# Cracking Risk Mitigation in Molten Salt 347H SS Hot Tank Welds

Zhenzhen Yu[1], Timothy Pickle[1], Yu Hong[1], Judith Vidal[2], & Chad Augustine[2]

Technical Track: PV, Thermal, and Storage Session

1. Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO 80401

2. National Renewable Energy Laboratory, Golden, CO 80401

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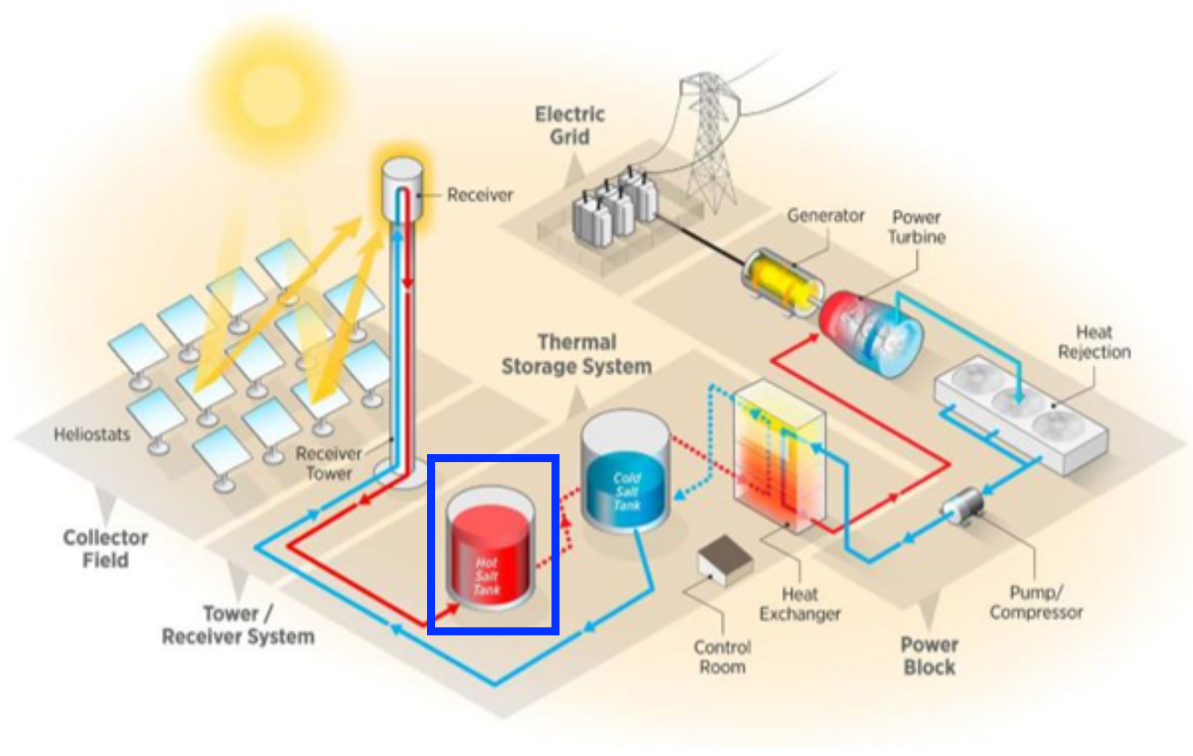
# Reported Cracking Issues in High Temperature Components

- More than 50 reheat cracking issues have been reported for austenitic steels (including 347H and 316H SS) [1,2]
  - Majority of the failures had no PWHT during fabrication
- Some reported cracking in HAZ of thick plates in high temperature service [3]
  - 347, 321, 316Nb, 310, 309, 316, and 304 SS
- TNO report on reheat cracking related failures in other alloys [4]
  - 800H, 16Cr13NiN, 617, 625, 304H, 321H, 347H, 310, 25/35Nb and 601 alloys
- Majority of reported alloys are precipitation strengthened.

[1] H. van Wortel, "Control of Relaxation Cracking in Austenitic High Temperature Components," presented at the NACE Corrosion, Nashville, TN, 2007.
[2]J. C. v. Vortel, "Prevention of Relaxation Cracking By Material Selection and or Heat Treatment," 2000.
[3] J. R.D. Thomas, "HAZ Cracking in Thick Section of Austenitic Stainless Steels-Part 1," *Welding Journal,* 1984.
[4] E. C. B. Dillingh, A; Aulbers, A.P., "Stress Relaxation Cracking-Augmented Recommended Practice," TNO2016.

# Cracking Risks in 347H Hot Tank Welds




CSP schematic [1]

- Cracks in the floor welds of thermal energy storage hot tanks in 2nd generation CSP
- Approximately 2” thick welds
- Tank material and weld filler- 347H SS
- Max service temperature ~ 565°C


[1] M. Mehos, C. Turchi, J. Vidal, M. Wagner, Z. Ma, C. Ho*, et al.*, "Concentrating Solar Power Gen3 Demonstration Roadmap," NREL/TP-5500-67464 January 2017.

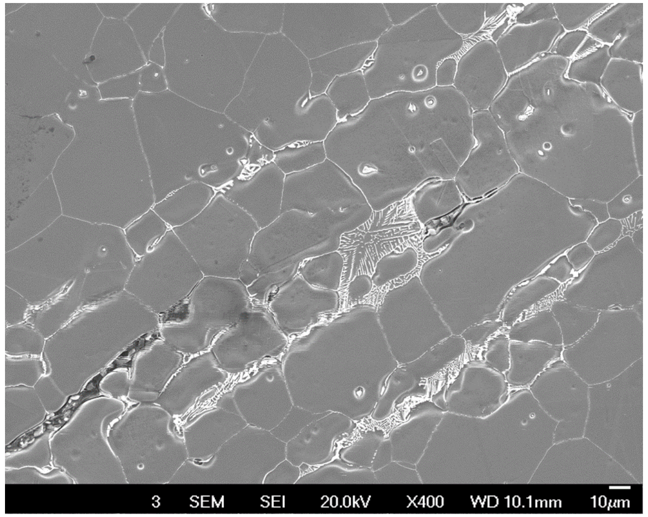
# 347H Stainless Steel Cracking Susceptibility

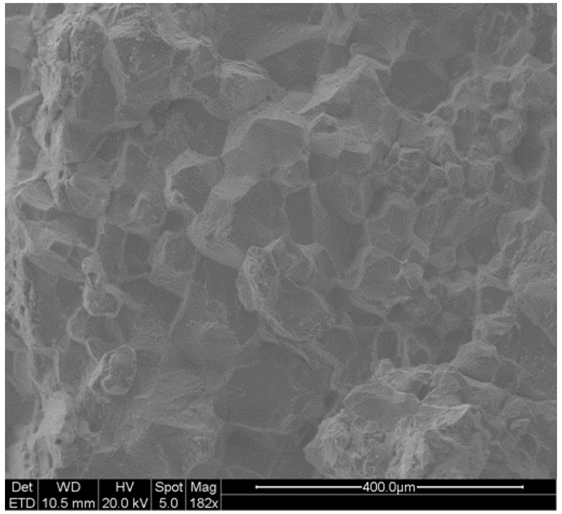
- The nominal alloying composition (wt%) of AISI type 347H stainless steel:

| C | N | Ni | Cr | Mo | Mn | Nb | Si | Cu |
|---|---|---|---|---|---|---|---|---|
| 0.05 | 0.031 | 9.11 | 17.29 | 0.32 | 1.01 | 0.58 | 0.51 | 0.21 |

- Nb stabilized 347H SS [1]
  - Mitigation of sensitization associated with formation of $Cr_{23}C_6$
  - Nb {C,N} precipitation strengthening at moderately elevated temperature (e.g. 590-650ºC)

- Partially melted zone (PMZ) hot cracking by the presence of a liquid film at high temperature [1]
- Ductility dip cracking in multi-pass welding by elevated temperature grain boundary creep [2, 3]
- Reheat cracking or stress-relief/relaxation cracking on grain boundaries [3, 4]




[1] R. W. Messler and L. Li, *Science and Technology of Welding and Joining,* vol. 2, p. 10, 1997.

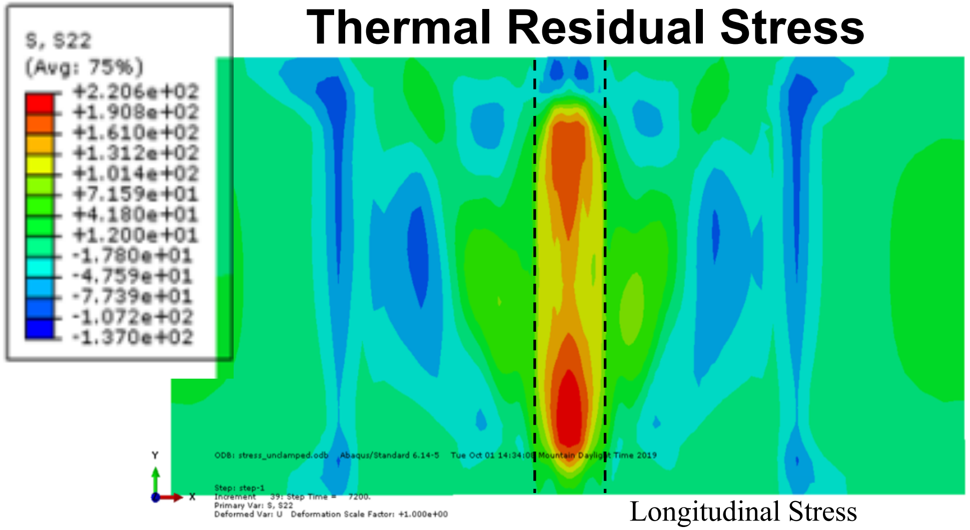
[2] J. R.D. Thomas, *Welding Journal,* 1984.

[3] D. K. J. Lippold, *Welding Metallurgy and Weldability of Stainless Steels*, ed: John Wiley and Sons, Inc., 2005.

[4] R. Kant and J. N. DuPont, *Welding Journal,* vol. 98, pp. 29-49, 2019.

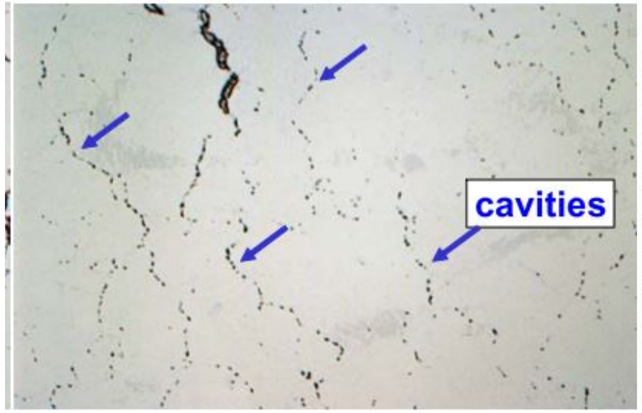
# Stress relaxation cracking characteristics

## Thermal Residual Stress

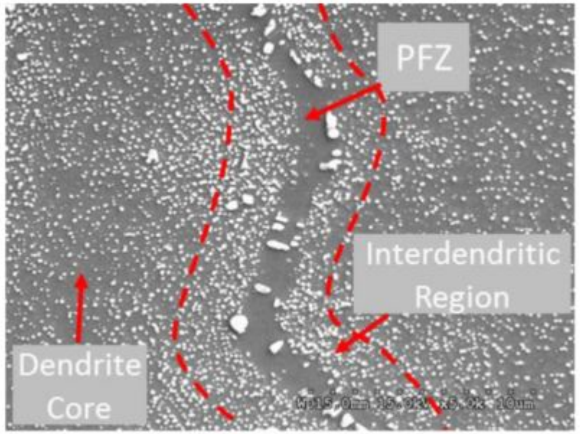



Longitudinal Stress

## + Susceptible Microstructure

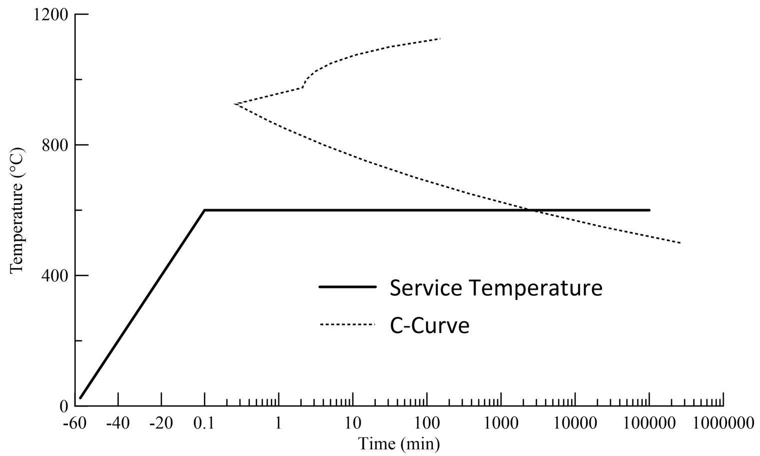



347H cavity formation ahead of crack [1]

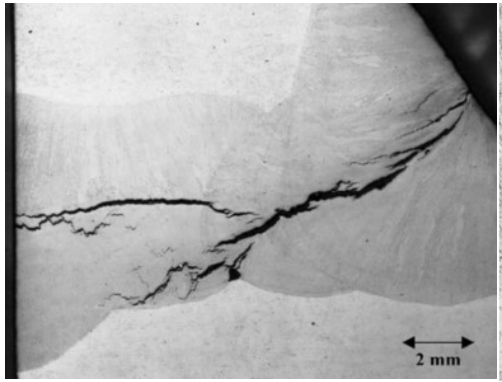



γ’ precipitation and PFZ in 740H WM [2]

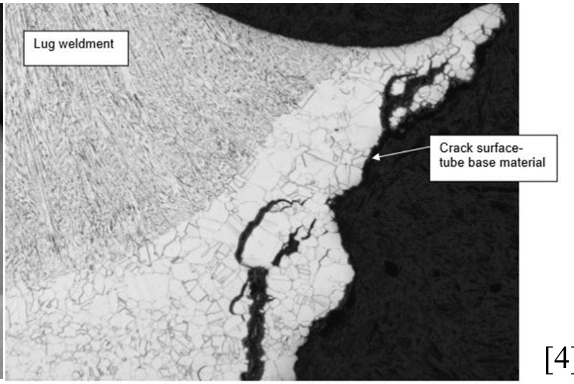
## + Reheating




## CRACKING!




[3]




[4]


[1] H. van Wortel, Control of Relaxation Cracking in Austenitic High Temperature Components, NACE Corros. Conf., 2007: pp. 1–16.

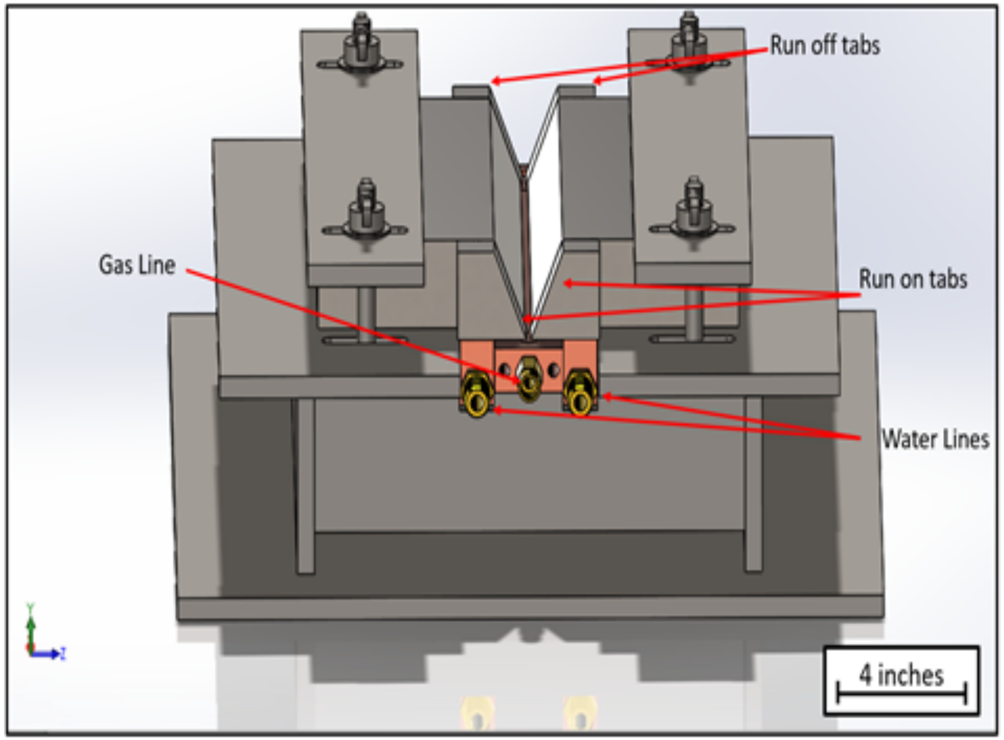
[2]J. A. Siefert, J. P. Shingledecker, J. N. DuPont, and S. A. David*Science and Technology of Welding and Joining,* vol. 21, pp. 397-428, 2016.

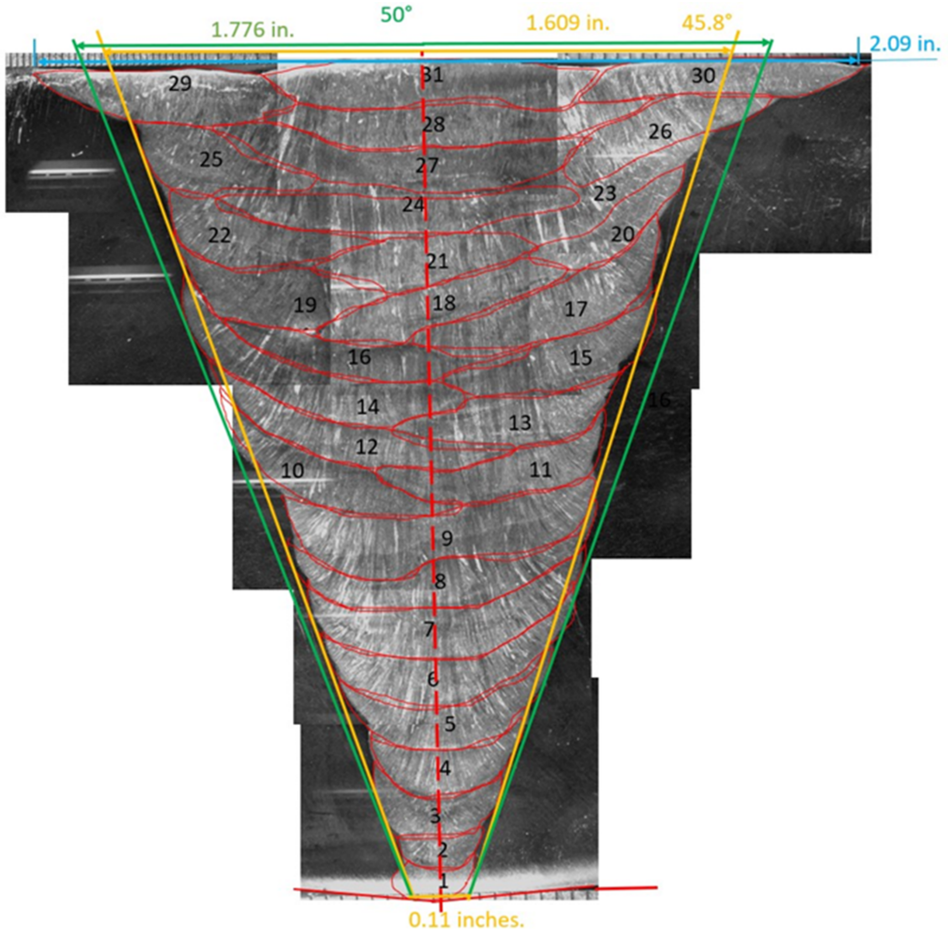
[3], D. K. J. Lippold, *Welding Metallurgy and Weldability of Stainless Steels*, ed: John Wiley and Sons, Inc., 2005.

[4] Xcel Energy Failure Analysis of superheat tubes

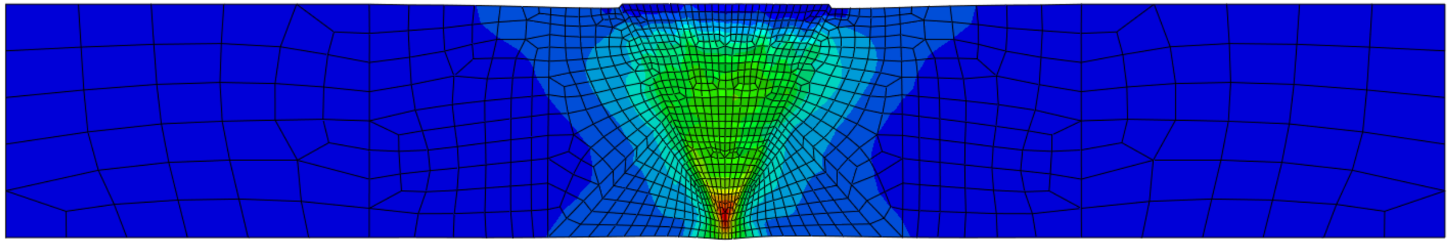
# Weldment Duplication

- 2” thick, 12” length, 12” wide
- Single v groove, 50° angle
- GTAW/SMAW processes
- High heat input~30-70 kJ/in. arc energy per unit length



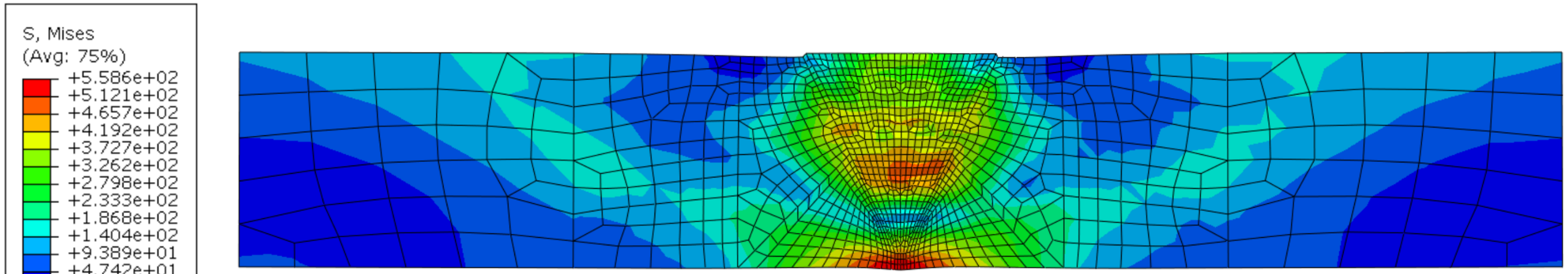




FEM mesh

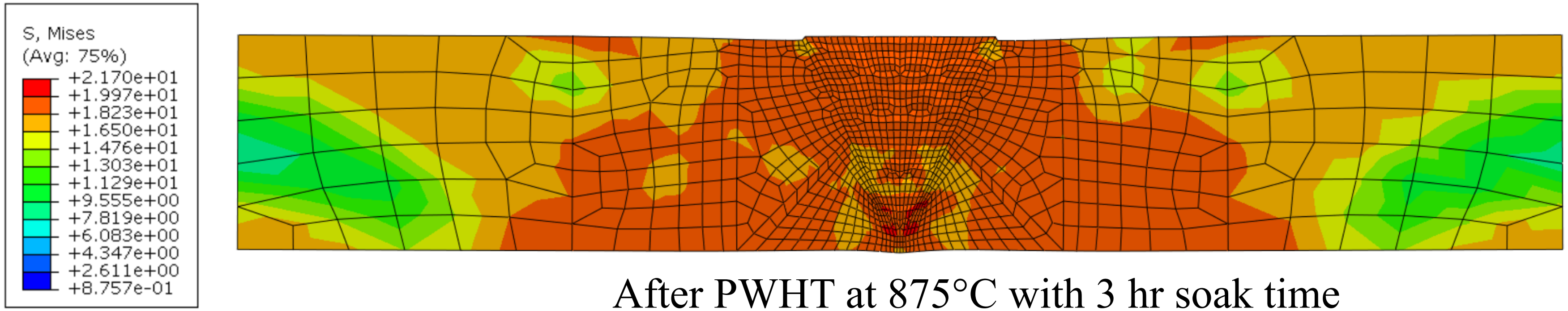


# FE Modeling of Residual Stress Contours

- Von Mises stress calculations exhibit high tensile residual stress in fusion zone (FZ) and heat-affected zone (HAZ);
- PWHT can lead to significant stress reduction;
- How does PWHT and service temperatures affect SRC susceptibility?



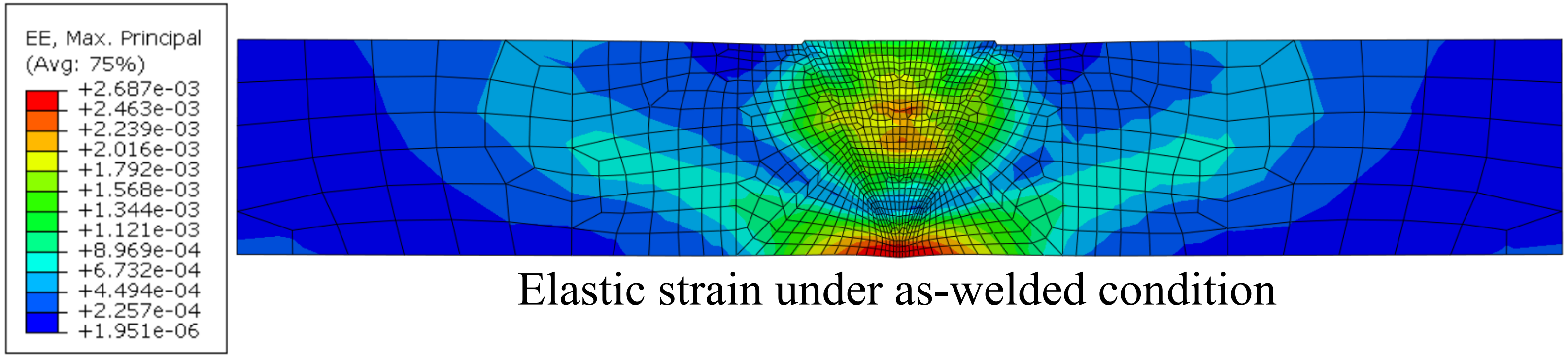

As-Welded (Unclamped)



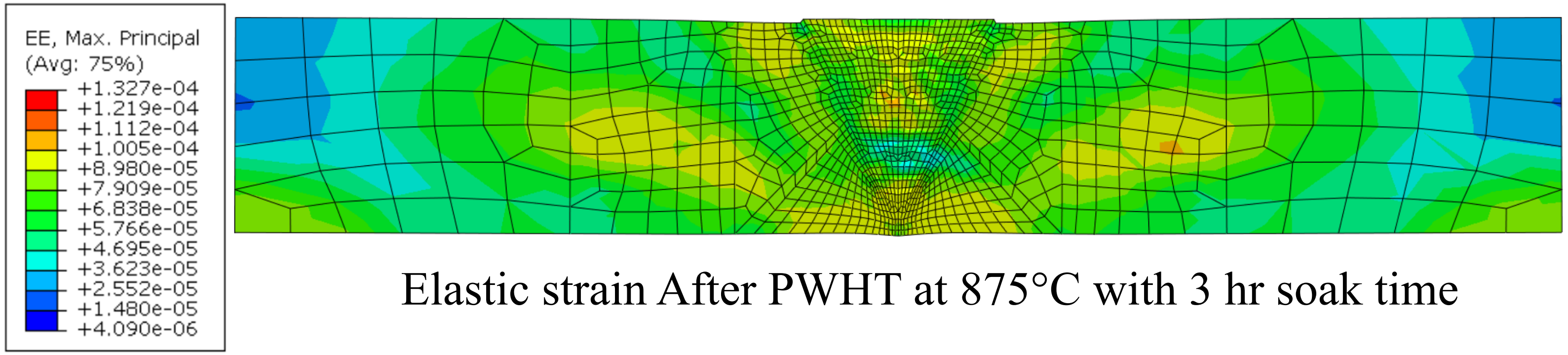

After PWHT at 875°C with 3 hr soak time

# FE Modeling of Welding and PWHT induced deformation

- Welding induced elastic strain can be up to 0.2% in weld root;
- PWHT assists to reduce elastic strain by creeping.



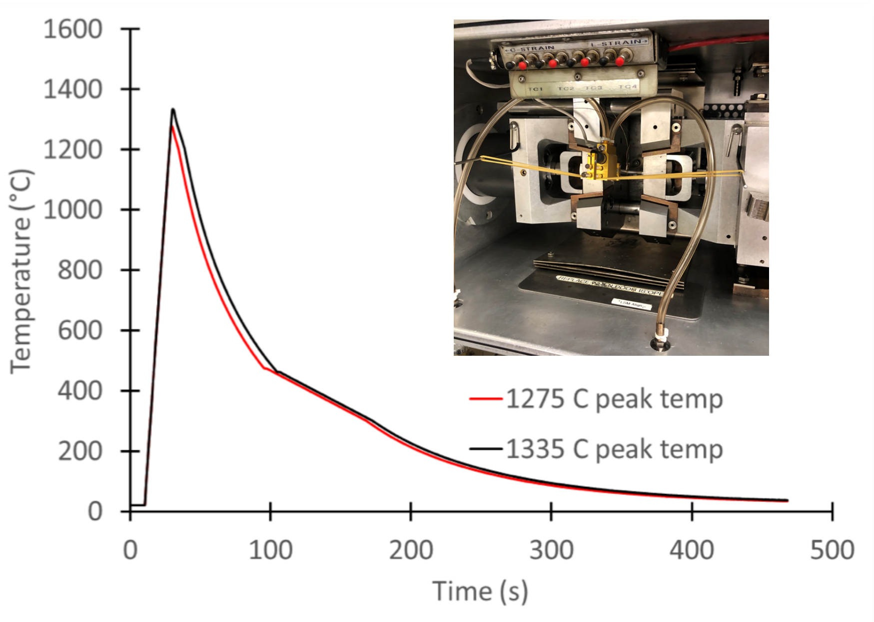

Elastic strain under as-welded condition




Elastic strain After PWHT at 875°C with 3 hr soak time

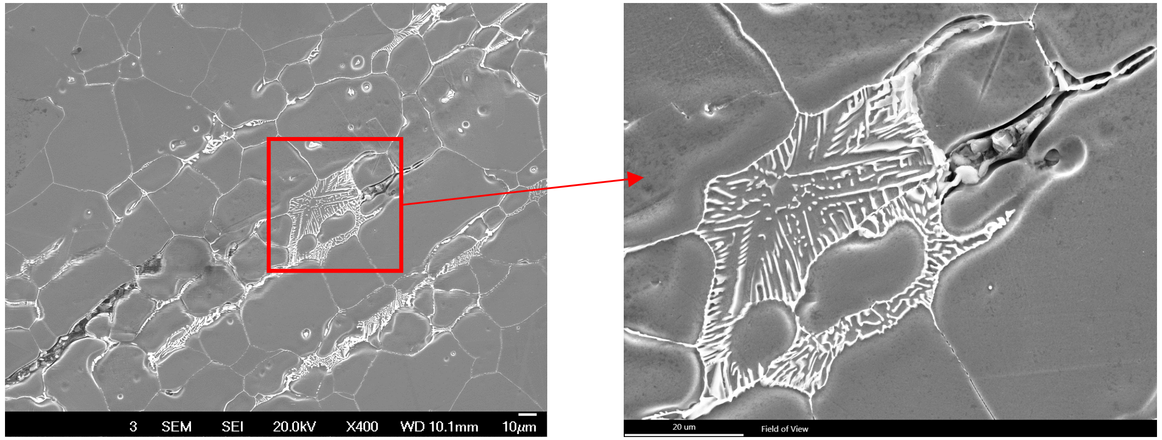
# Gleeble Simulation of Thermal History

**First step**:
Simulate thermal cycle experienced by HAZ




- Variable: peak temperature
- Force = 0 kN

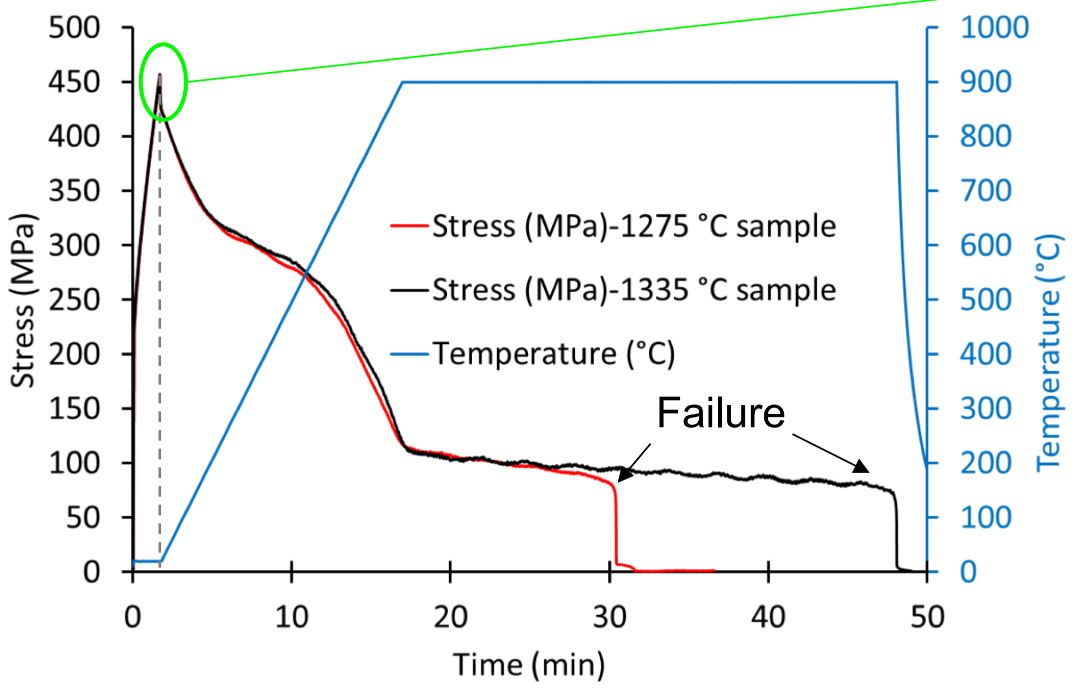
Welding microstructures in partially melted zone (PMZ)




- PMZ liquation (1335 °C peak temp)
- White feature: Nb (C,N)
- Dark grey: γ-austenite

# Gleeble Testing of Reheat Cracking Susceptibility

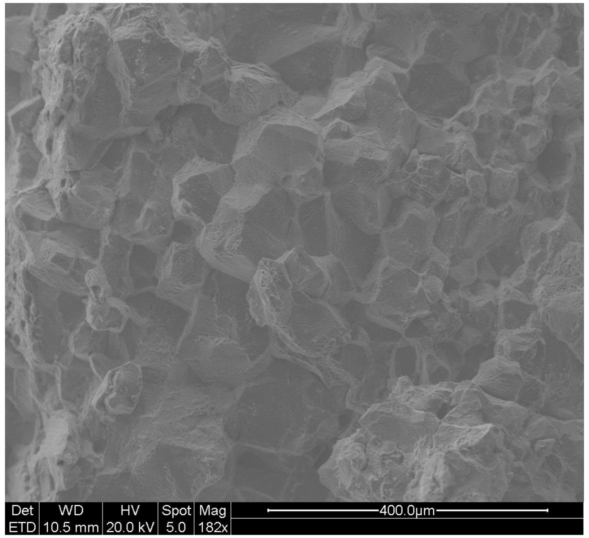
**Second step**: crack susceptibility test simulating residual stress/strain and service temperature





Presence of α' TRIP martensite with 17.4% of applied strain

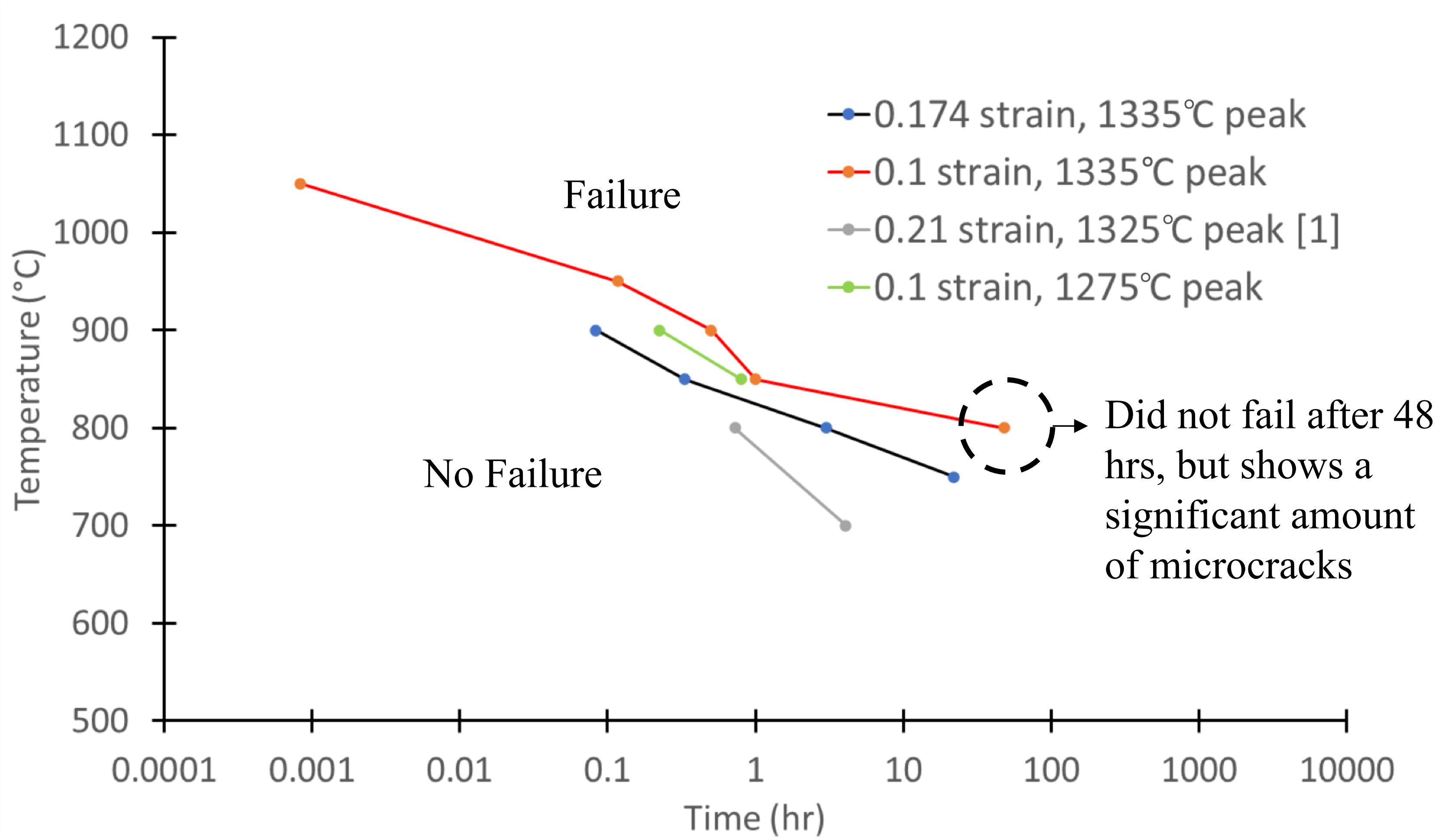
Fracture surface



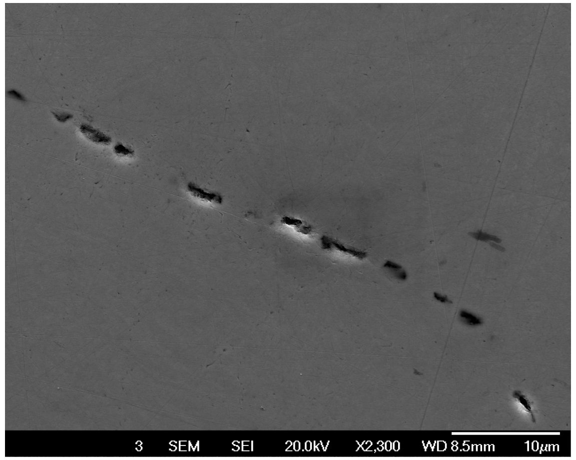

Intergranular cracking

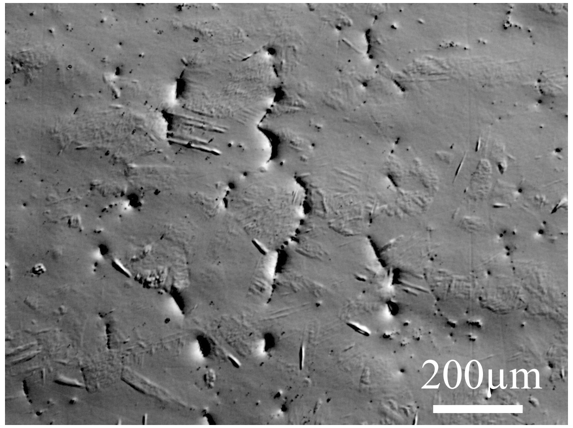
- Stroke moves during heating to eliminate thermal expansion effect on stress drop but $\Delta\varepsilon=0$ at isothermal temperature

# Reheat Cracking Susceptibility Result




Did not fail after 48 hrs, but shows a significant amount of microcracks

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[1]R. Kant and J. N. DuPont, "Stress Relief Cracking Susceptibility in High-Temperature Alloys," *Welding Journal,* vol. 98, pp. 29-49, 2019.

# Conclusions and Potential Mitigation Solutions

**Conclusions**

- 347H SS thick weldments are susceptible to reheat cracking during TES service temperatures
- PMZ and CGHAZ are susceptible to SRC during one-step PWHT

**Future work on mitigation solutions:**

- For existing tanks, run 2-step PWHT simulations on Gleeble:
  - 1st step at lower temps for stress relief
  - 2nd step at higher temps to stabilize Nb (C,N)
- For future tanks:
  - Evaluate crack susceptibility of 316L SS with low carbon (a new nuclear grade SS) as a possible alternative material
  - Evaluate filler E 16.8.2 with a higher creep rupture strength than 347H SS and a higher creep elongation than 347H filler metal.

# Acknowledgements


- This project is financially supported by Department of Energy SunShot division under grant # DE-EE00033458 & National Renewable Energy Laboratory (NREL)
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