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Elevated Temperature Behavior of Pinch Welded 304L and 316 Tube

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Zahra Ghanbari, T. Ivanoff, C. Laursen, D. Pendley,

M. Maguire, C. Finfrock

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Elevated Temperature Behavior of 304L and 316 of Interest for Pinch Welds

304L and 316 both have desirable strength, ductility, and corrosion resistance over a broad range of temperatures, making them attractive for many structural applications.

Resistance pinch welding allows for sealing of tubing by applying simultaneous current and force to collapse a tube together and allow the interior walls to bond.

Resistance pinch welded tubes made from these alloys can be subjected to brief, elevated temperature excursions during which they are required to remain intact.

- Temperatures of interest are near 1000°C
- Times are 1-10 hrs (order of magnitude)
- Internal pressure in tubes is expected

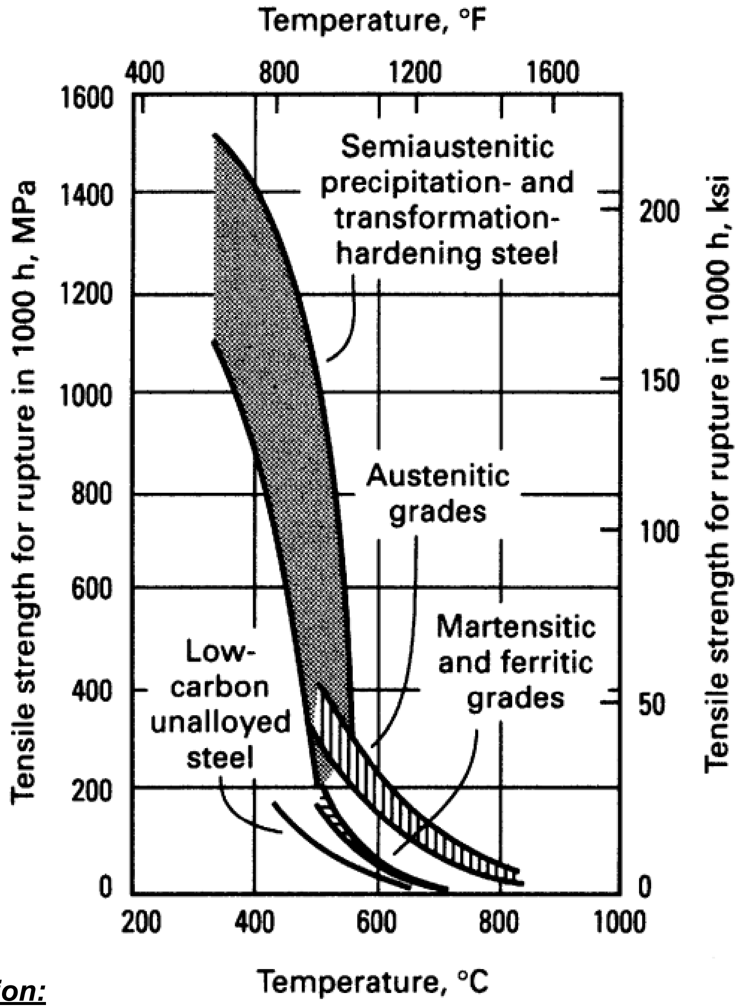


Figure Caption:

General comparison of the hot-strength characteristics of austenitic, martensitic, and ferritic stainless steels with those of low-carbon unalloyed steel and semiaustenitic precipitation- and transformation-hardening steels

[1]***ASM Handbook: Wrought Stainless Steels: Selection and Application***

Specifically, elevated temperature stress-rupture behavior is of interest

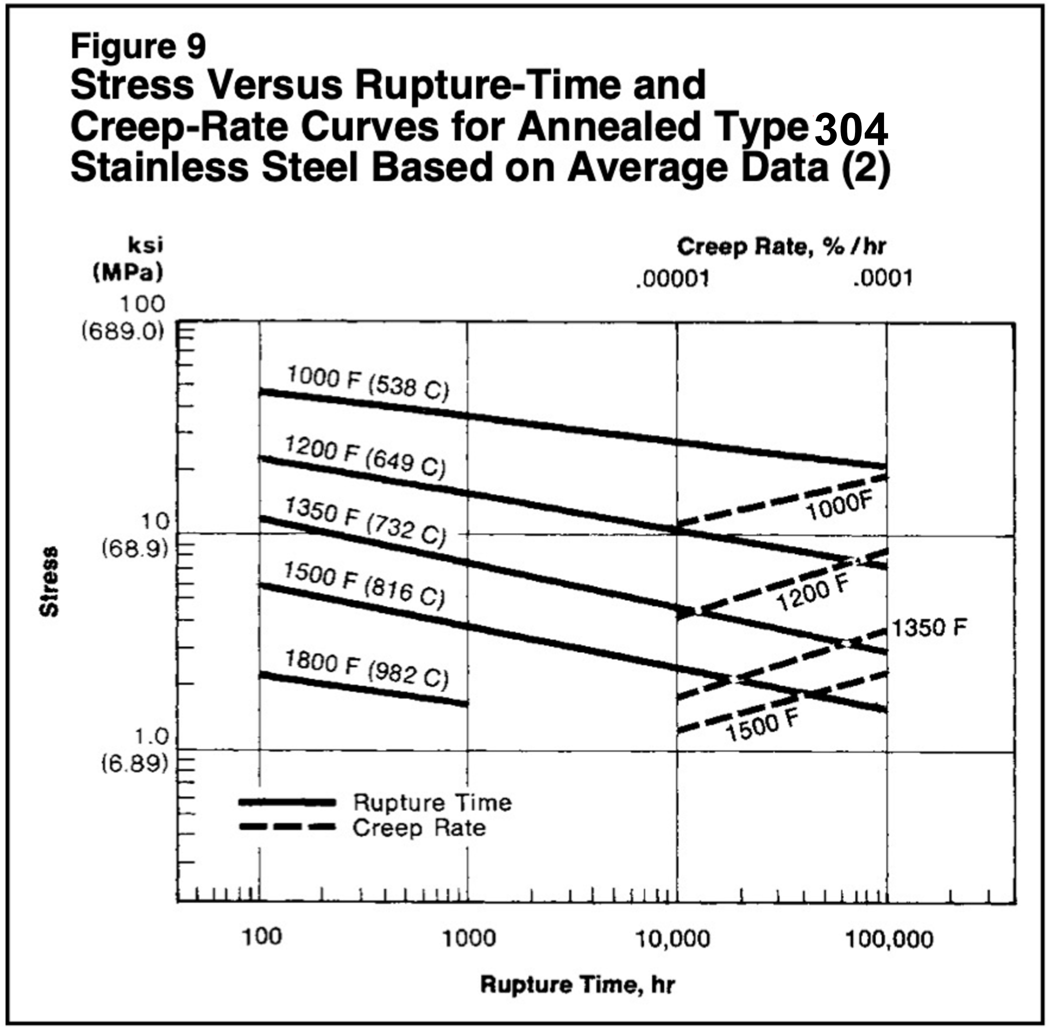
Limited Creep Rupture Data Exists for 304 & 316L at Elevated Temperature

Limited data exists for high temperature mechanical properties near 1000°C. This is especially important given that this temperature is:

- Well above any typical use temperature for these steels, and thus data is relatively sparse
- Fully into the creep regime for essentially all conventional austenitic or ferritic stainless steels
- Significant extrapolation of properties is required for short-time creep estimates

Added complication for our case:

- Oxidation of 304L and 316 in air expected at these temperatures
- Rupture time associated with combined loss of wall thickness from scaling and creep effects not captured



[1]*AISI High Temperature Characteristics of Stainless Steels (AISI, A Designer's Handbook Series)*

Absence of data requires direct pressure testing of resistance pinch-welded tubes at elevated T

Max Pressure Predicted via ASME B31.1 Power Piping Calculations

Establishment of starting test pressures was desired

Internal research has shown that resistance pinch welds are stronger than the un-welded tubing at normal use temperatures.

- Thus, failure at elevated temperature also expected to occur in tube-body
- Power piping calculations can be used to evaluate max. allowable pressure as starting point for testing

For appropriately conservative design purposes, it is common to apply reductions in material properties (stresses) per ASME codes

- However, there are no "code" allowable stresses published for these steels in the vicinity of 1000°C

As a starting point, conservative (in rupture-time) stresses were selected as inputs:

- Use stress of 2.2 ksi from 100 hr, 982°C
- Provides conservativism in rupture time

Parameters	Equation variable	Dimension
Inner diameter	d	0.069"
Outer diameter	D_0	0.125"
Wall thickness	t_m	0.028"
Allowable stress*	SE	2200 psi
B31.1 coefficient, W	W	1
B31.1 coefficient, y	y	0.7
ASME B31.1 pressure, max.		1450 psi

**Engineering-judgement-based considering 100 hr rupture time, and slightly higher temperature (1000C)*

ASME B31.1-2020

104 PRESSURE DESIGN OF COMPONENTS

104.1 Straight Pipe

104.1.1 Straight Pipe Under Internal Pressure. Straight pipe under internal pressure shall have a minimum wall thickness calculated per para. 104.1.2.

(20) **104.1.2 Straight Pipe Under Internal Pressure — Seamless, Longitudinal Welded, or Spiral Welded**

(a) *Minimum Wall Thickness.* The minimum thickness of pipe wall[3] required for design pressures within the prescribed temperature limits for materials permitted by para. 123.1, including allowances for mechanical strength, shall not be less than that determined by eq. (7) or eq. (8), as follows:

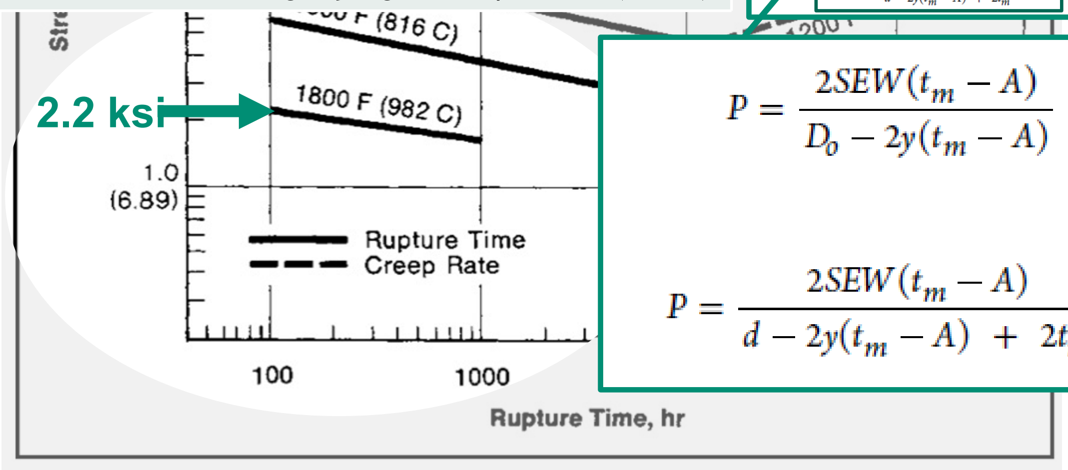
$$t_m = \frac{PD_o}{2(SEW + Py)} + A \quad (7)$$

$$t_m = \frac{Pd + 2SEWA + 2yPA}{2(SEW + Py - P)} \quad (8)$$

Design pressure shall not exceed

$$P = \frac{2SEW(t_m - A)}{D_o - 2y(t_m - A)} \quad (9)$$

$$P = \frac{2SEW(t_m - A)}{d - 2y(t_m - A) + 2t_m} \quad (10)$$



$$P = \frac{2SEW(t_m - A)}{D_o - 2y(t_m - A)}$$

$$P = \frac{2SEW(t_m - A)}{d - 2y(t_m - A) + 2t_m}$$

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Calculated maximum allowable pressure of approximately 1450 psi

(per ASME B31.1 Power Piping Code)

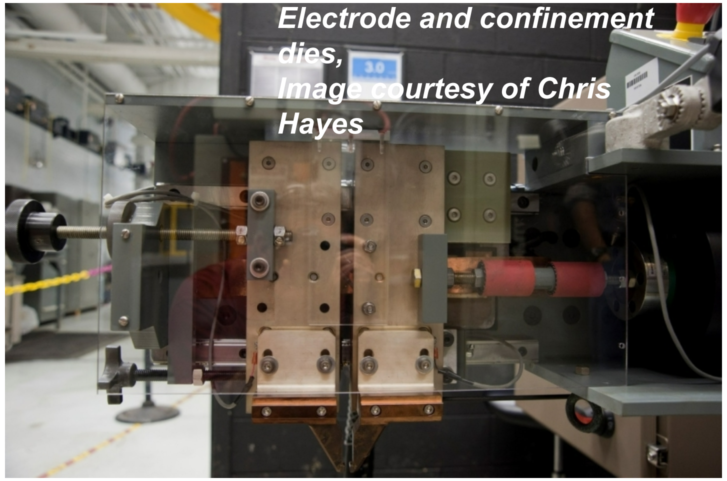
Elevated Temperature + Pressure Tests in Tube Furnace

Tube materials:

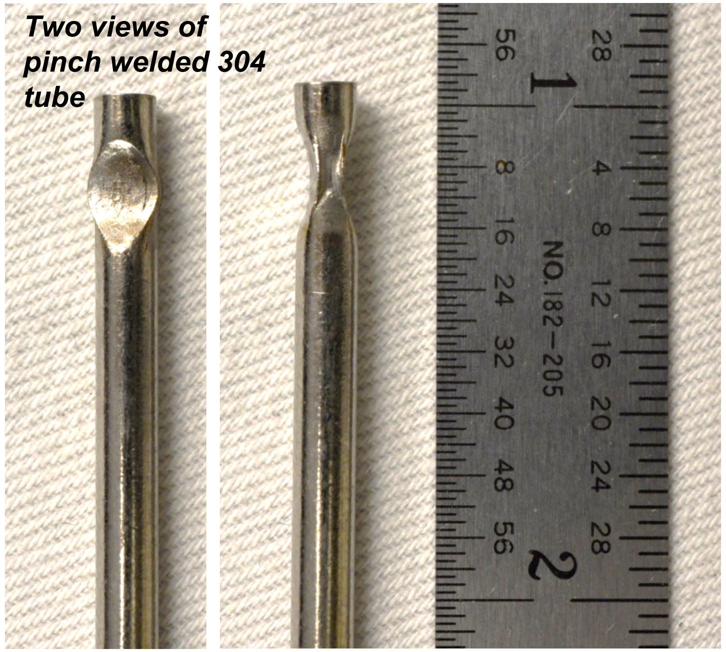
- 304/304L, acid cleaned
- Swagelok 316, electropolished

Assembly/inspection:

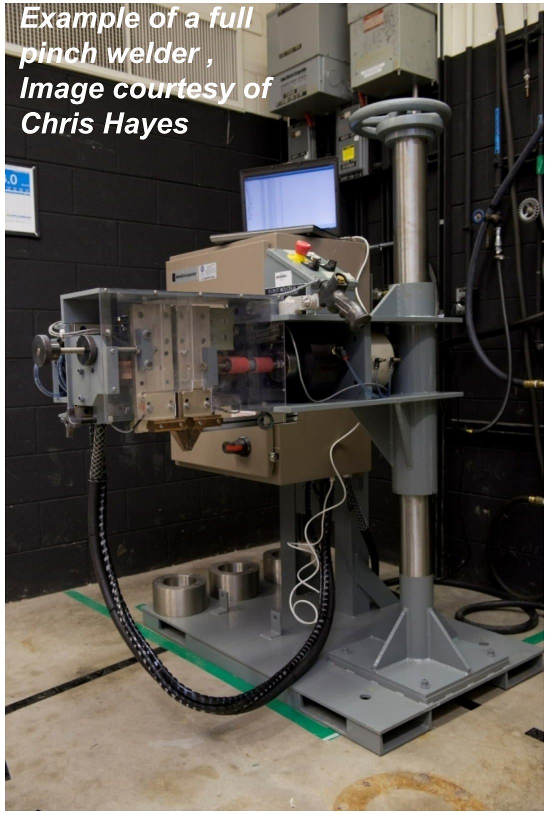
- Pinch weld one end of tube
- Orbital weld on extension tube
- Borescope inspection



Electrode and confinement dies, Image courtesy of Chris Hayes



Two views of pinch welded 304 tube



Example of a full pinch welder , Image courtesy of Chris Hayes

Elevated Temperature + Pressure Tests in Tube Furnace

Tube materials:

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- Swagelok 316, electropolished

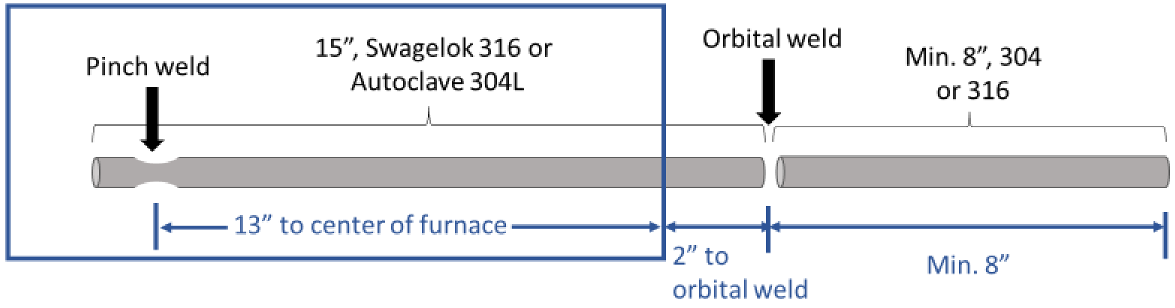
Assembly/inspection:

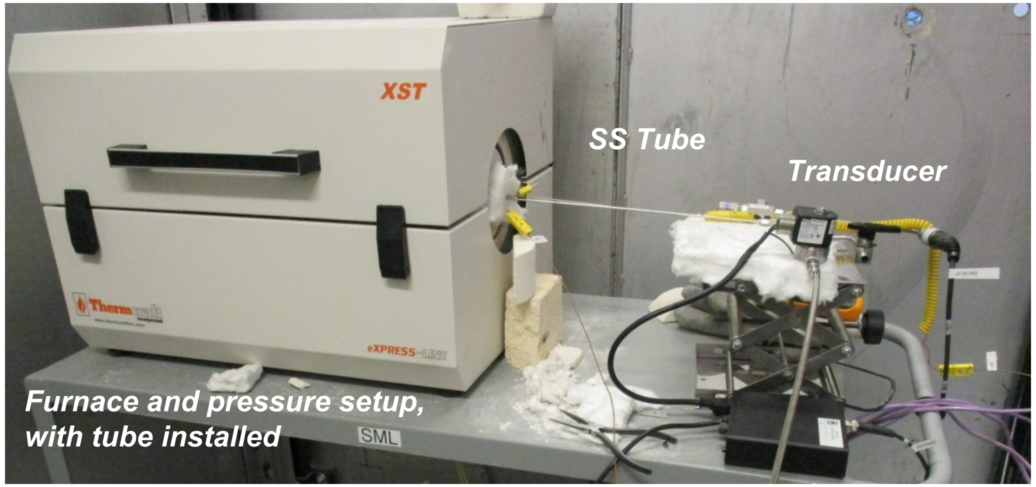
- Pinch weld one end of tube
- Orbital weld on extension tube
- Borescope inspection

General test details:

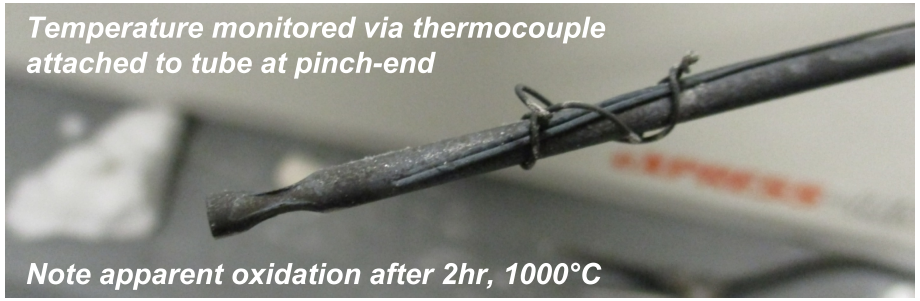
- Furnace heated to 1000 °C
- TC secured to tube and inserted into furnace
- Nitrogen back-pressure applied in range of 500 - 4750 psig
- During testing, pressure was monitored throughout tests

Schematic of prepared tubes with relationship to furnace





Furnace and pressure setup, with tube installed


Temperature monitored via thermocouple attached to tube at pinch-end

Note apparent oxidation after 2hr, 1000°C

Pressure Testing at 1000°C Support Max Pressure Calculations

Multiple 1000°C test series performed; applied pressure adjusted

Series A: Iteratively increase applied pressure from 500-1500psi (~ASME-B31.1-based max. pressure)

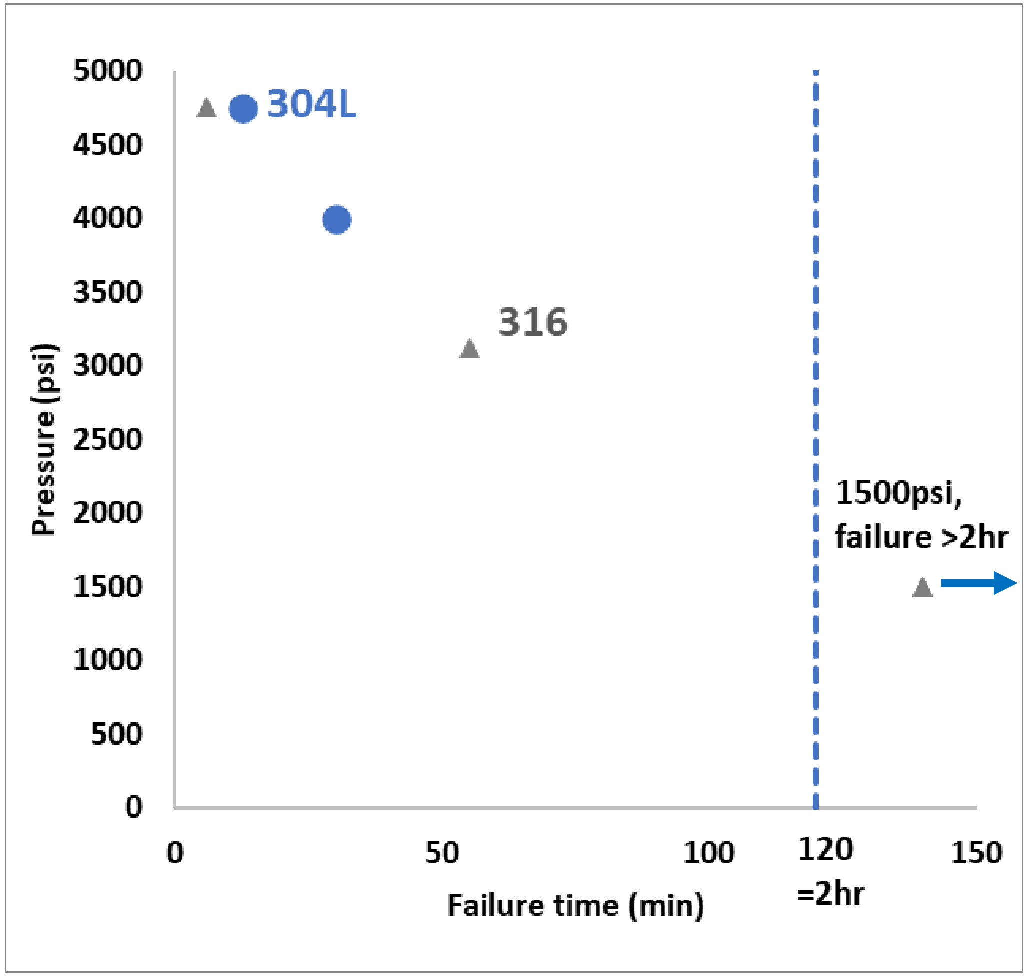
- No tube failures (leaks) after 2hr exposures each 500, 1000, and 1500psi (6hrs total in air at 1000°C)

Series B: Bound pressure range with max pressure achievable in setup: 4750 psi (~3 x ASME B31.1 max. pressure)

- 304L: Failed at 20min, 4750psi
- 316: Failed at 10min, 4750psi

Series C: Further refine pressure-time relationship with intermediate pressure tests (split difference in A and B pressures)

- 304L: Failed at 30min, 4000psi



Takeaways: 1) Survival for 2 hrs at 1500psi suggests appropriate conservatism in B31.1 max. pressure calculations,
2) Both tubes sustained ~3x max. pressure (4750 psi) for a 10's of minutes

Comparing Stress-Failure Time Results to Literature

Multiple 1000°C test series performed; applied pressure adjusted

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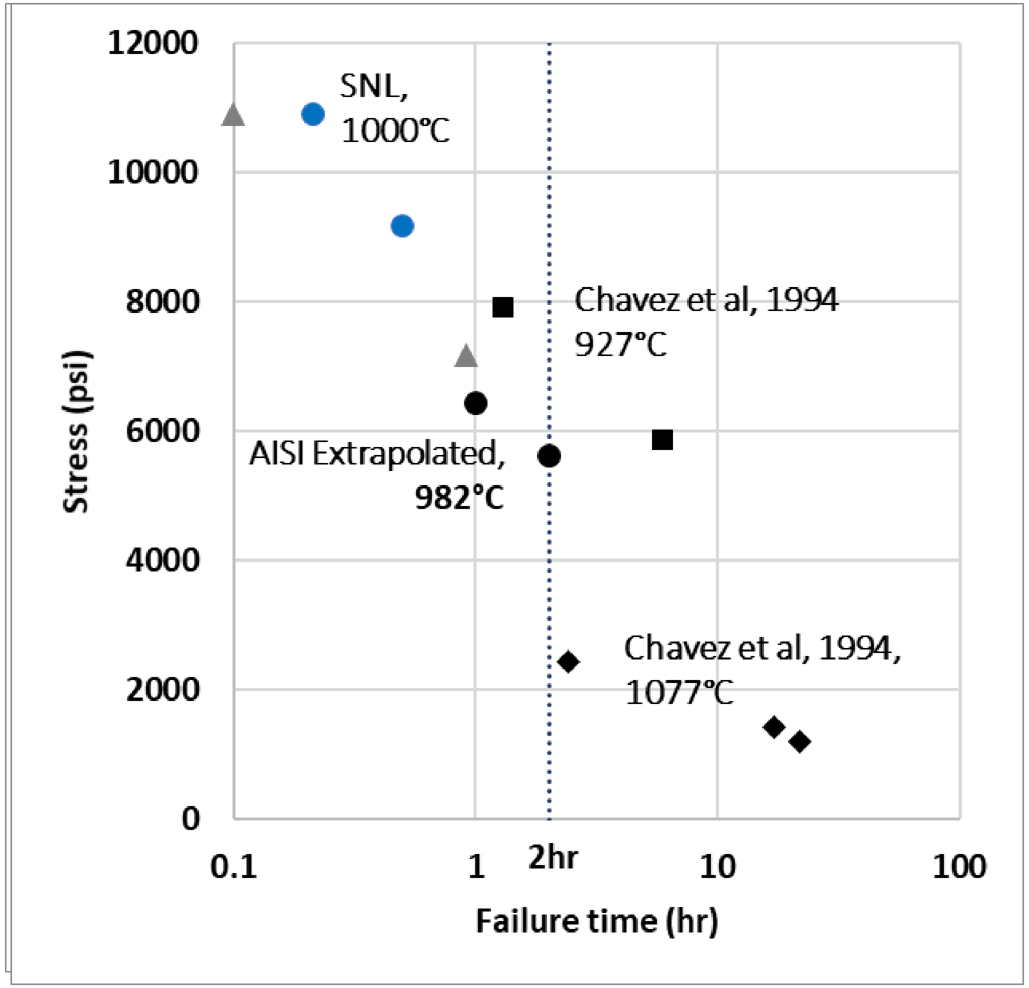


Short-time stress-rupture data not unreasonable when compared to literature data; longer hold tests (and conventional creep tests) needed to better define and compare trends

Failure Occurred in Tube Body; Notable Oxidation Observed

Bending of tubes at pinched ends suggests notable softening

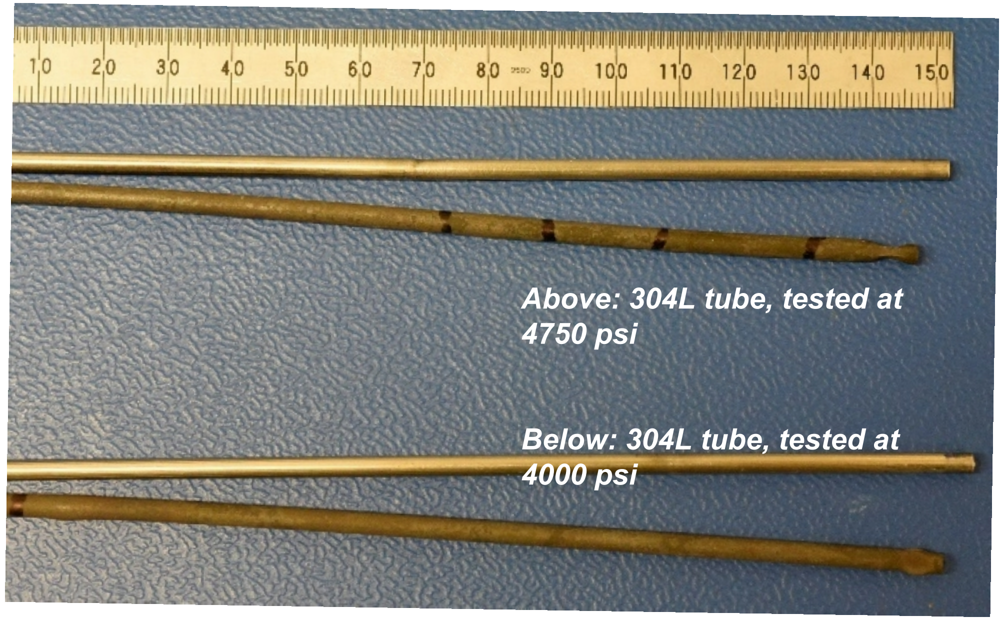
- At high temperature, weight of the pinch weld and TC likely caused ends to droop

No tubes failed at pinch weld

- Supports understanding of relative weld vs tube strength
- Black marks indicate crack locations, i.e. some tubes had multiple failure points
- Bulging was sometimes observed adjacent to crack locations, but not always

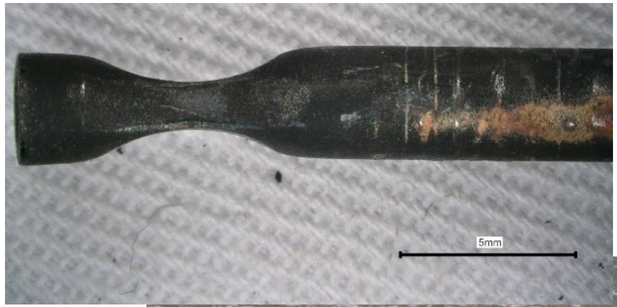
Oxidation apparent on all specimens

- Qualitative differences in oxide color and appearance observed



Above: 304L tube, tested at 4750 psi

Below: 304L tube, tested at 4000 psi

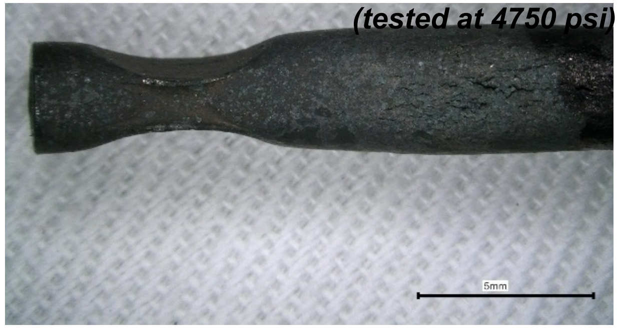


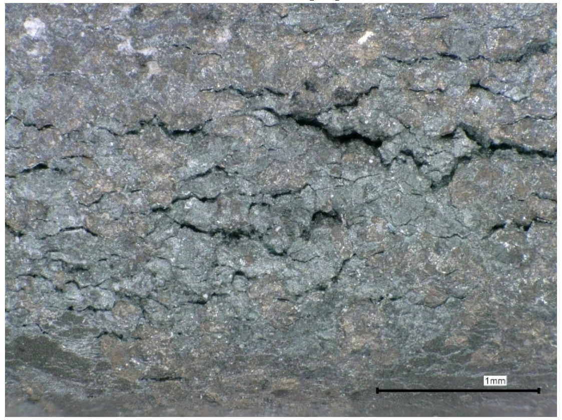
Left: 316 pinch weld showing notable oxidation

Below: Example crack in 316 tube (tested at 4750 psi)

Below: 304L pinch weld showing notable oxidation

Right: Example crack in 304L tube (tested at 4750 psi)





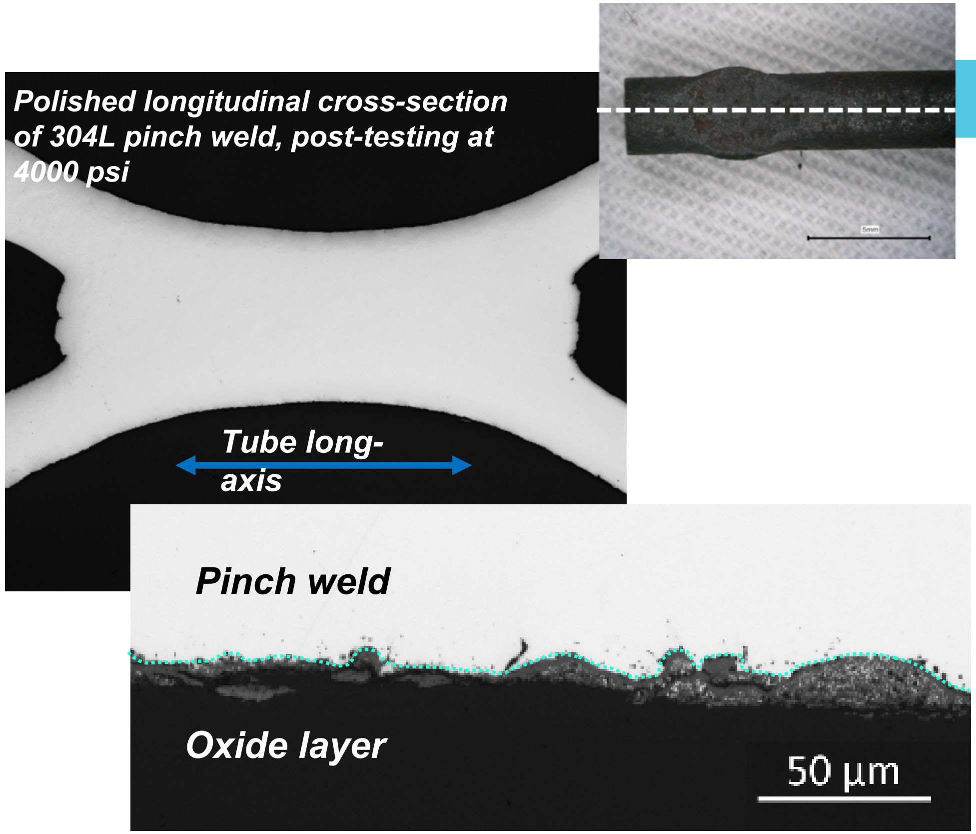
Pinch Weld Integrity Maintained

In all cases, resistance pinch weld appeared overall unaffected post-testing in all cases

- Neither increasing pressure, or exposure (oxidizing) time at temperature degraded welds
- Note absence of porosity, bond line in polished cross

Oxide appears intermittent and thin in cross-section

- Intermittent layer thickness may be a result of combined natural variability in oxide thickness, and some loss of oxide during sample prep
- Comparisons in oxide layer thickness are ongoing

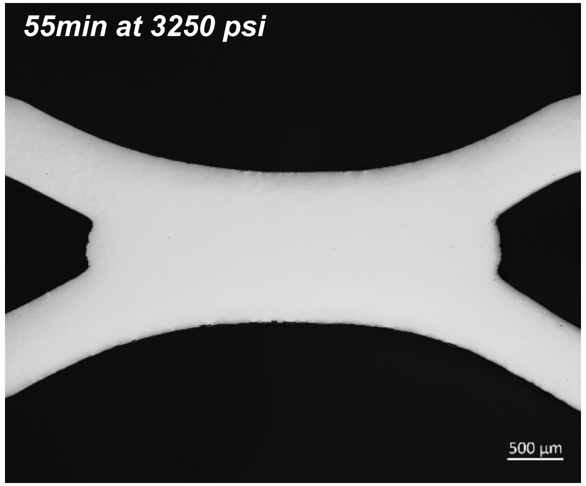


Polished longitudinal cross-section of 304L pinch weld, post-testing at 4000 psi

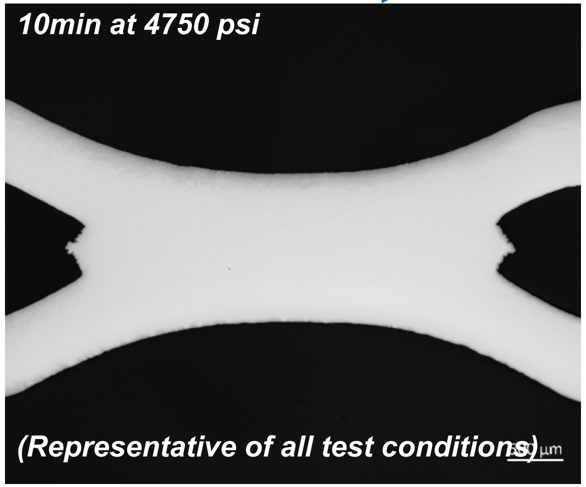
Increasing applied pressure

2hrs each at 500, 1000, 1500 psi

***6hr total, highest exposure time in oxidizing environment*



55min at 3250 psi



10min at 4750 psi

(Representative of all test conditions)

Pinch welds, 316 tubing, post-testing at 1000C

Cracking Observed on Tube ID and OD

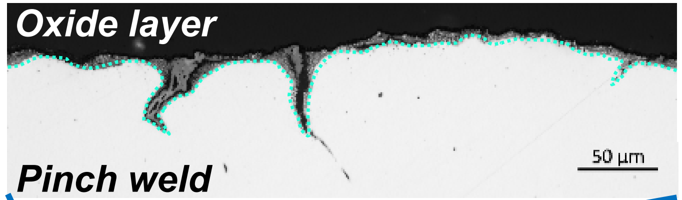
Transverse sections of tube as-received, heat treated only, and heat treated+ surface cracks were compared in an effort to isolate contributions of oxidation versus pressure to failure

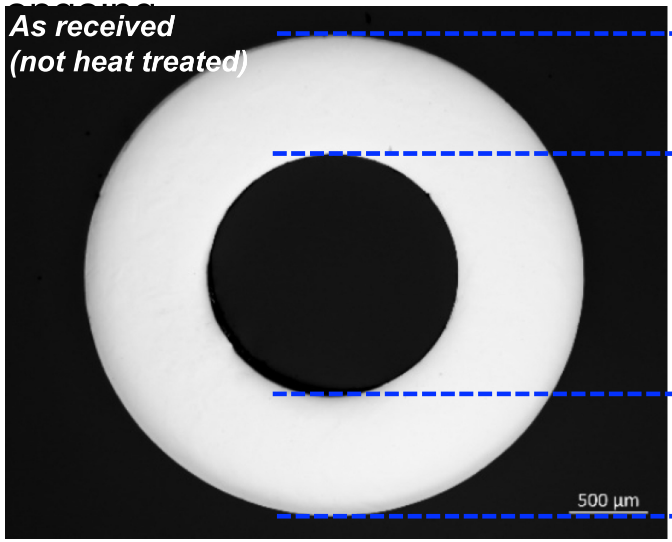
Heat treated sections:

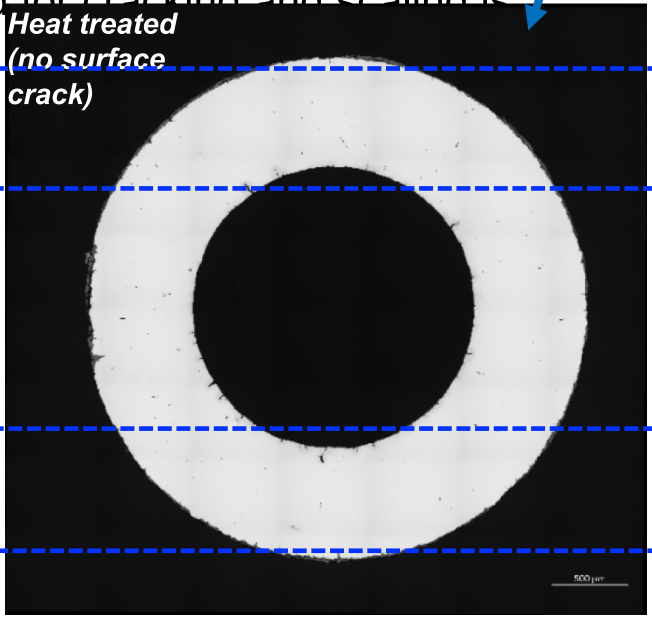
- Expansion of tube ID and OD observed
- Surface oxide observed; similar character to oxide on pinch weld
- Most severe cracking (amount and extent) in surface-cracked regions
- Development of quantification method for cracking and scaling is ongoing

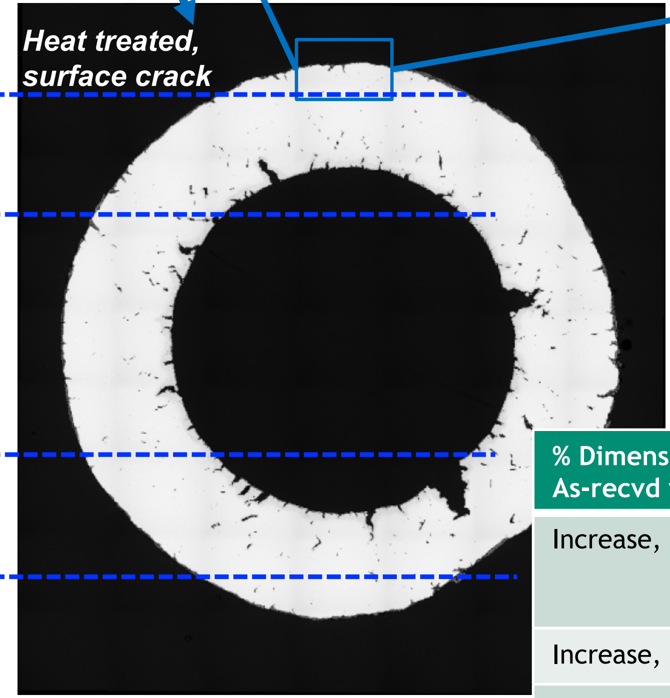
Uncracked, heat treated

Cracked, heat treated





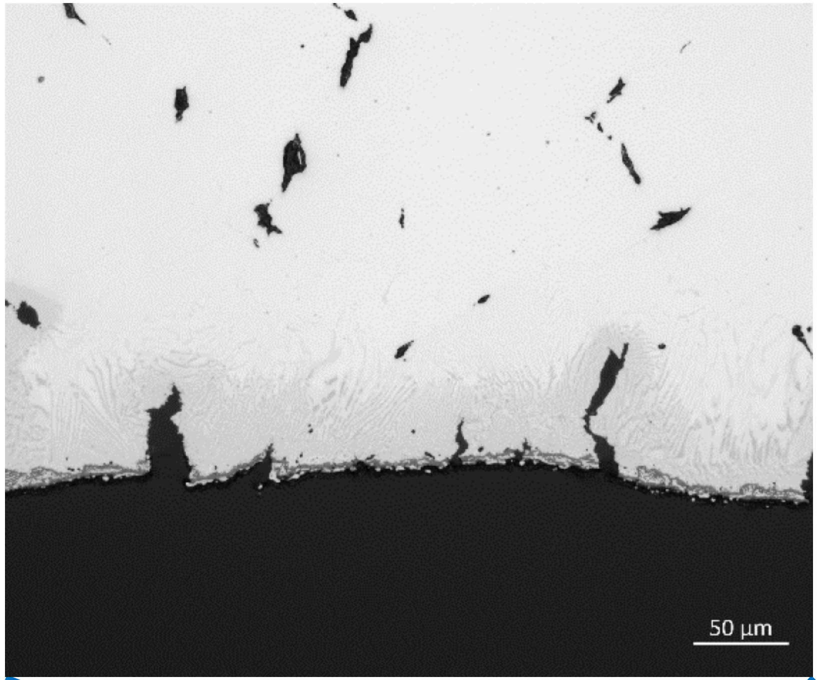




304L tubing, post-testing at 4750 psi

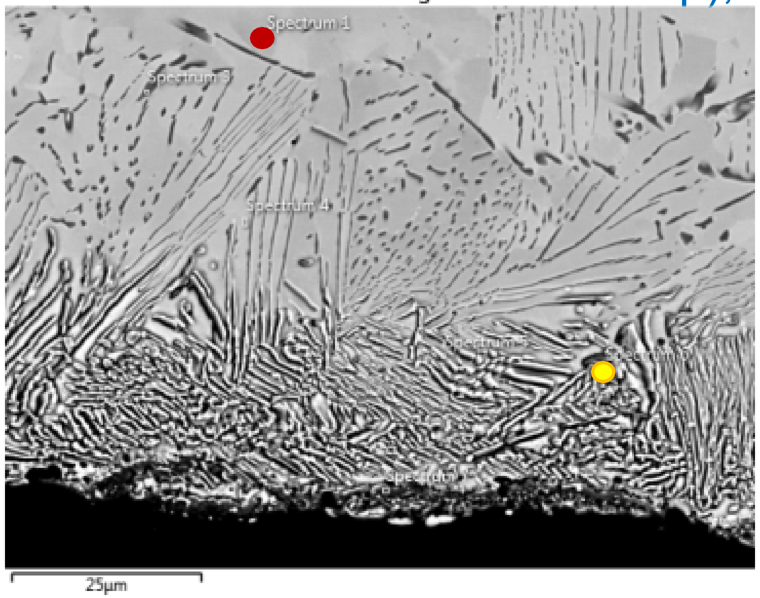
% Dimensional Change, As-recvd vs Surface Cracked	
Increase, OD:	9%- calipers, 11% images
Increase, ID:	29%
Wall thinning:	17%

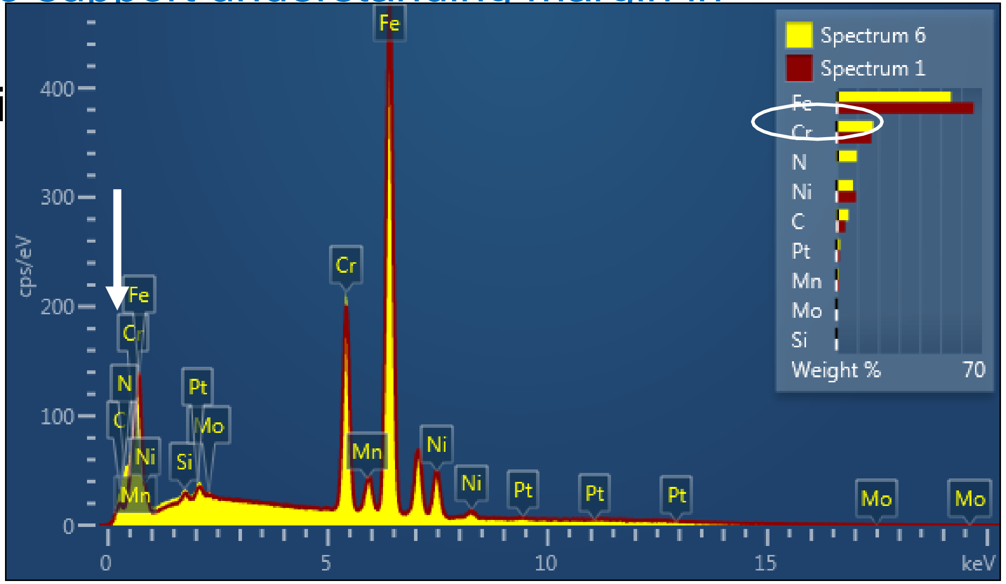
Cracking Observed on Tube ID and OD

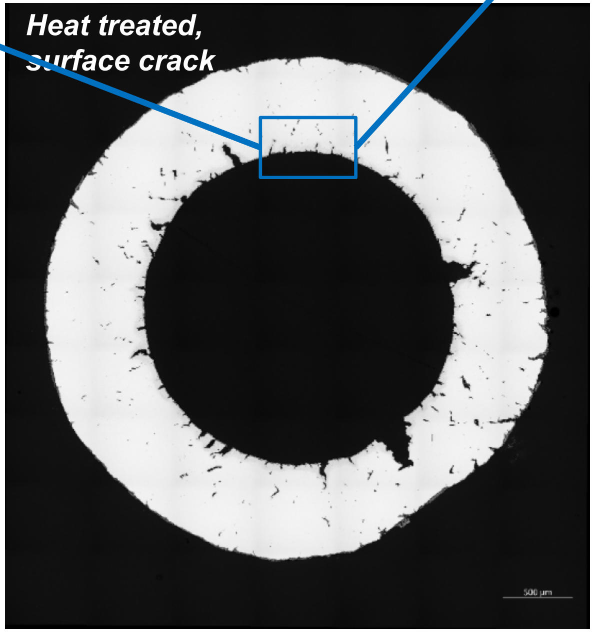


Unexpected observation:

- Lamellar features associated with cracks on tube ID
- Identified at N-rich phases; recall: Pressurization was with [nitrogen]
- Interactions between N and Fe are known, and lower temperature nitriding is well studied (not associated with pressurization)
- Property degradation associated with N-Fe interactions provides additional conservatism (in addition to exterior oxidation and bulk creep), to support understanding margin in







Conclusions and Future Work

- **Pinch weld integrity preserved in 304L and 316 pinch-welded tubes tested at 1000°C at pressures from 500-4750psi**
  - All tubes sustained pressure for at least 10’s of minutes (up to > 2hrs)
  - Stress-rupture vs time data from this study seems to lie between neighboring temperatures reasonably well (if trends were extrapolated); additional tests at longer times would help define behavior
- **All tubes showed some surface oxidation and cracking**
  - Oxide layer thickness comparisons complicated by natural variation and potentially loss of layer during metallography
  - Cracking was most extensive in regions that also exhibited surface cracks; method to quantify and compare extent of cracking is under development
- **N-rich lamellae associated with ID cracks**
  - Likely the result of nitriding from N used for pressurization
  - Additional characterization work is ongoing
- **Future work:**
  - Experiments to decouple oxidation, creep, and nitriding effects
  - Creep testing of 304L and 316 to further define elevated temperature stress-rupture behavior