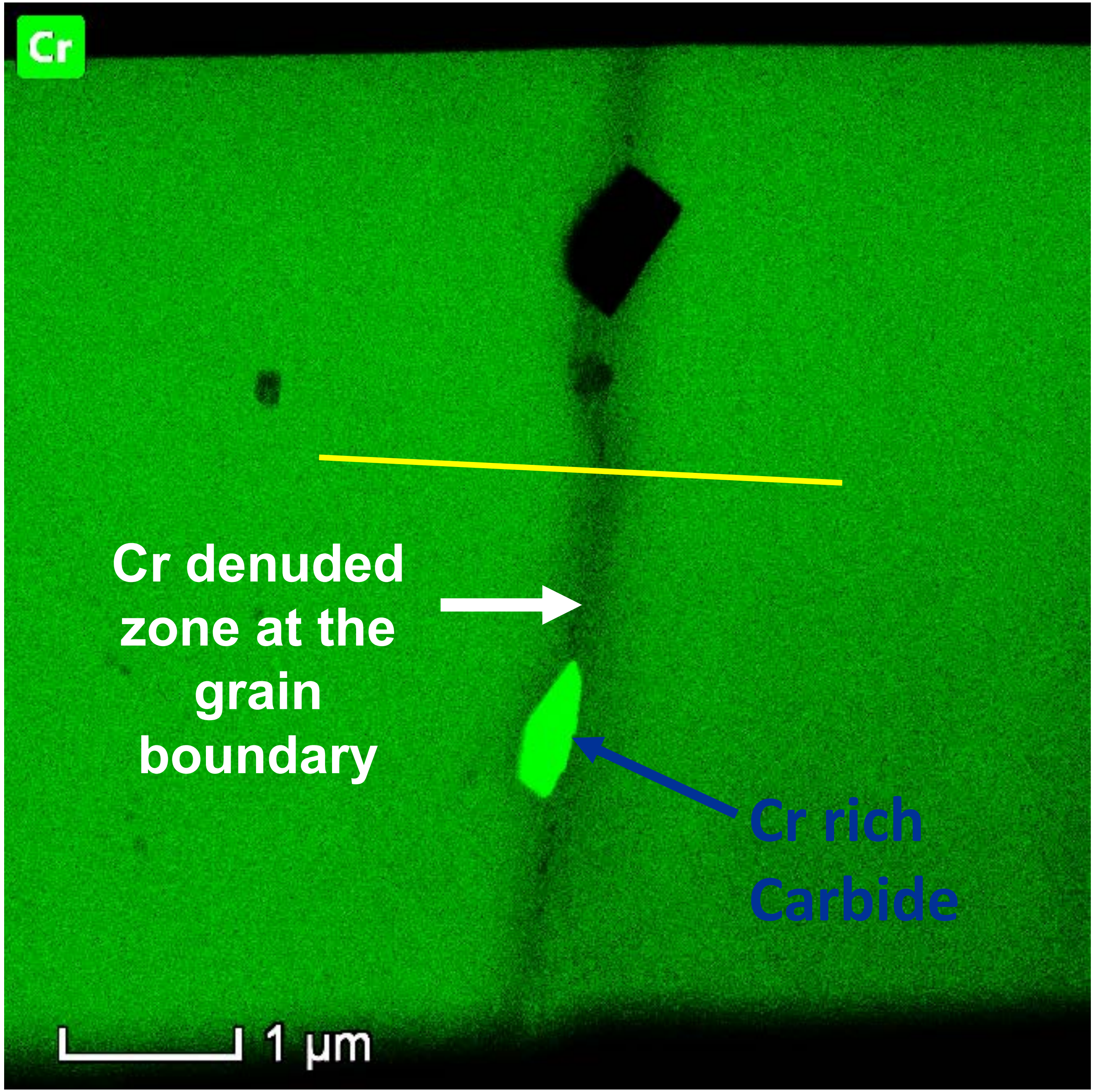


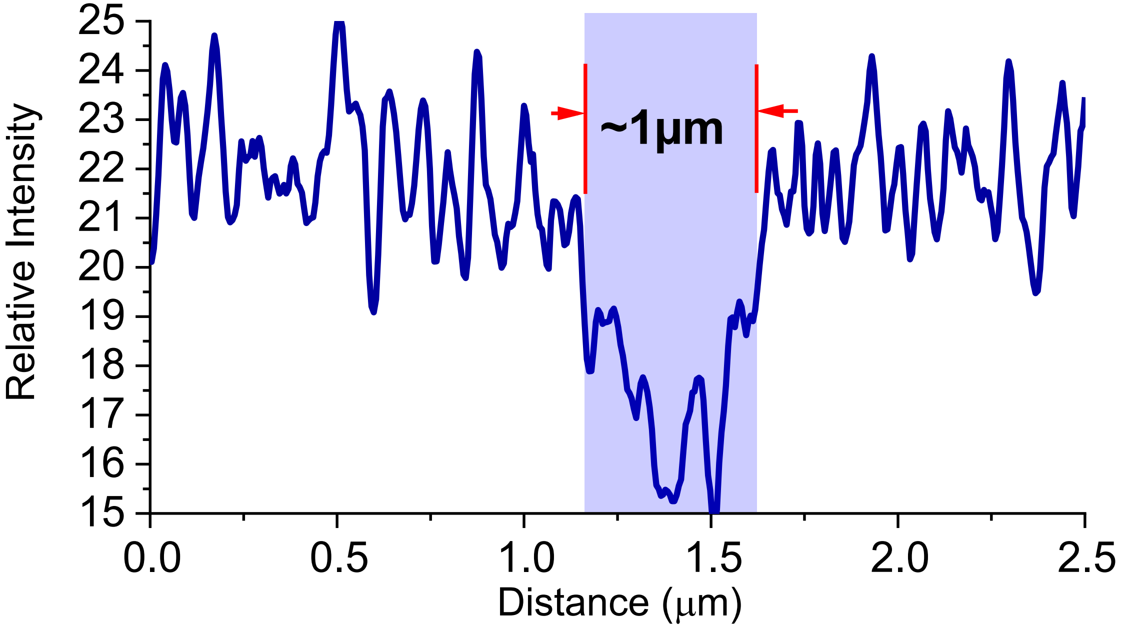
TEM sample taken from ahead of crack tip showing a creep cavity at grain boundary



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

Case Study: STEM-EDS Cr Distribution Map





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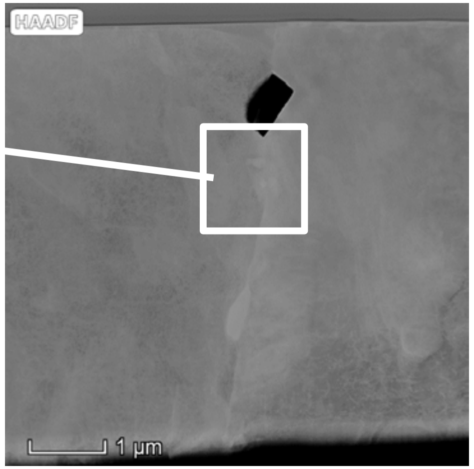
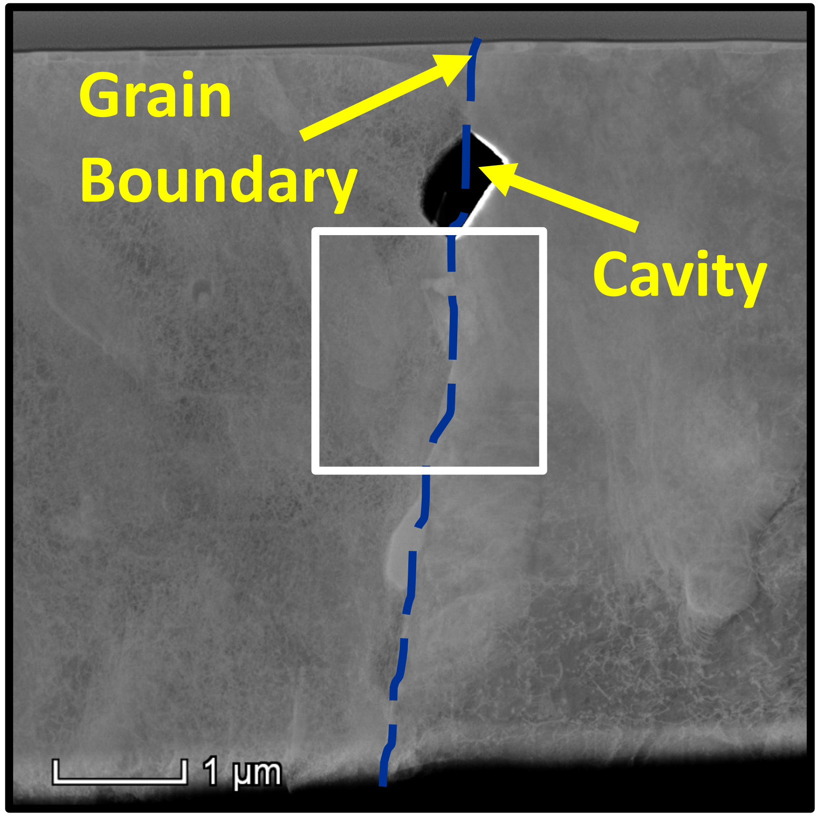
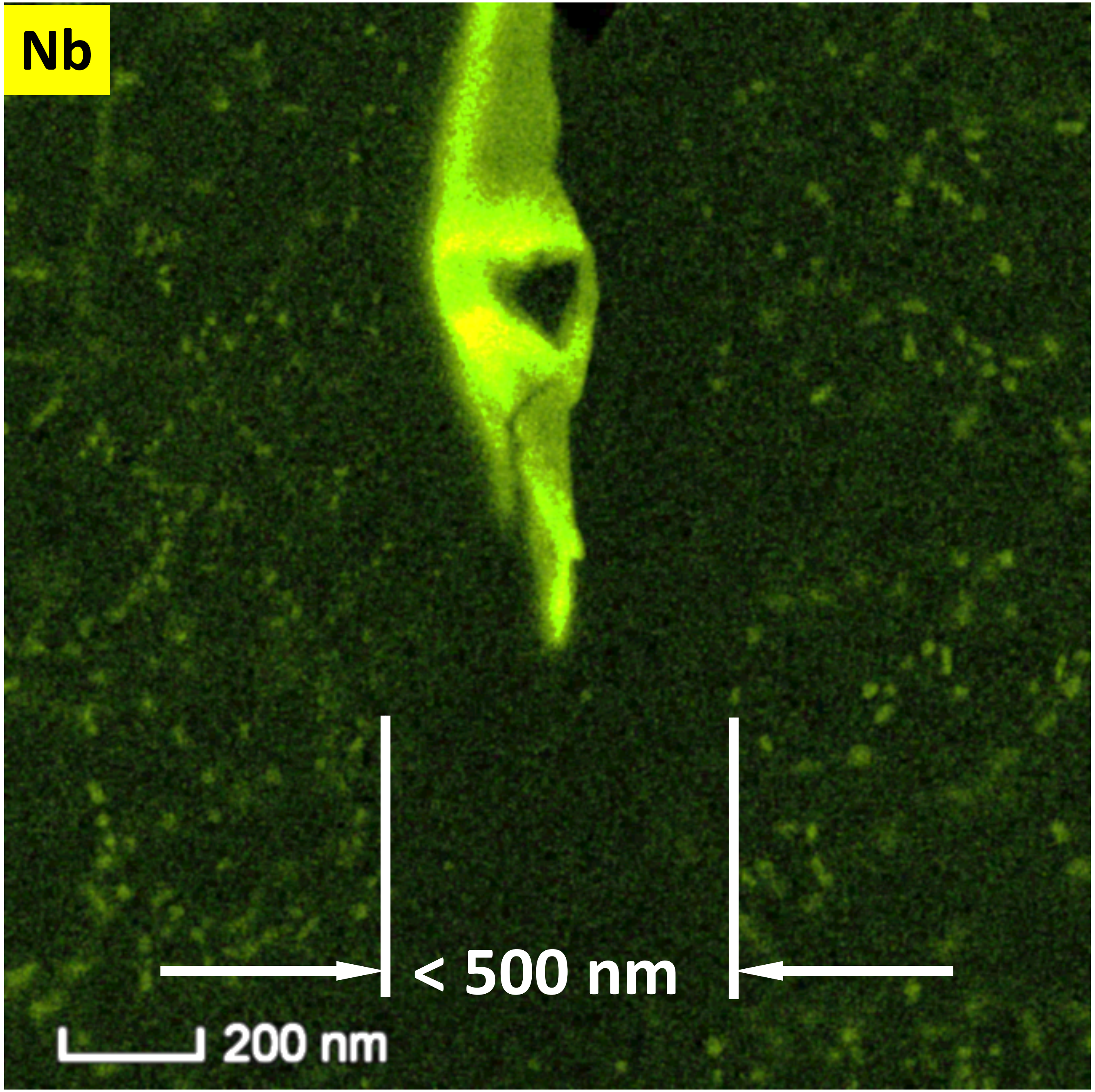


Case Study: STEM-EDS Nb Distribution map at GB



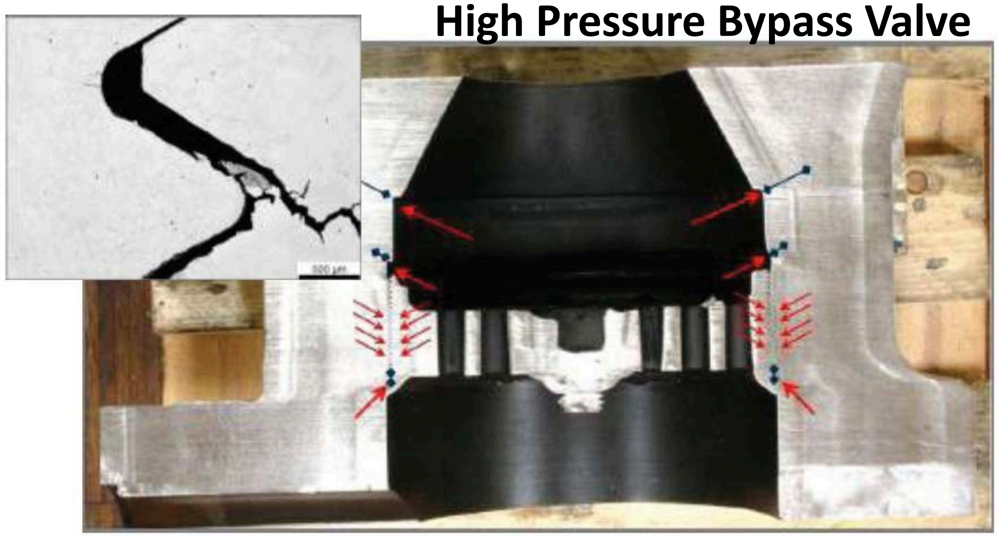


Very fine (~20 nm) Nb-rich precipitates forming within grains and a narrow PFZ at the grain boundary

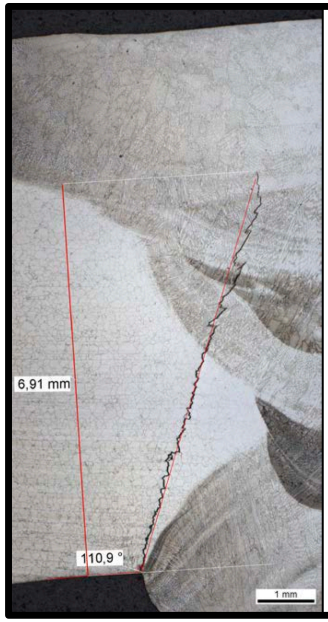
Case Studies: Nickel-base alloys

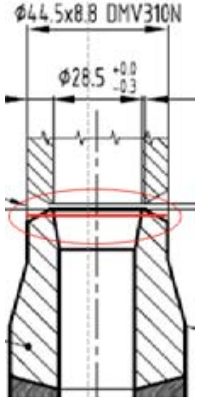
In-Service SRxC in Alloy 617

High Pressure Bypass Valve



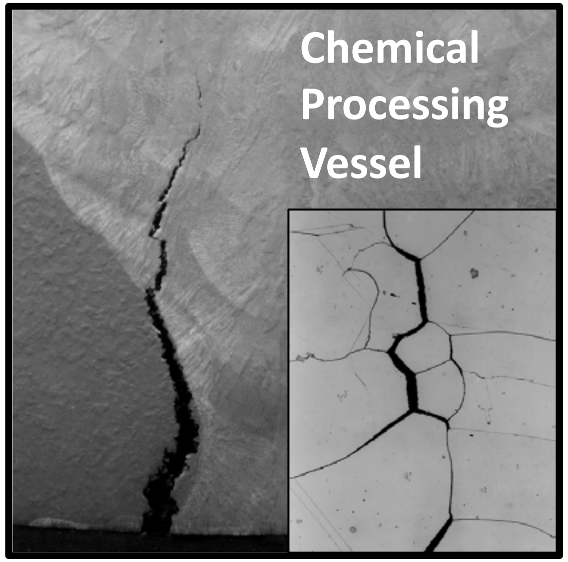
Supercritical Coal Boiler Tube Weldment



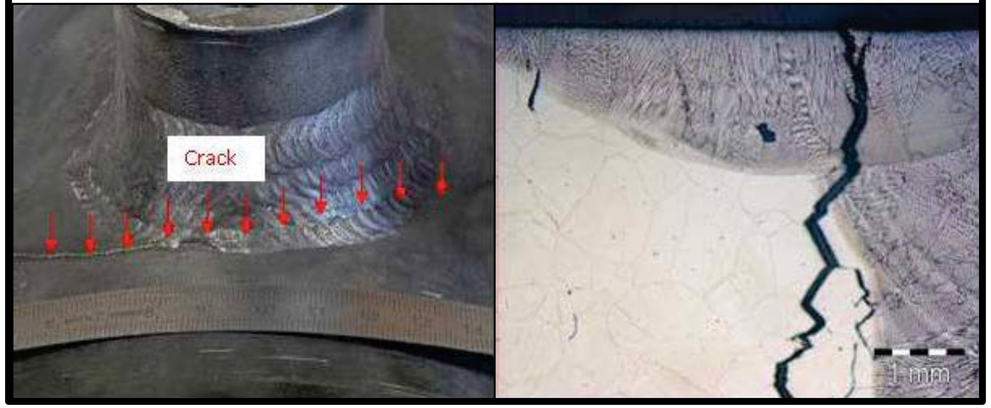


Steam Attemperator

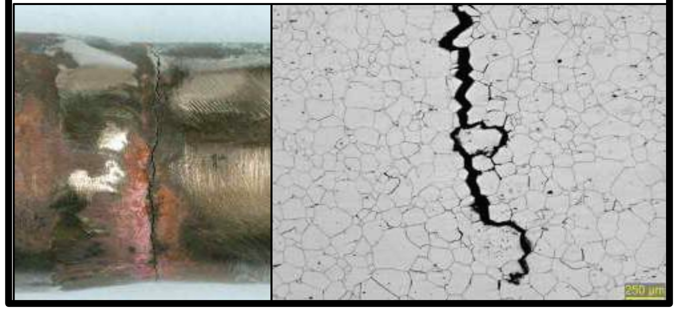
Chemical Processing Vessel



Thick-wall steam piping crack



Superheater Tube Weldment



[1] "Component test facility for a 700C power plant (Comtes700)." Final Report, 2013. EUR 25921 EN © European Union 2013.
[2] Hans van Wortel. "Application of Alloy 617 in the Chemical Process Industry." TNO Science and Industry, Presentation to ASME.
[3] Hans van Wortel. "Control of relaxation cracking in austenitic high temperature components". Presentation, VeMet conference, March 17, 2009, Marknesse, the Netherlands.
[4] Simon Heckmann, Anne Woestmann, Ken Mitchell. "Recent Damage Evaluations on Austenitic Boiler Tubes associated with Supercritical Plant." Presentation to EPRI – Program 87 Technology Transfer, Seattle, WA USA, June 18-19, 2018.

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*

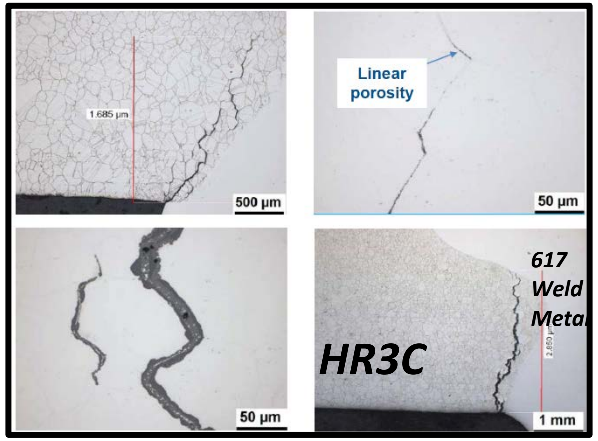
"Component test facility for a 700C power plant (Comtes700)." Final Report, 2013. EUR 25921 EN © European Union 2013.
C. Stolzenberger, COMTES700 Scholven. "VGB-Workshop "Material and Quality Assurance", May 13-15, 2009.

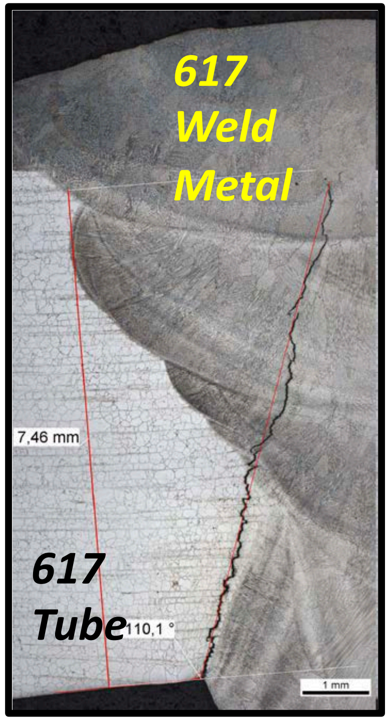
Component	Time	Description of damage
High-pressure bypass valve	22,000 hrs	Cracking found propogating from thread roots during inspection after service
Superheater transition piece	<10,000 hrs	Relaxation crack in cold deformed and welded region of tube
Spray attemperators	<10,000 hrs	Multiple cracks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

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"*

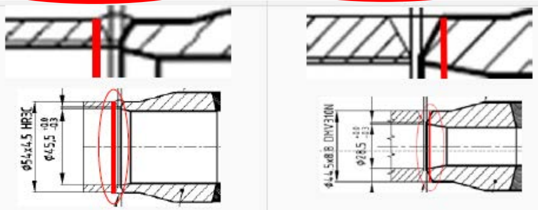
In-Service SRxC – Coal-fired 617 DMW experience

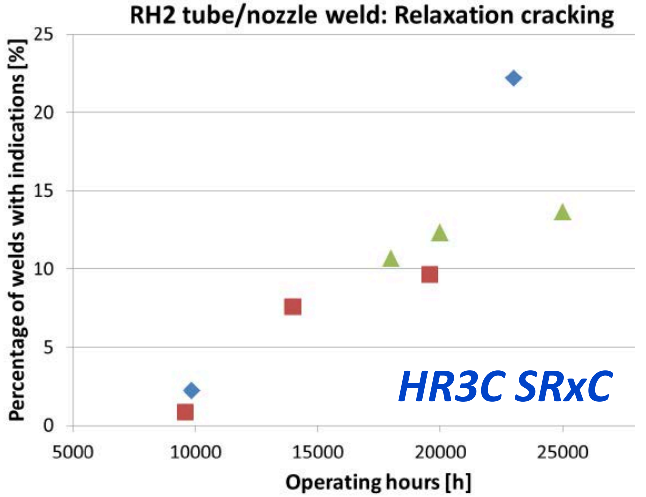
- Superheater and reheater sections, configuration:
  - HR3C (austenitic stainless steel) to alloy 617 transition piece (617 filler metal) to T92 steel
- SRxC observed in BOTH alloys after ~10,000hrs in service (steam temperature ~580-620°C)
  - ‘Leaks’ and ‘bursts’
  - Specialist field inspection techniques developed
  - Considered “Thin-section welds”
- **Challenges for repair procedure development**
  - Best heating method to minimize variability in field application (up to 980ºC)
  - Potential for alternative ‘lower strength’ filler metal
  - Concerns for sensitization in stainless steel
    - SCC failures have also been observed
  - T92 cannot exceed 800ºC; target = 720ºC





Relaxation cracking	
Austenitic tube/nozzle welds	Nickel-base tube/nozzle welds
HR3C	Alloy 617
Fusion line/HAZ	Fusion line/HAZ
RH2 (950 tubes)	SH4 (798 tubes)



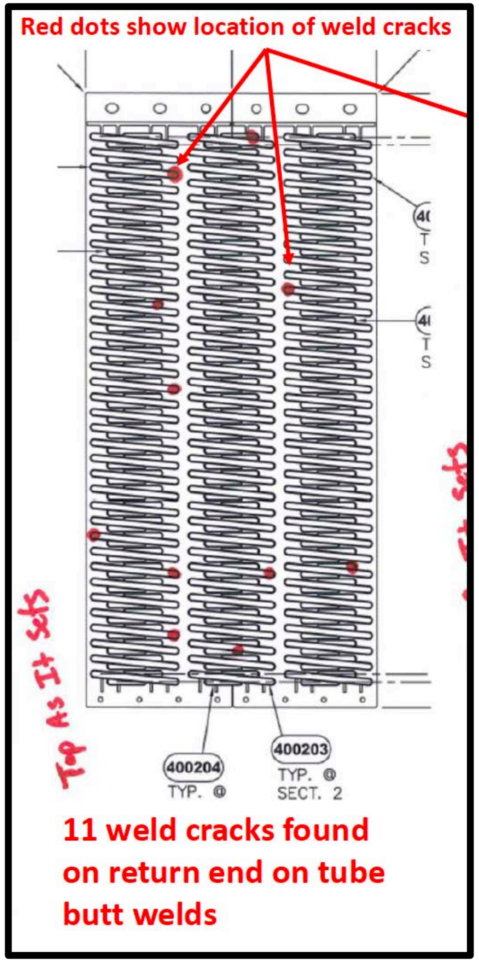


Simon Heckmann, Anne Woestmann, Ken Mitchell. “Recent Damage Evaluations on Austenitic Boiler Tubes associated with Supercritical Plant.” Presentation to EPRI – Program 87 Technology Transfer, Seattle, WA USA, June 18-19, 2018.

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)

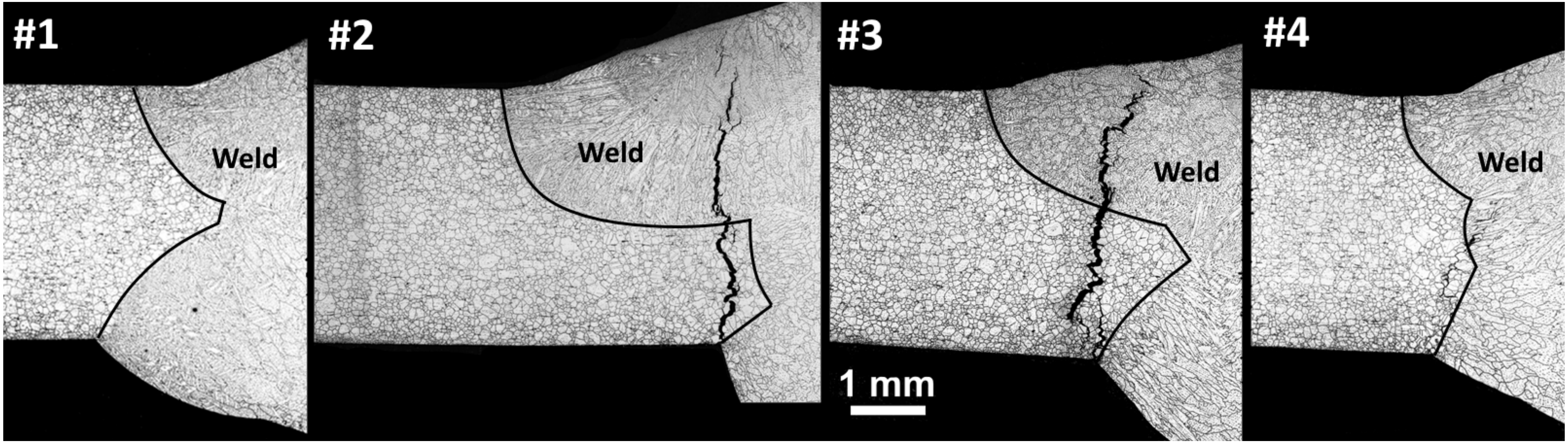


First large-scale application of 740H welding (>1,600 welds) including a range of weld geometries and thicknesses

Heat-Treatment (Fabrication) SRxC: 740H

Crack Propagation around the tube circumference

Outside diameter

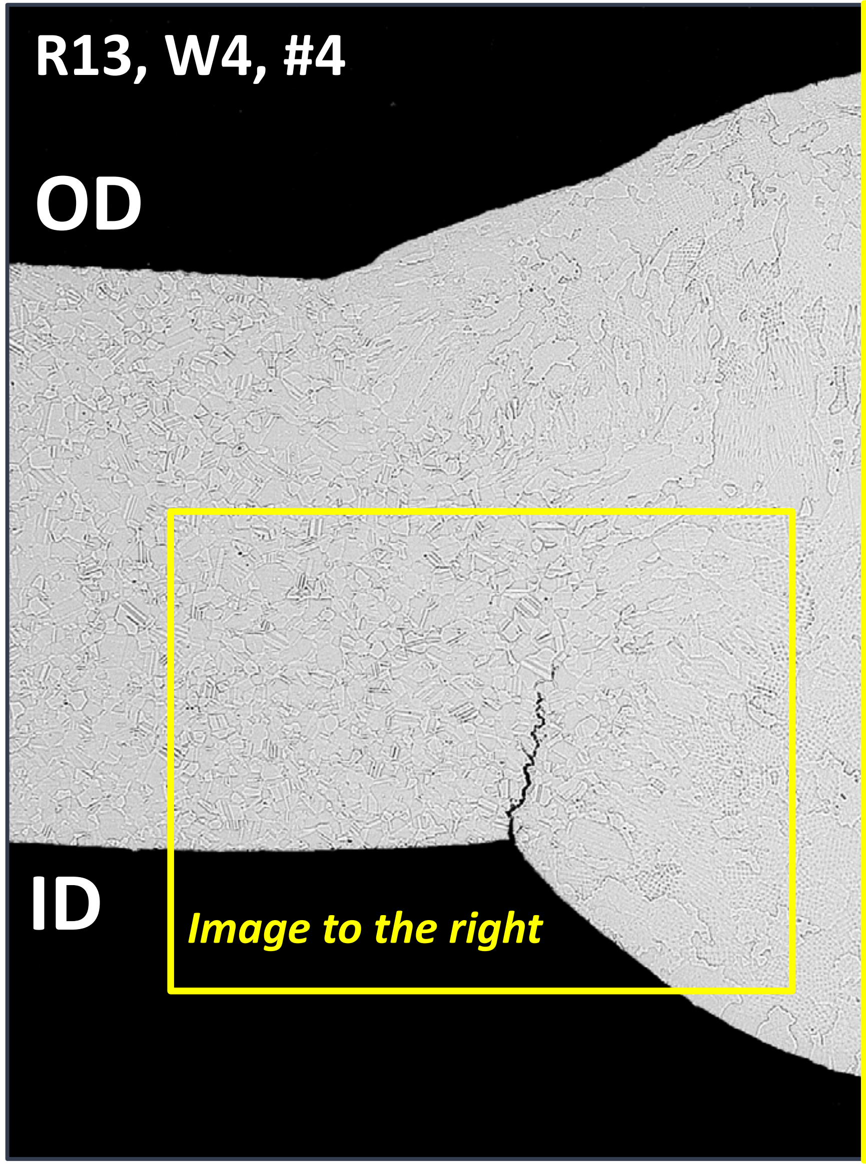


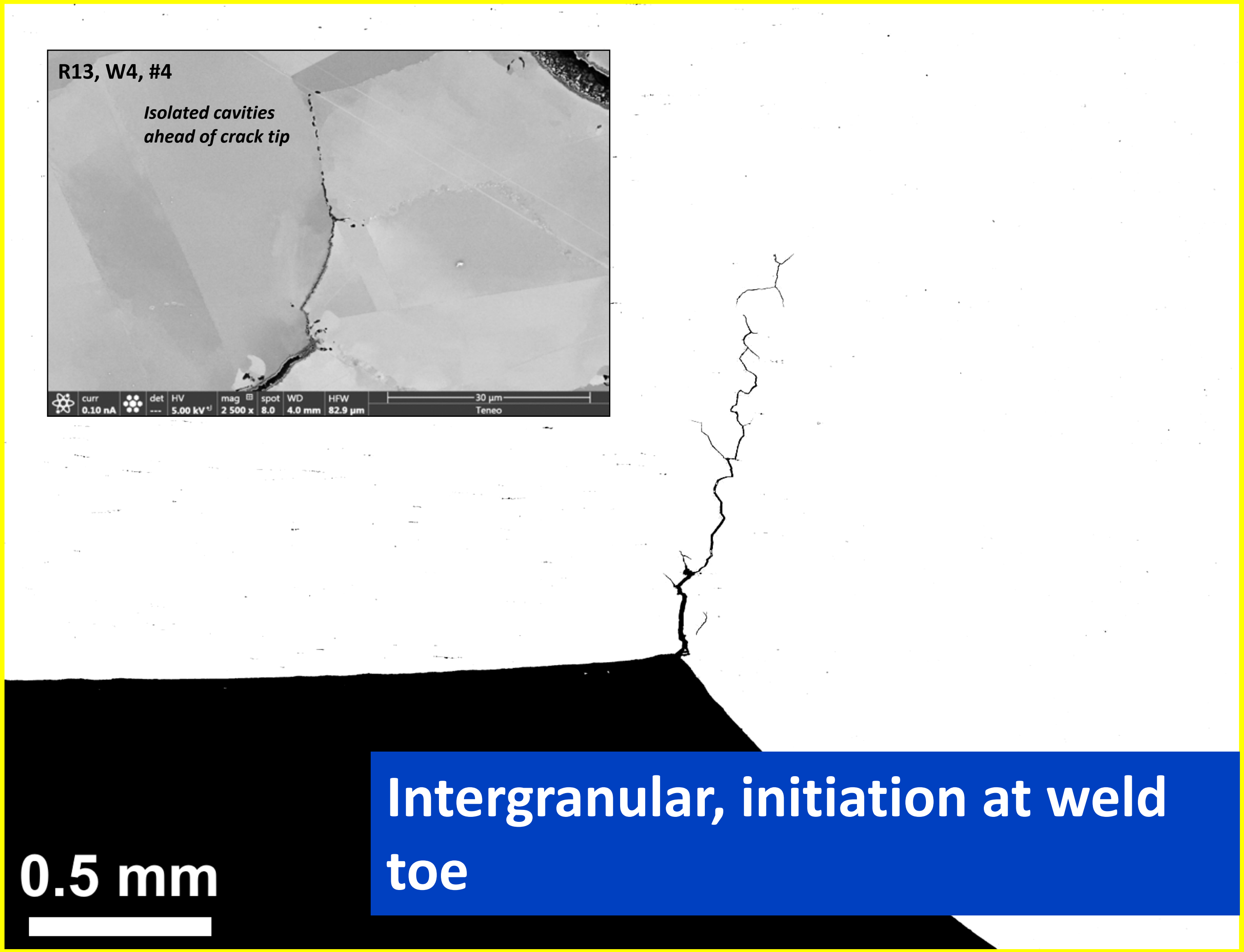
Inside diameter

#1	#2–#3	#4
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

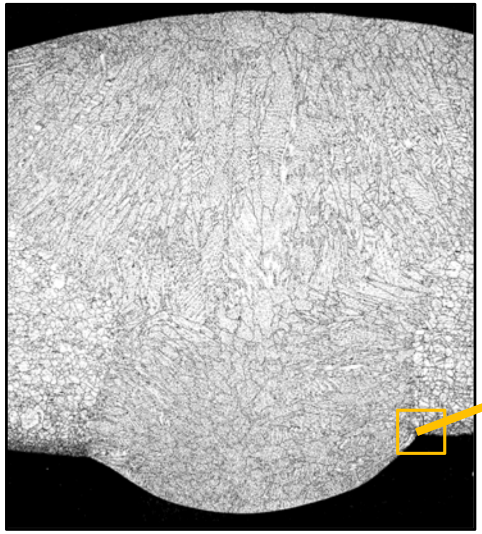
Heat-Treatment (Fabrication) SRxC: 740H - Morphology



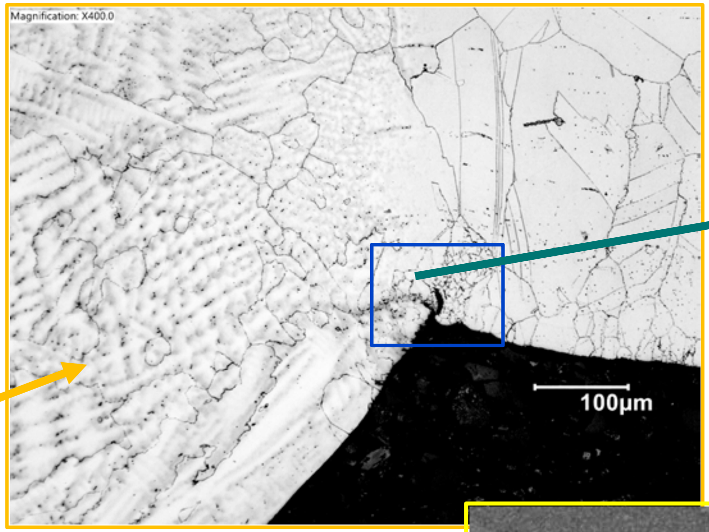


Intergranular, initiation at weld toe

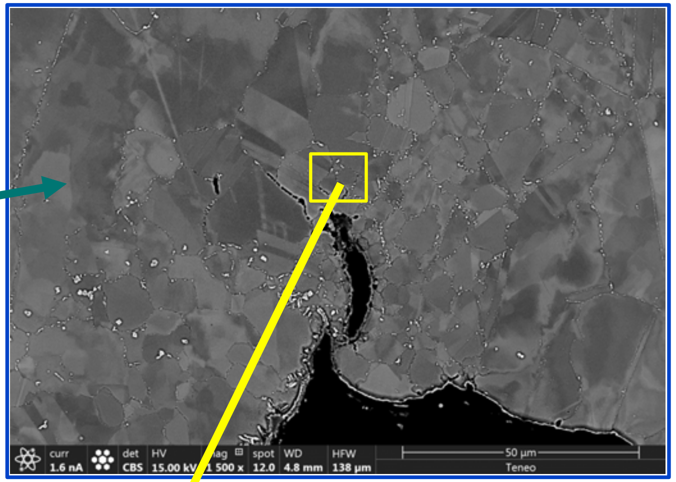
Heat-Treatment (Fabrication) SRxC: 740H - Morphology



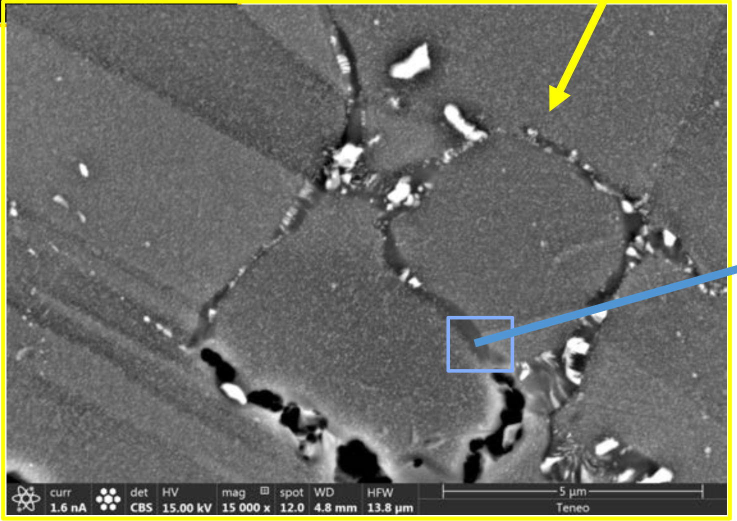
Macro (optical)

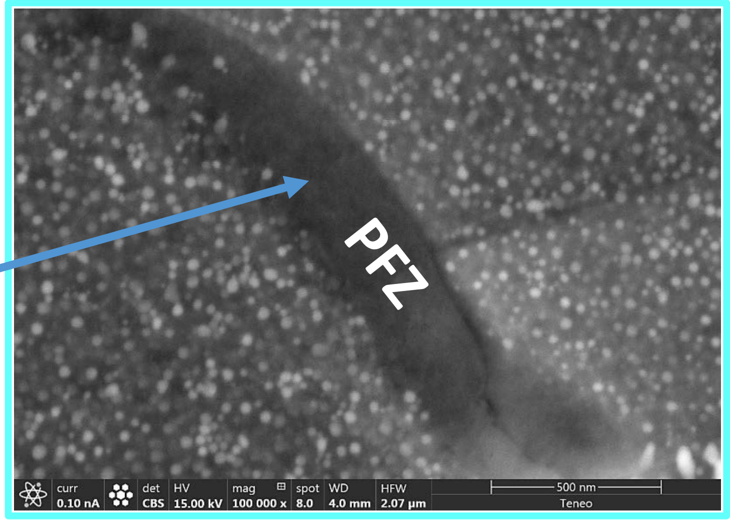


Micro (optical)



Micro (SEM)

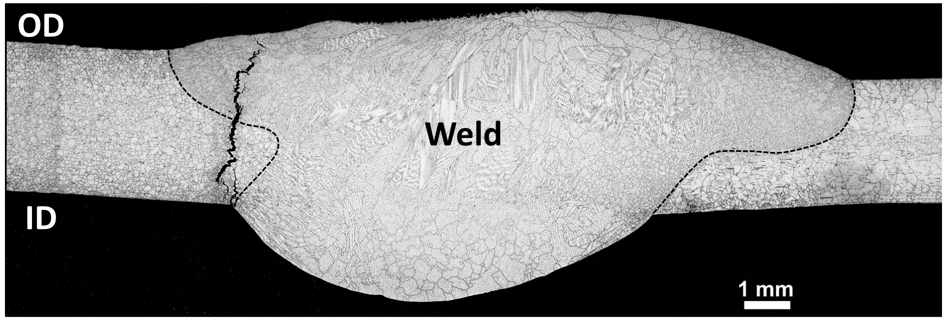




Precipitate Free Zones (PFZs) identified at grain boundaries in limited HAZ/FL areas

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)

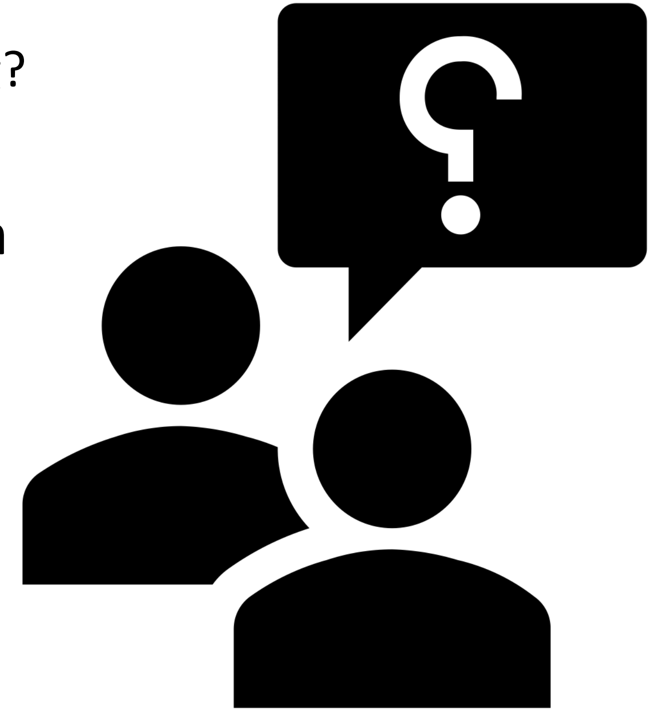


Opportunity to utilize data and leverage with future additional research to develop specs which go 'beyond code' for future 740H tube fabrication

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

How much of this will be reported on a material cert?

- **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

How much of this will be documented for the end-user?

- **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

How much of this can be controlled ?

No single research project can address all the potential variables

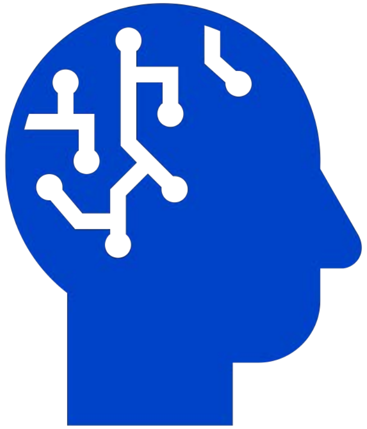
EPRI advocates integrated research in materials characterization, testing, modeling, and practical fabrication processes

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

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, sCO_2, 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