Investigation of Weldment Cracking During Fabrication of a 700°C Fired sCO_2 Heater

Paper #170

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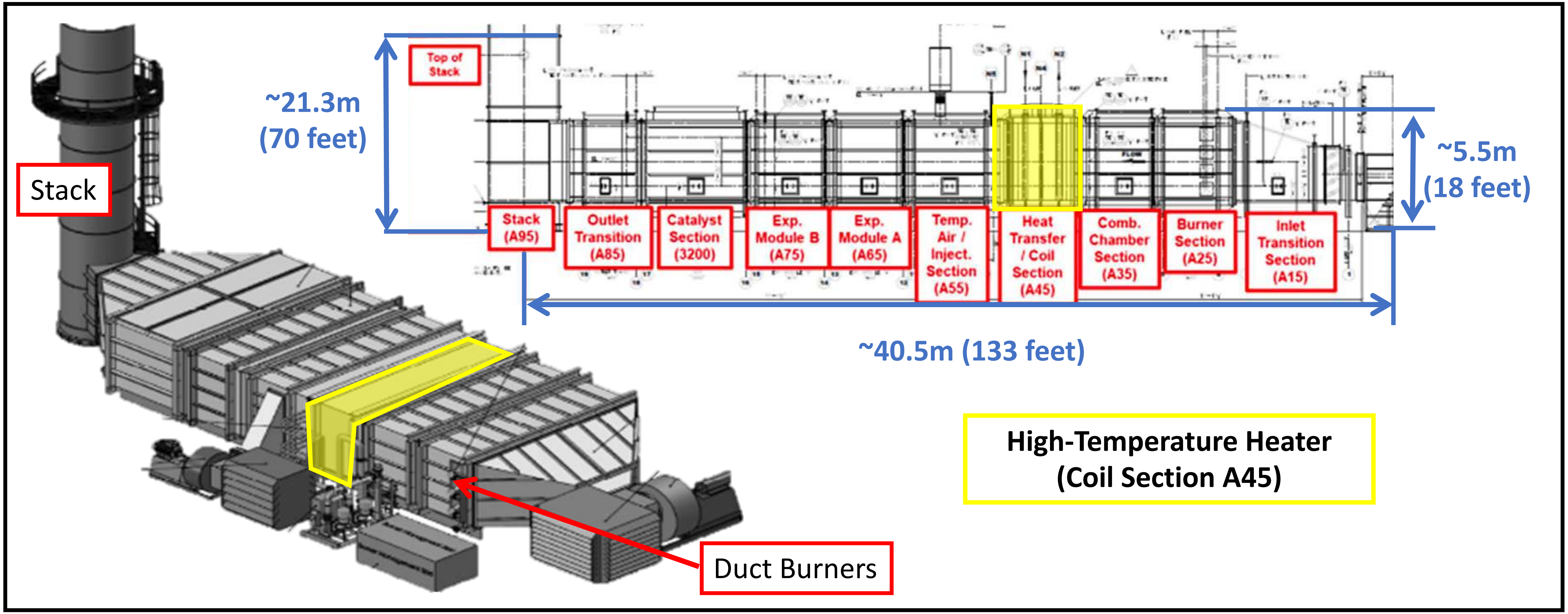
STEP Fired Heater Design

- Component Design Conditions:
  - 50MW$_{th}$ natural gas fired heater
  - ASME Section I & applicable state and local emission requirements

Cycle Configuration	Qin [MW]	Pnet [MWe]	NOx [lbs/hr]	Heater Inlet [bar]	Heater Inlet [°C]	Heater Outlet [bar]	Heater Outlet [°C]	Heater Outlet [kg/s]
100% Simple	21.30	6.50	0.910	212.0	319	208.0	500	95.7
40% Simple	13.47	3.58	0.510	173.6	355	171.0	500	76.2
100% RCBC	22.54	10.30	1.440*	254.1	542	**250.3**	**715**	103.1
40% RCBC	10.21	4.03	0.056	172.9	593	170.3	**715**	66.9
500C RCBC	21.15	7.59	1.063	254.1	355	250.3	500	116.6

- Optimus Industries selected by STEP project team to design and fabricate the heater
  - 30yrs experience in boiler & pressure part design
  - >170 combined cycle HRSGS (>1700 pressure parts)
  - Experience in welding and fabrication of range of materials and alloys

STEP Heater Design



Design approach similar to Heat Recovery Steam Generator (HRSG) but high-temperature coil exceeds state-of-the-art HRSGs by ~100°C

STEP Heater Coil Design

- 4000-psig (275.8 barg) / 1,125°F – 1,375°F (607.2°C – 746.1°C)
- High-Temperature Module
  - Inconel ® Alloy 740H® (740H)
    - 1.5” (38.1mm) OD tubes w/ spiral wound, 304SS & 409SS welded fins
    - 4.5”, 8.625”, 11.25” (114, 219, and 286 mm) OD Pipe headers w/ Grayloc (clamp style) connections to supply/return piping
    - Headers, end plates, tubes, & flanges Floating coil design to minimize thermal expansion stress in tubes and headers
  - Cast tubesheets (Nickel-Chrome alloy) support coil at even intervals, allow tubes to freely slide through supports
  - Welded fin parameters (height, pitch, style (solid vs. serrated) & material) used to control tube metal temperature at various sections through the coil:
  - Optimus / Special Metals developed and tested continuous fin welding procedures to ensure effective bonding of stainless fin strip to 740H tube.

~25,000 kg (55,000 lbs) of 740H including ~6,100 m (~20,000 feet) of tubing

740H Fabrication Considerations

Built to Code Case 2702-3

- Welding was conducted only on solution annealed (SA) + aged material
  - Most materials procured were in the SA + aged condition so they could be directly welded including the finned tubing
  - Tubes to be used for cold-bending operations were procured in the SA condition to reduce bending loads
    - For cold-forming strains exceeding 5%, a SA + age must be performed on the entire part. Therefore, tube bending was performed on short tube lengths of SA tubes and then given a SA + aging heat-treatment before being welded into the assembly (see Figure 2a)
  - Header pipes were delivered in the SA condition to permit ease of manufacturing (e.g., cutting operations such as bore hole penetrations)
- All welds required an aging post-weld heat-treatment (PWHT) which could be performed locally or on the entire component
  - It was decided to weld the entire coil first, place it in a frame, and perform the PWHT of the entire assembly
  - Later, weld repairs were performed locally with ceramic heating pad blankets as is typically used in field PWHT

Note: welding now permitted in the SA condition per current Code Case

740H Welding Procedures

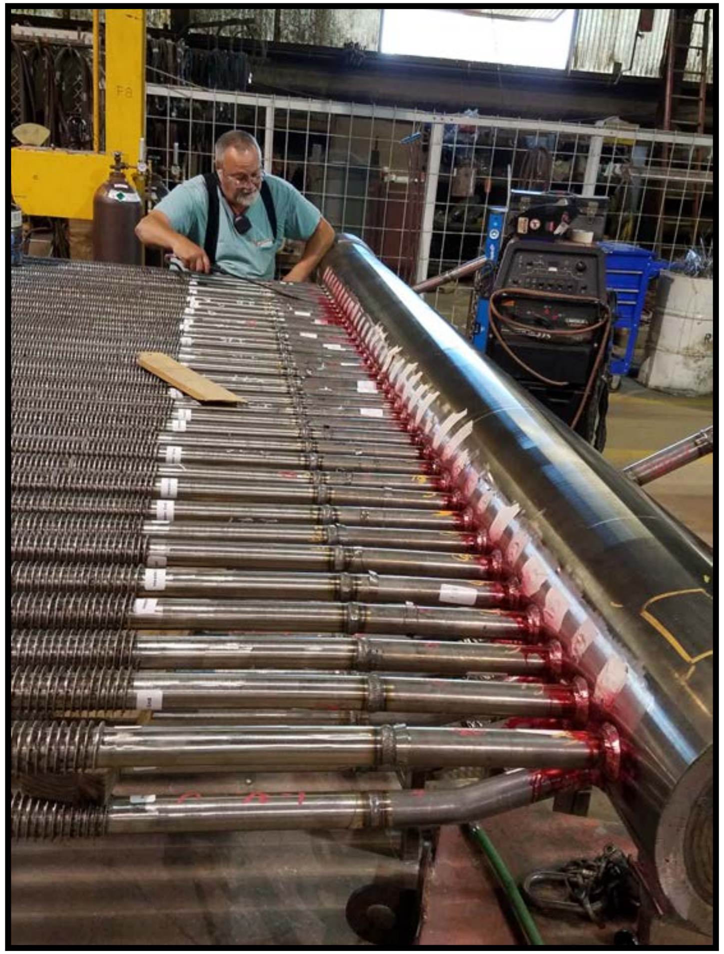
Built to Code Case 2702-3

- Types of Weld Procedures
  - 740H-740H
  - 740H-dissimilar (P8, P43, P45)
- Welding Process: manual GTAW (Pulsed MIG not used in coil fab)
- Inert gas purge required (He-Ar mixture) of coil internal volume
  - Coil opening closures critical to establishing a complete and thoroughly purged environment
- PQRs
  - 2 welders qualified for headers welding
  - 6 welders qualified for tube welding

Welder training critical to success (see SMC 740H welding guide)

Non-Destructive Evaluation (NDE)

- All NDE performed in accordance with ASME Section V
- Types of NDE performed <u>*during/after welding*</u>:
  - Visual: Internal root checks on tube to header & tube butt welds
  - Liquid Penetrant Testing (PT) on finished welds
  - Radiograph Testing (RT) of all butt welds
  - *Phased Array Ultrasonic Testing (PAUT) of all tube butt welds (supplementary test to RT)
- Hydrostatic test per ASME Section I
  - Test performed after coil completion
  - Minimum test pressure = 1.5 x MAWP = 6000 psig
  - *Alternate test pressure = 7,299 psig



***PAUT & alternative pressure hydro conducted after coil PWHT**

Welding & Fabrication

Welding of tube bends to straight sections of coiled tubing

End Prep.

Tube-to-tube butt welds (1,296 tube butt welds in the heater design)

Welding and Fabrication

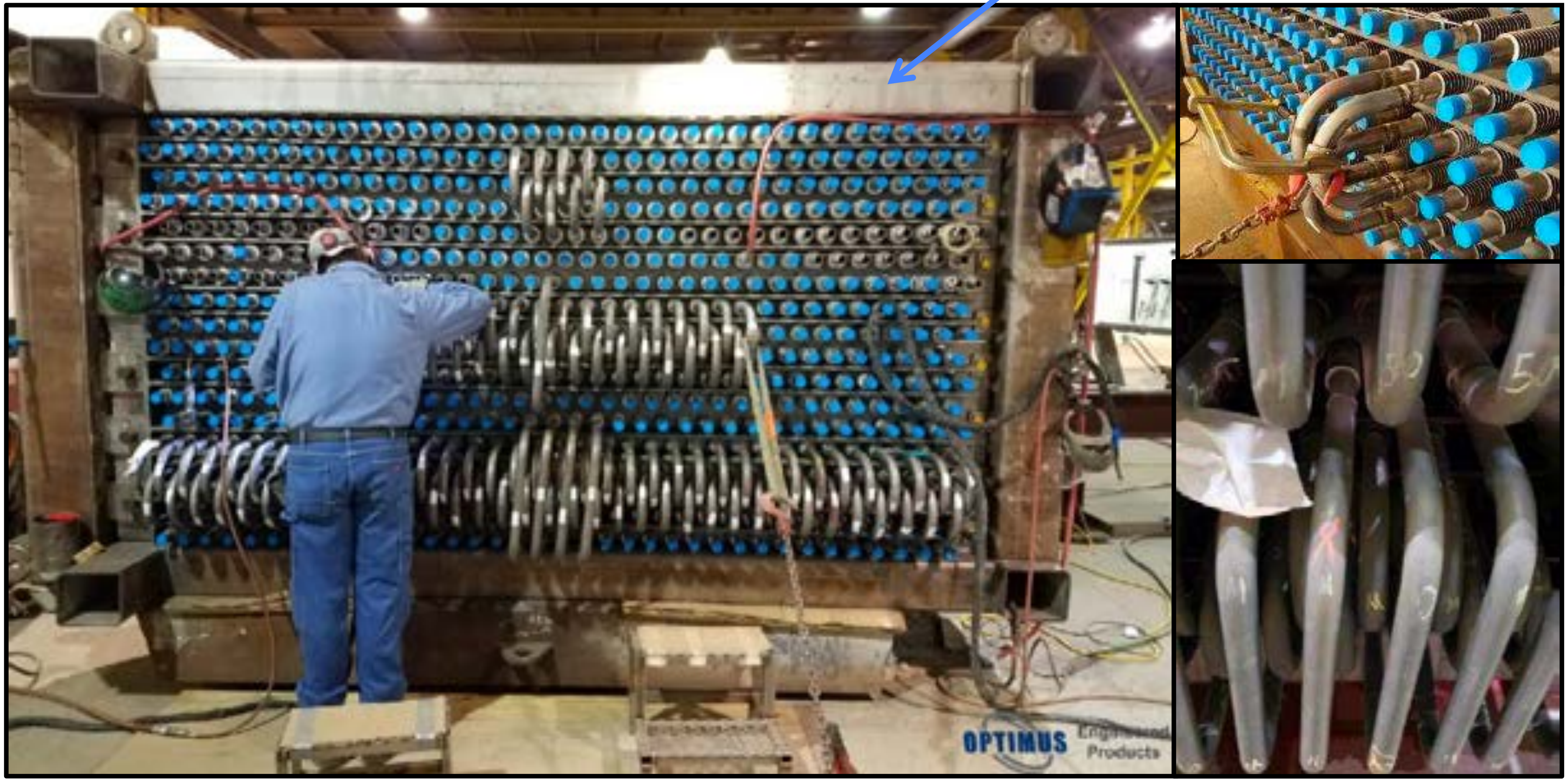
Tube-to-header welds (set-on design, 292 welds total)

Welding & Fabrication

Thicker-section and transition welds

Welding & Fabrication

Frame to hold module for assembly and heat-treatment



Closure welding on the 'return' end of the coil

Post-weld Heat-Treatment (PWHT)

- PWHT performed per Code Case 2702 on entire assembly
  - 1,400°F – 1,500°F (760°C – 815°C)
  - Min. 4 hour soak up to 2 inch (50 mm) thickness
  - Add 1-hour per add'l 1 inch (25 mm) of thickness

Coil Assembly in Frame Prior to Heat-Treatment

Temperature records indicate successful heat-treatment (5hrs)

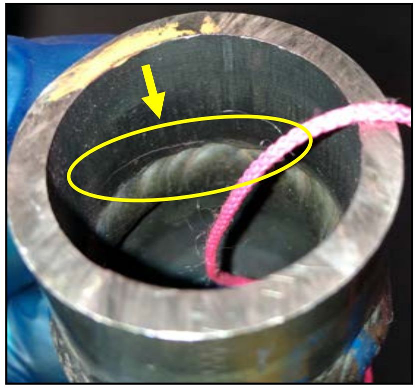
Indications after PWHT

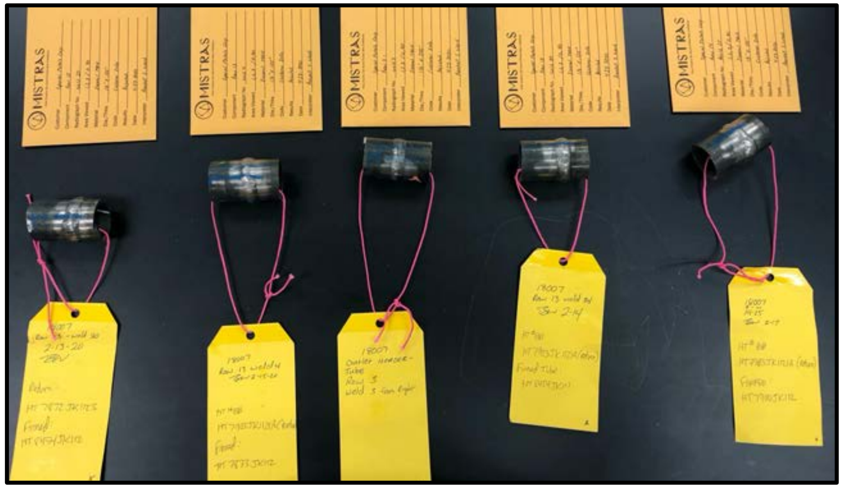
- Linear indications found in a few welds (12) after PWHT and initial hydro test
  - Only in Tube-to-tube butt welds
- Repair method developed
  - Could not grind out (ID contamination)
  - Cut tube on either side of weld (allows for tube ID cleaning) & prep tube ends
  - Weld new tube "pup" piece in per applicable WPS, NDE via PT/RT
  - Local PWHT (ceramic heating pads), NDE via PT/RT
- Additional indications found after subsequent hydro tests (16 total)

Concern if welds may have cracks that were not identified by pressure test

Laboratory Cracking Investigation

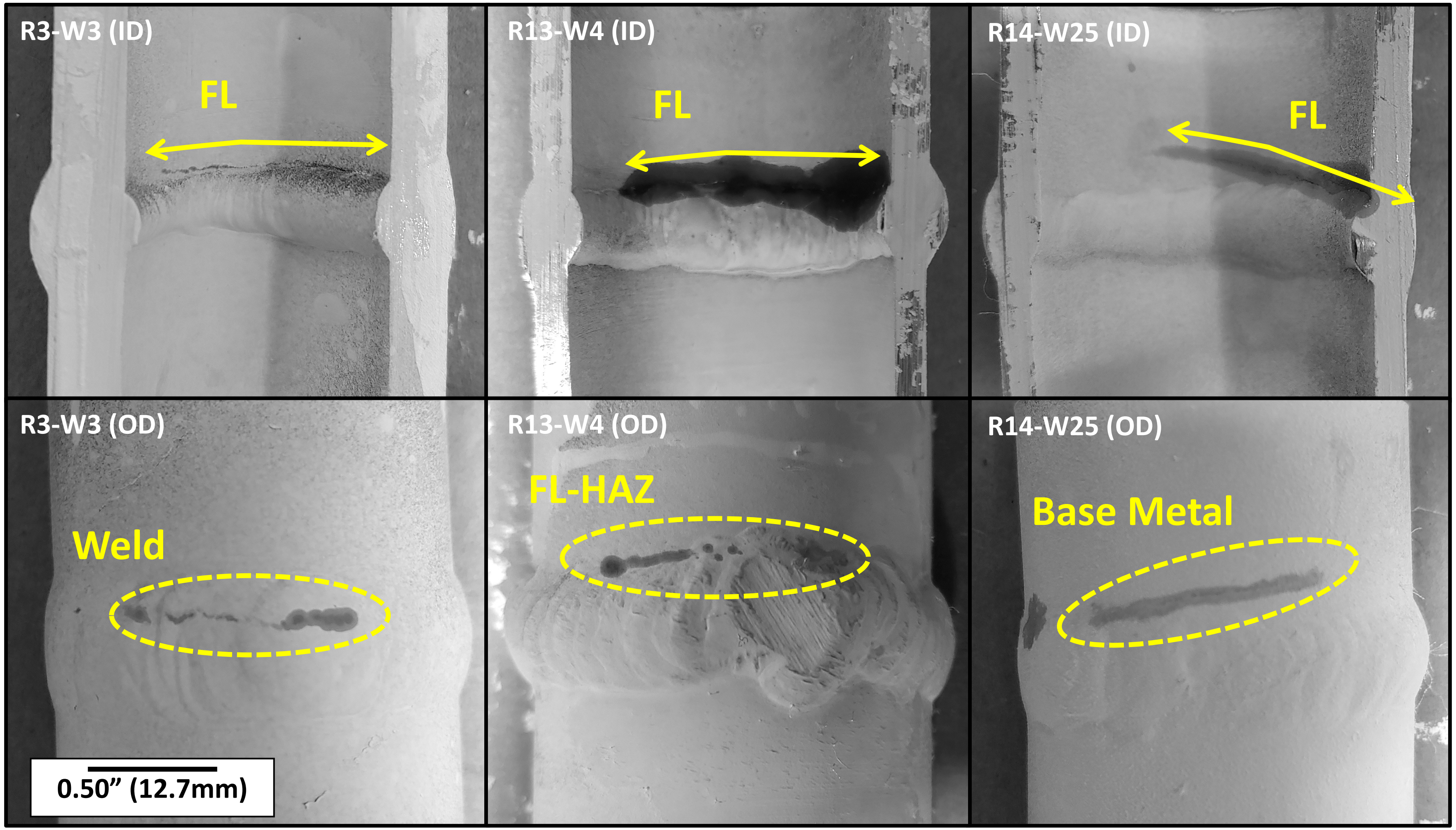
- 5 through-wall cracked samples initially evaluated
  - Likely crack locations marked
    - Review of RT films
    - PAUT in EPRI Labs
  - Split tubes to access ID
    - Dye Pen. to identify exact crack location
  - Metallographic sectioning
    - Up to 5 mounts per tube
    - Macro metallography, Hardness mapping, electron microscopy
- After 100% PAUT of coil 5 additional samples were analyzed to validate NDE approach





Extensive study with over 30 metallographic mounts examined

Macro damage characterization

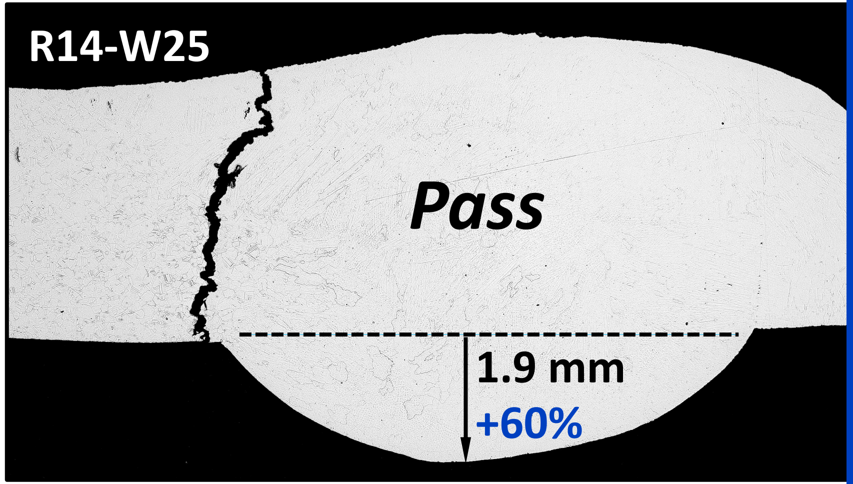


Inner Diameter: 1/3 circumference

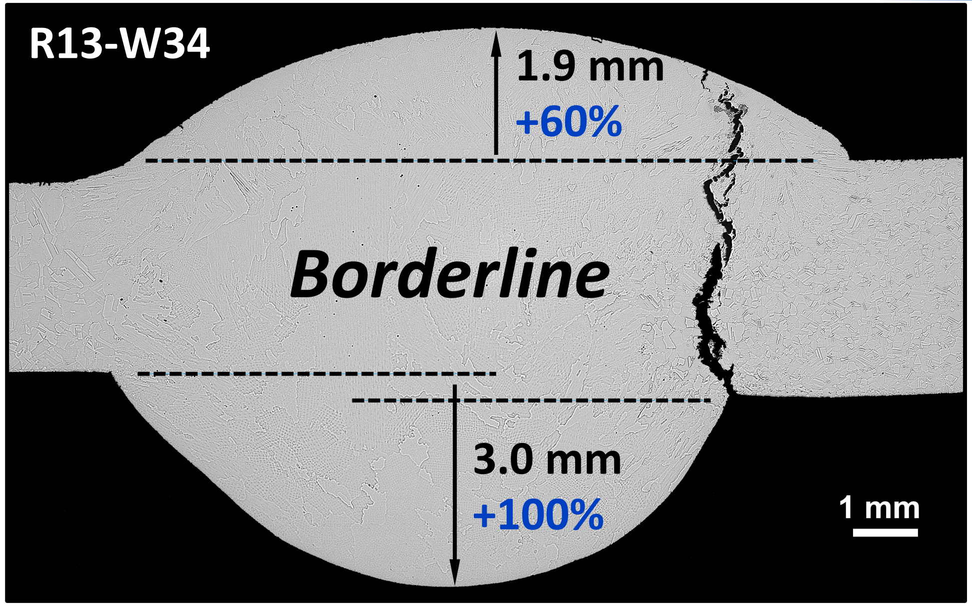
Outer Diameter

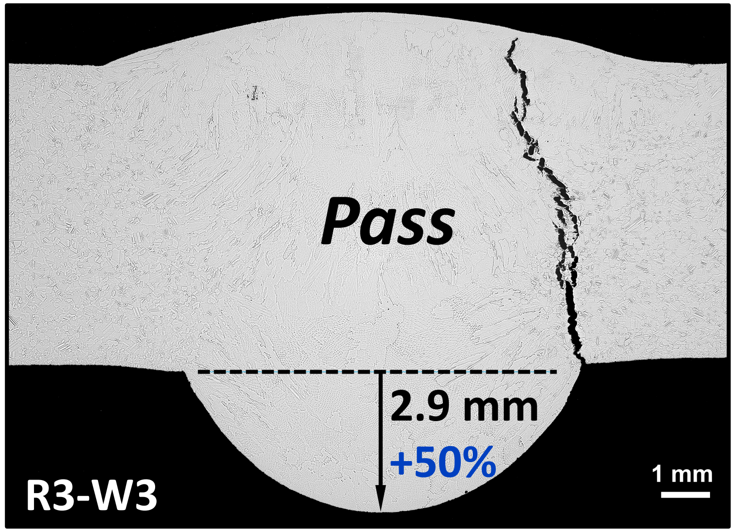
I.D. initiated near fusion line with variable propagation

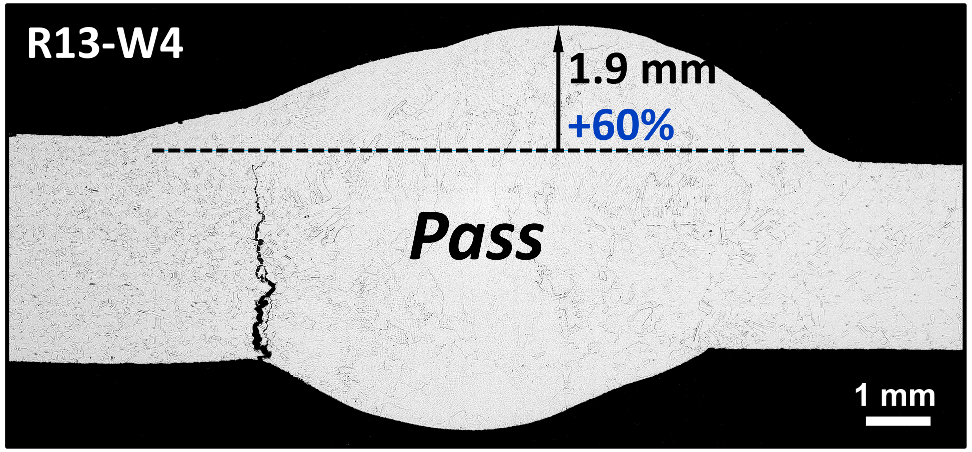
Workmanship

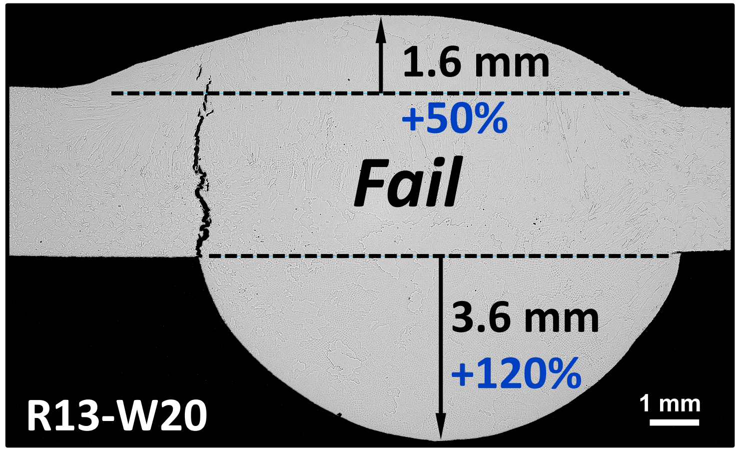


Reinforcement limitations given for each face in ASME B&PV Code Sec. I, PW-35.1 lists a maximum of 2.5 or 3.0 mm or 4.0 mm (depends on tube wall thickness)





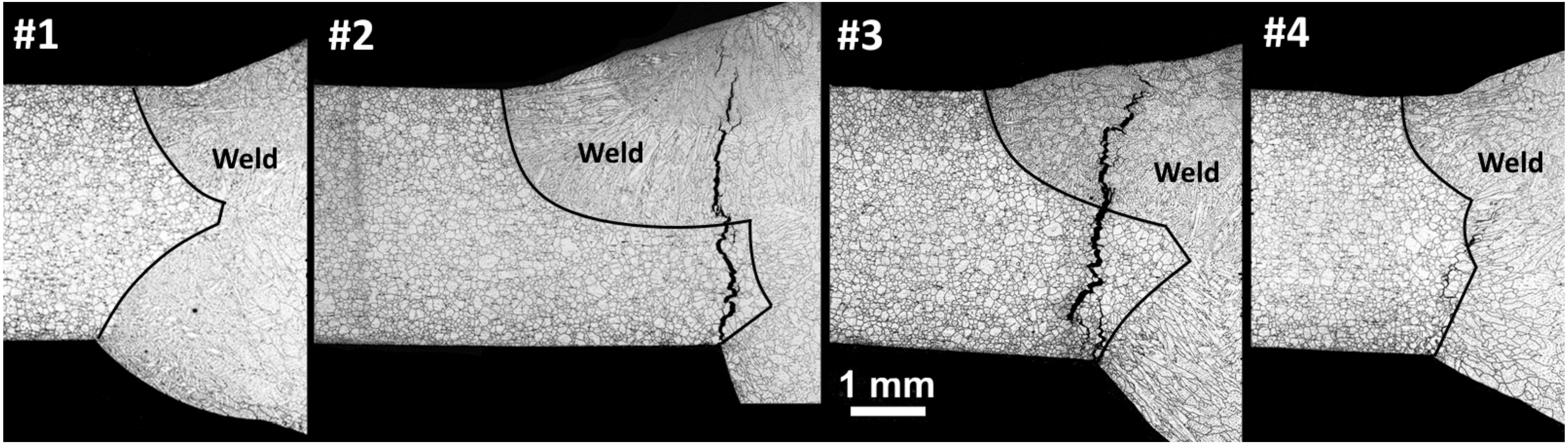




No welding defects noted, but workmanship was variable

Crack propagation around circumference

Outside diameter

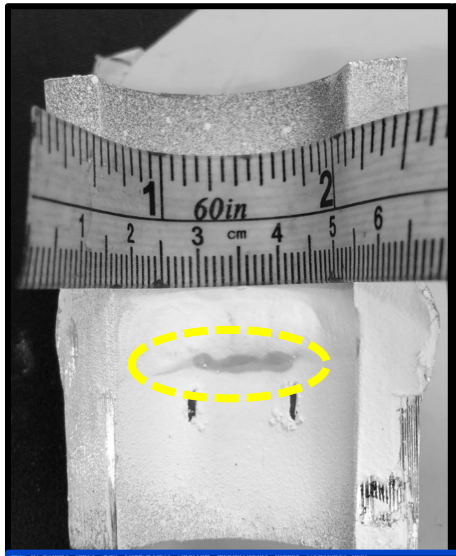


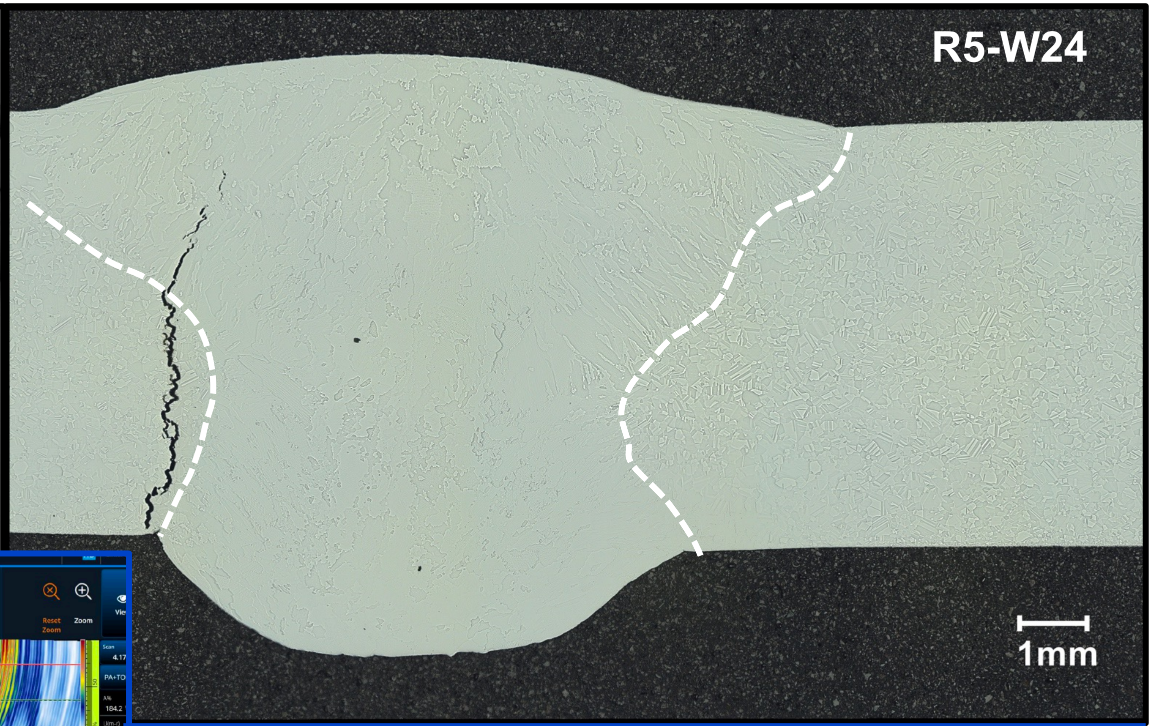
Inside diameter

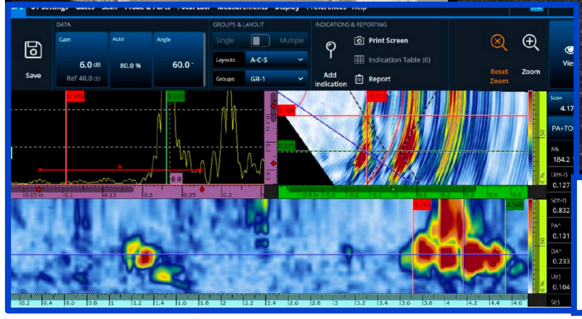
No damage	Initiation at weld toe on the ID, propagation through HAZ and into the weld	Initiation at weld toe on the ID, propagation through HAZ

Clear evidence for crack initiation at weld toe at fusion line on I.D.

PAUT Validation





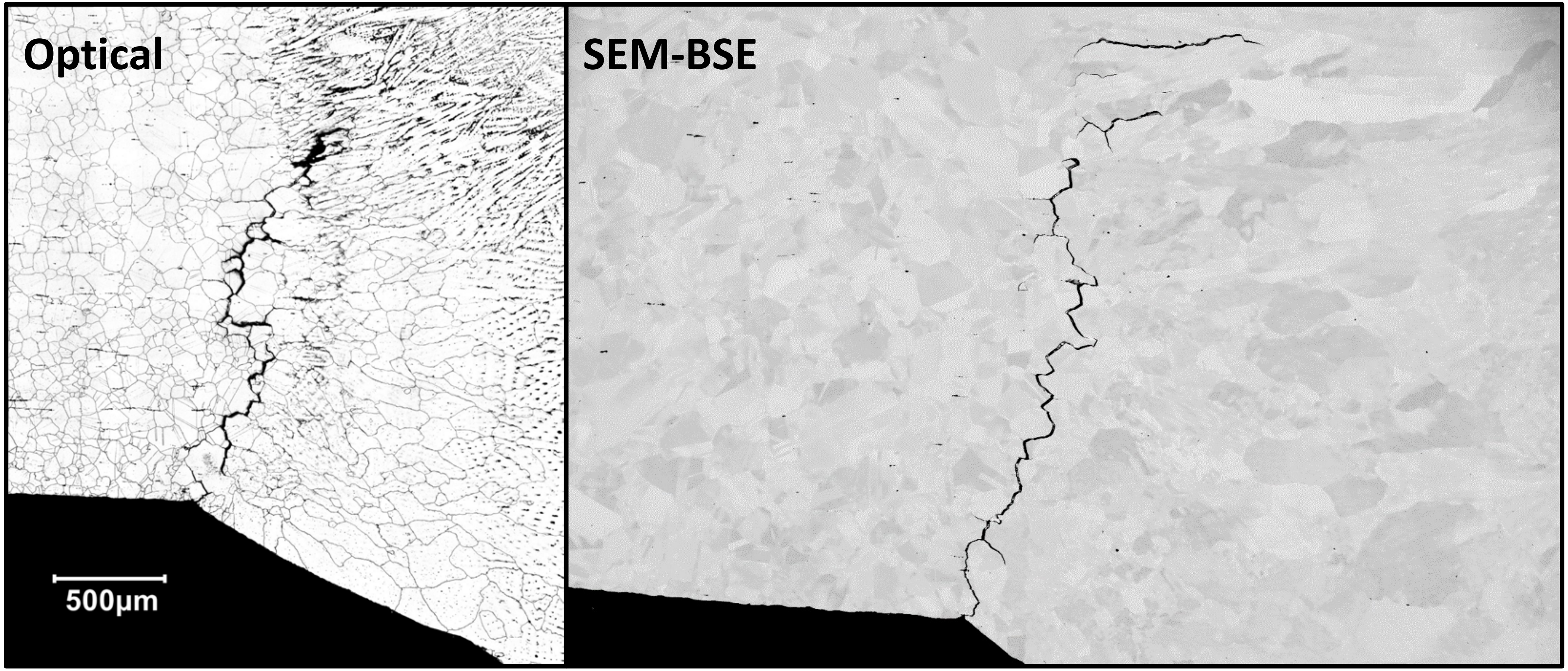


Measured crack length: 4.3-5.4 mm
PAUT depth measurement 3.2mm

- 5 tubes with PAUT indications were removed
- All 3 crack like-indications were confirmed
- 2 indication (not crack-like) were confirmed not to have cracks

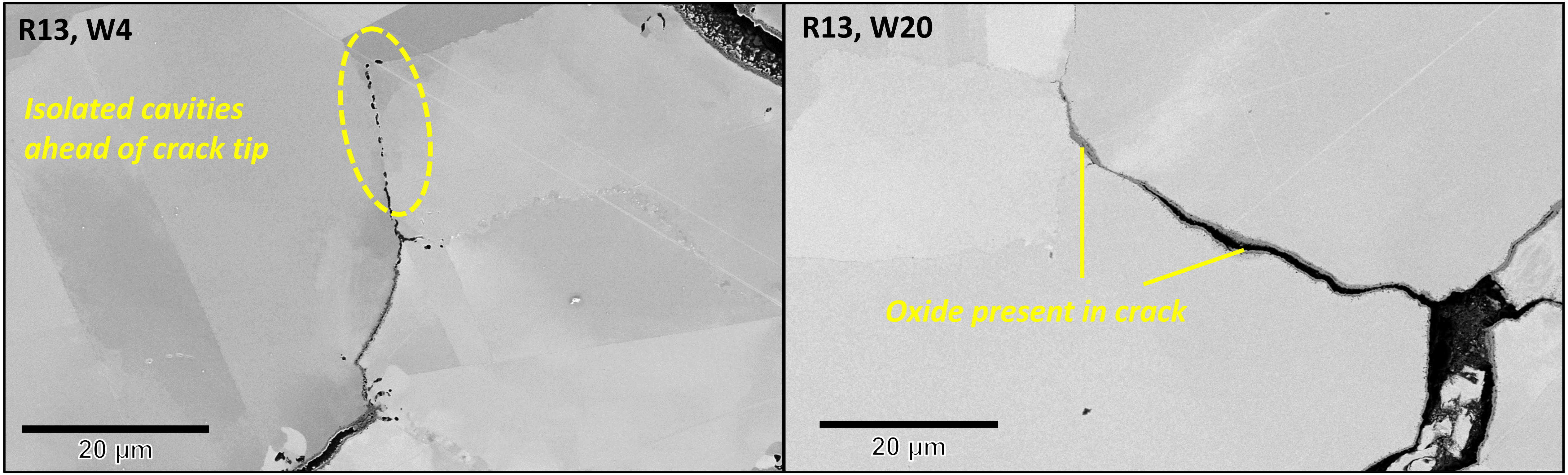
PAUT was able to identify and reasonably size significant cracks with same I.D. initiation as through-wall leaks from hydro testing

Intergranular cracking



Cracking was entirely intergranular in nature with minimal branching

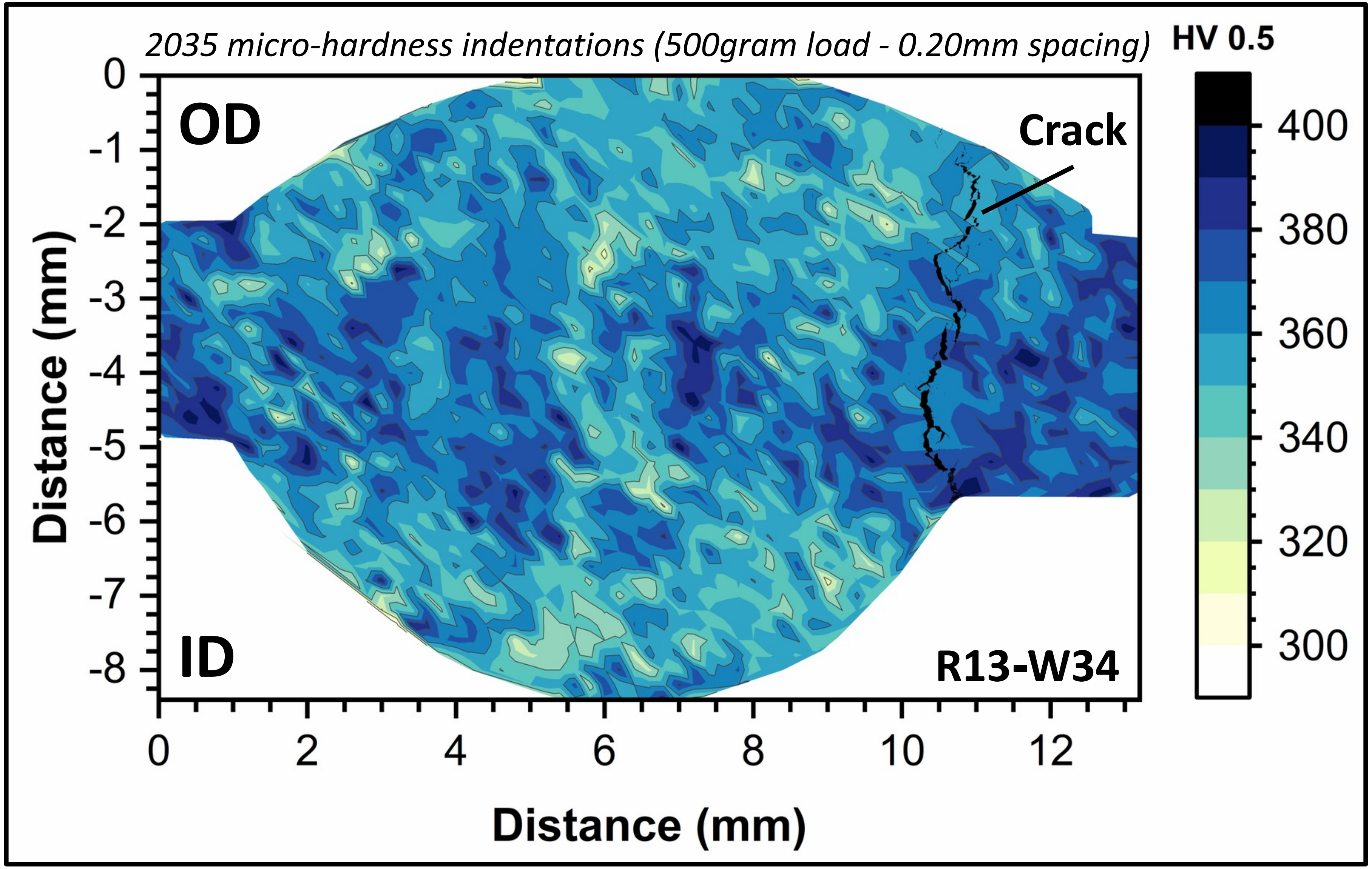
Microstructural Observations



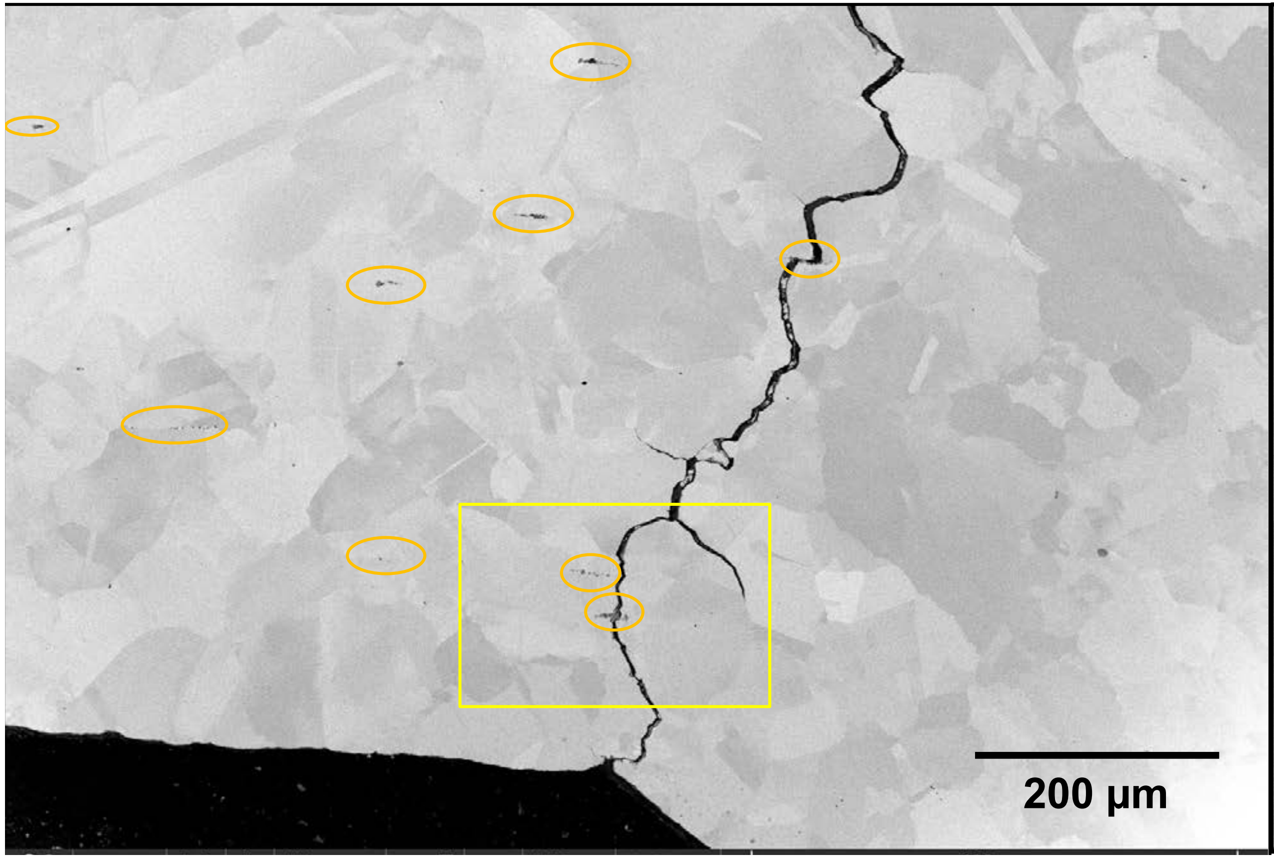
Isolated cavities formed ahead of crack tips and oxide in cracks suggesting cracks occurred early in the PWHT cycle

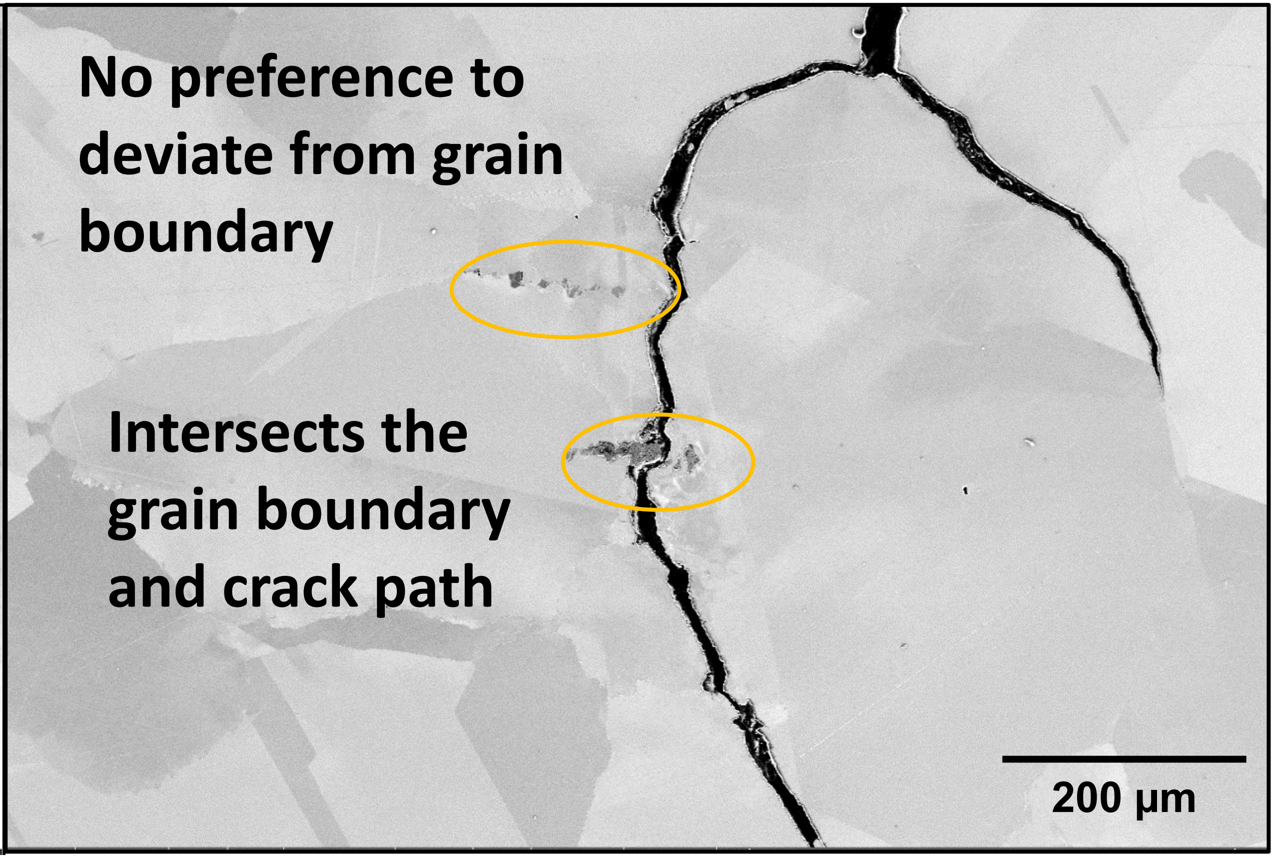
Hardness Mapping

No evidence of improper PWHT or excessive cold work near weld



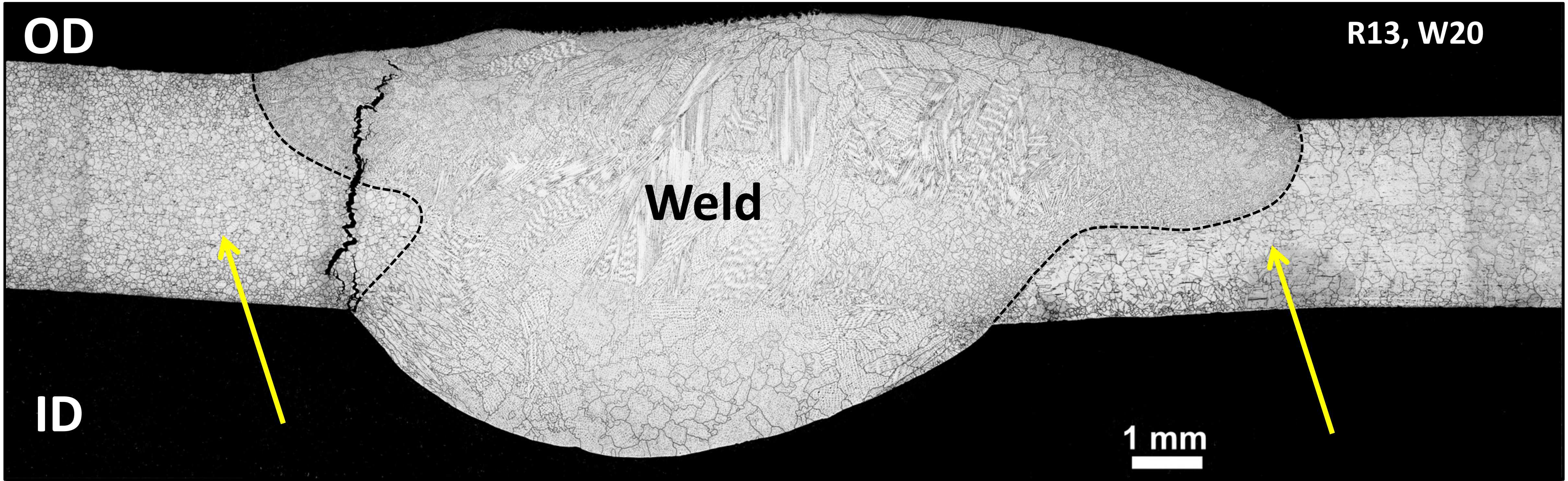
Microstructural Observations





No cracking preference to typical carbide stringers in material

Microstructural Observations

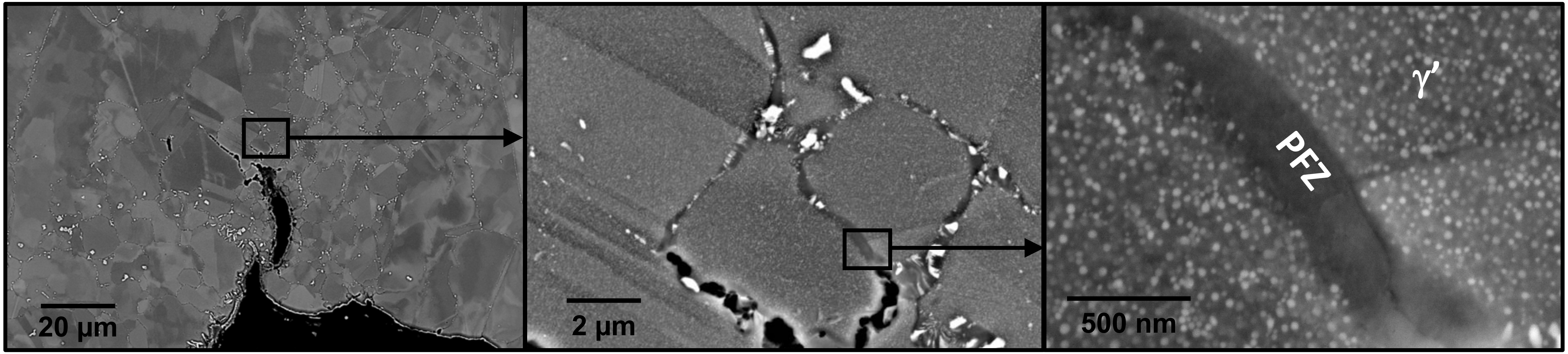


Cracking occurred (for this weld) in finer grain heat

No preference to cracking based on grain size or biased to specific heats

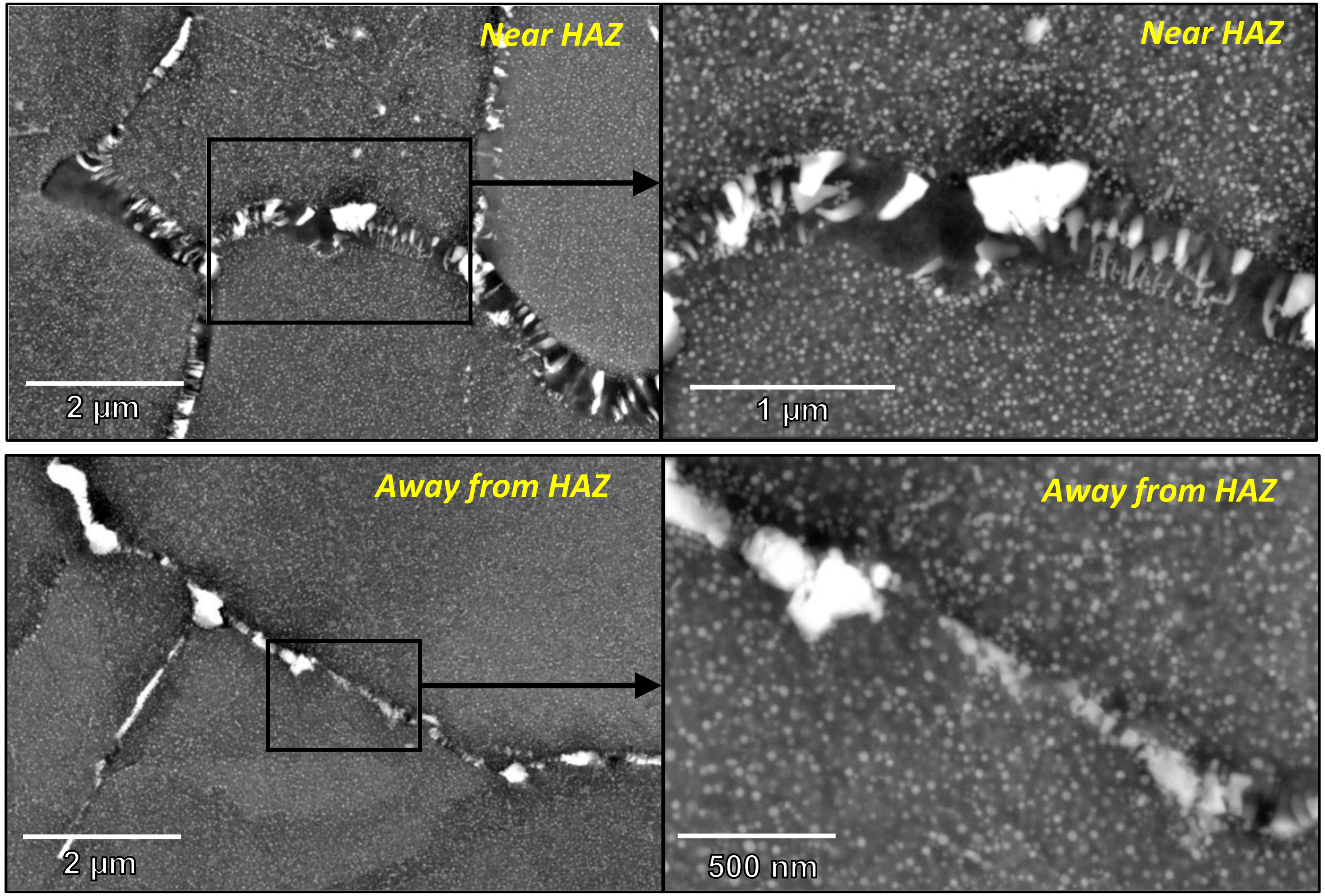
Detailed characterization

- The crack initiation location was subjected to detailed characterization in the SEM
  - Only possible due to extensive macro characterization and evaluation of over 30 samples



Precipitate Free Zones (PFZs) identified near the crack initiation

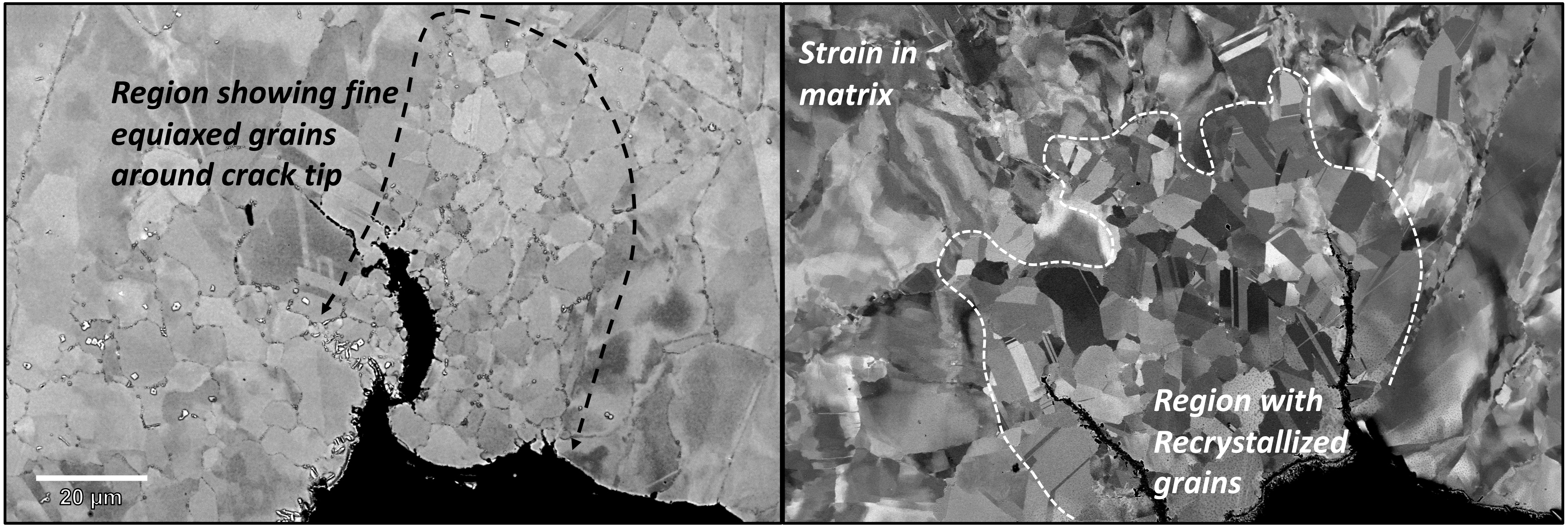
Detailed characterization



- Grain boundaries in HAZ region showed precipitate coarsening resulting in PFZs
- Regions adjacent to HAZ in base metal showed typical grain boundary morphology and fine gamma prime precipitates

PFZs generally only observed after long-term thermal (creep) exposures – new finding for weldments after PWHT

Detailed characterization



Small region of recrystallized grains identified near crack initiation suggesting very high localized strains

740H Fired Heater Welding Summary

Type	Weld Description	Cracking / NDE Indications	Total Number of Welds	Failure Rate
Thick-wall	End Plates	0	4	0%
	Flange-to-header	0	2	0%
Thin-to-thick	Tube-to-header	0	292	0%
Dissimilar	740H to 347H	0	4	0%
Thin-to-thin	Tube-to-tube butt welds	39	1,296	3.0%
	Repairs*	0	87	0%
Total		39	1,685	2.3%

**Repairs included pup piece installations for 39 cracks/indications (2X repair welds), 3 segments removed for additional NDE verification (2X repair welds) plus 3 sacrificed welds during repairs (1X repair welds)*

Cracking and rejectable indications were restricted to the tube-to-tube butt welds

Butt-Weld Fabrication & Cracking Details

Location	Tube Thickness mm (inches)	Through-wall Cracks	PAUT NDE Identified Cracks	Total Cracks Repaired	Total Original Welds	Percent Cracked & Repaired
Return	2.67 (0.105)	1	0	1	108	0.9%
	2.67 to 3.18 (0.105 to 0.125)	5	4	9	108	8.3%
	3.94 (0.155)	3	2	5	216	2.3%
	5.59 (0.220)	2	12	14	216	6.5%
	Total	*11*	*18*	*29*	*648*	***4.5%***
Header	2.67 (0.105)	0	0	0	108	0.0%
	3.18 (0.125)	1	1	2	108	1.9%
	3.18 to 3.94 (0.125 to 0.155)	0	1	1	108	0.9%
	3.94 (0.155)	0	1	1	108	0.9%
	3.94 to 5.59 (0.155 to 0.220)	1	2	3	108	2.8%
	5.59 (0.220)	3	0	3	108	2.8%
	Total	*5*	*5*	*10*	*648*	***1.5%***
Total		***16***	***23***	***39***	***1,296***	***3.0%***

3X more repairs on return end

Thicker tubes and transition show more repairs

Cracking is not random, clear bias to return end of the assembly

Failure Mechanism Determination

1. **Timing**: Cracking occurred during PWHT
   a) NDE (full RT) prior to PWHT did not identify any cracks but 39 cracks or rejectable indications were identified after PWHT
   b) Cracks had a thin oxide layer suggesting cracking early during PWHT cycle
2. **Morphology**: The cracking is intergranular
   a) Exclusively intergranular with minimal/no branching
   b) Isolated cavitation observed in front of some crack tips
   c) Growth of crack did not follow a specific microstructural constituent (FL, HAZ, BM)
3. **Stress State**: Strong evidence for highly localized stress
   a) Geometric stress concentrations at toe region of weldment
   b) Significant microstructural changes in the weld toe region on the ID
      - Small recrystallized zone
      - Non-recrystallized grains showed higher channeling contrast indicative of strain
      - PFZ and coarsened zone formation without long-term aging (needs a driving force)

Stress Relaxation Cracking (SRxC) during PWHT [also known as strain age cracking (SAC)]

Root Cause(s)

1. **Material Factors**:
   a) Alloy chemistry – no evidence of bias to individual heats or chemistries (24 heats used in the heater) - Inconclusive
   b) Grain size – no evidence of bias to larger grains
   c) Non metallic inclusions, porosity, or other hard features – stringers did not contribute to crack initiation or progression
2. **Thermal History**:
   a) Welding process: All welds made using manual GTAW – no trend with welders, no weld defects found in over 30 metallurgical mounts, over 1500 successful welds made in a variety of components sizes
   b) PWHT: No evidence of improper PWHT from heat-treat records and hardness testing

Note: automated welding and alternative PWHT temperatures were not considered

Root Cause(s)

3. **Stress State**:

    a) While the welding process generally appears to be well controlled, the welding thermal cycle clearly had a pronounced effect on the tubular components of the STEP heater

        a) The fabrication sequence and design of the heater appears to be a significant factor in the application of manual welding of 740H.

            – Welder Access and positioning was favorable for all thick section welds and header end tube welds

            – Return-end welds were more difficult – limited access resulted in highly variable weld geometry and stress concentrations

        b) Welding residual stresses: scale with local constraint

            – Bias to thicker butt welds or thickness transitions (with cracking on thicker tubes

            – Alignment was required for closure welds to be (note, no evidence of excessive cold work)

Shop fabrication was well controlled, but stress state appears to be a significant factor in the cause of cracking

Practical Implications & Next Steps

- Practical considerations for 740H users
  - Consider joint location and fabrication sequence in design
  - Avoid excessive joint reinforcement and other geometric stress concentrations
    - Automated welding may help better control these variables
  - Volumetric inspection should be performed after PWHT (in addition to staged or limited inspection during welding) to ensure component is free of SRxC defects
- Current EPRI research to extend these learnings [DOE SETO funded effort (DE-EE0009378)]:
    - Detailed characterization of other industry cracking and SRxC lab studies on 740H to evaluate material, heat-treatment, and stress state variables
    - Workshop conducted (Dec 2021) with 740H users
    - End Goal is ***Industry Guideline Specification for 740H Procurement and Fabrication*** which goes above beyond the minimum code requirements

Interested in reviewing the draft guideline? – contact John Shingledecker (jshingledecker@epri.com) or John Siefert (jsiefert@epri.com)

Summary – Success!

- A gas fired heater was designed and successfully produced with an outlet condition of 715ºC and 255bar for the DOE STEP facility
  - The heater coil is the largest known application of an age-hardenable nickel-based alloy, 740H, to ASME B&PV code
  - The fabrication involved over 1600 welds with a low initial failure rate of <1%
- After PWHT, a small percentage (3%) of tube-to-tube butt welds experience cracking which was determined through a detailed metallurgical investigation to be due to SRxC during the PWHT cycle
  - Variable stress state was a significant factor in the cracking
  - The bias in cracking to the return end was likely due to the combination of challenging welder access, less flexibility (closure welds), and thickness transitions
  - Weld repairs and full volumetric inspection using PAUT was successfully completed
- Learnings from this work are being applied to future industry guidance & research

This first-of-a-kind fired heater has been shipped to site and installed to support the STEP Facility and testing program

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