Funded by:

Mechanical Failure Risk Analysis and Management for In-Service CSP Nitrate Hot Tanks

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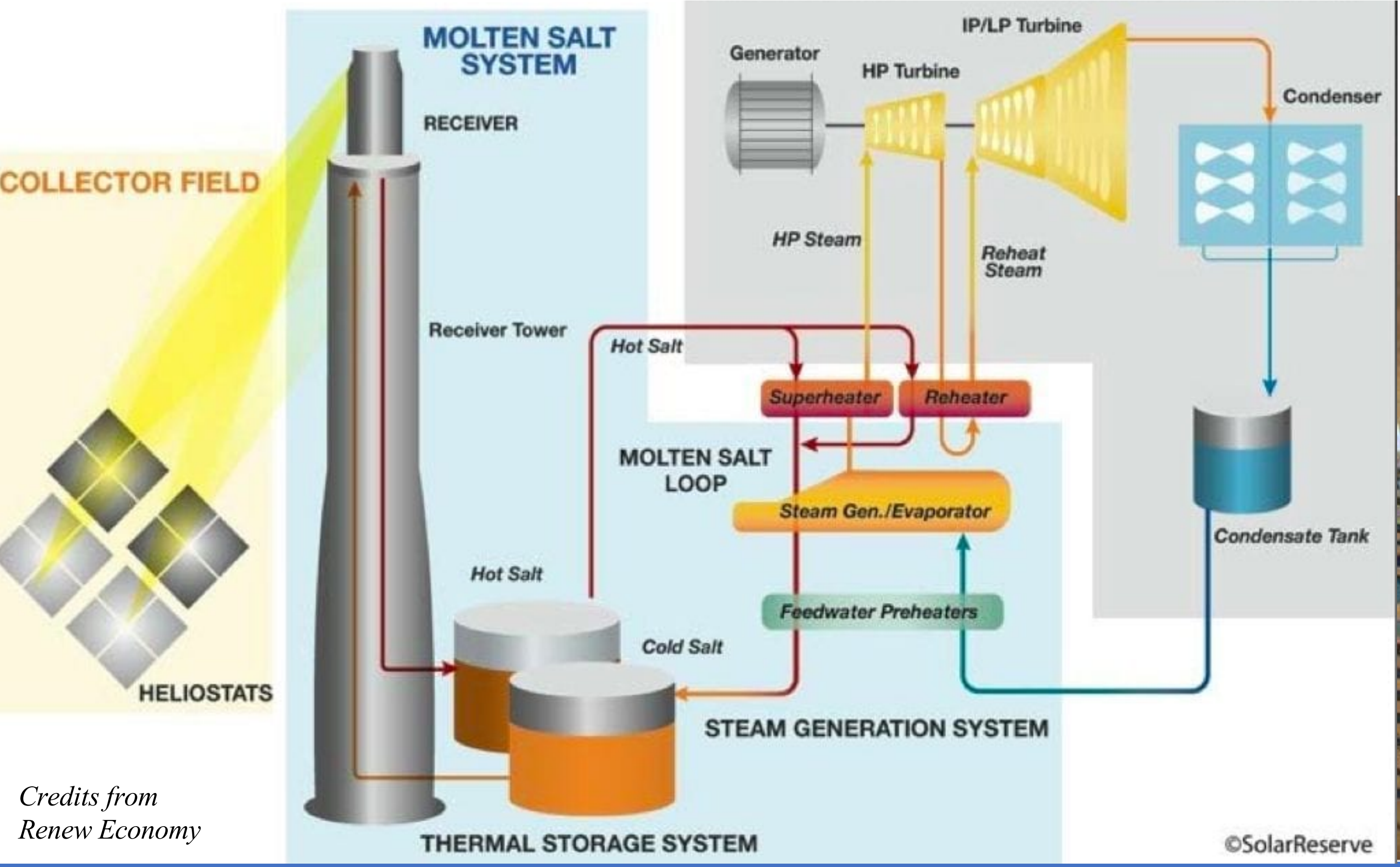
Technical Review Meeting:

Evaluation of Welding Issues in High Nickel and Stainless Steel Alloys for Advanced Energy Systems

March 10, 2021

Concentrating Solar Power (CSP)

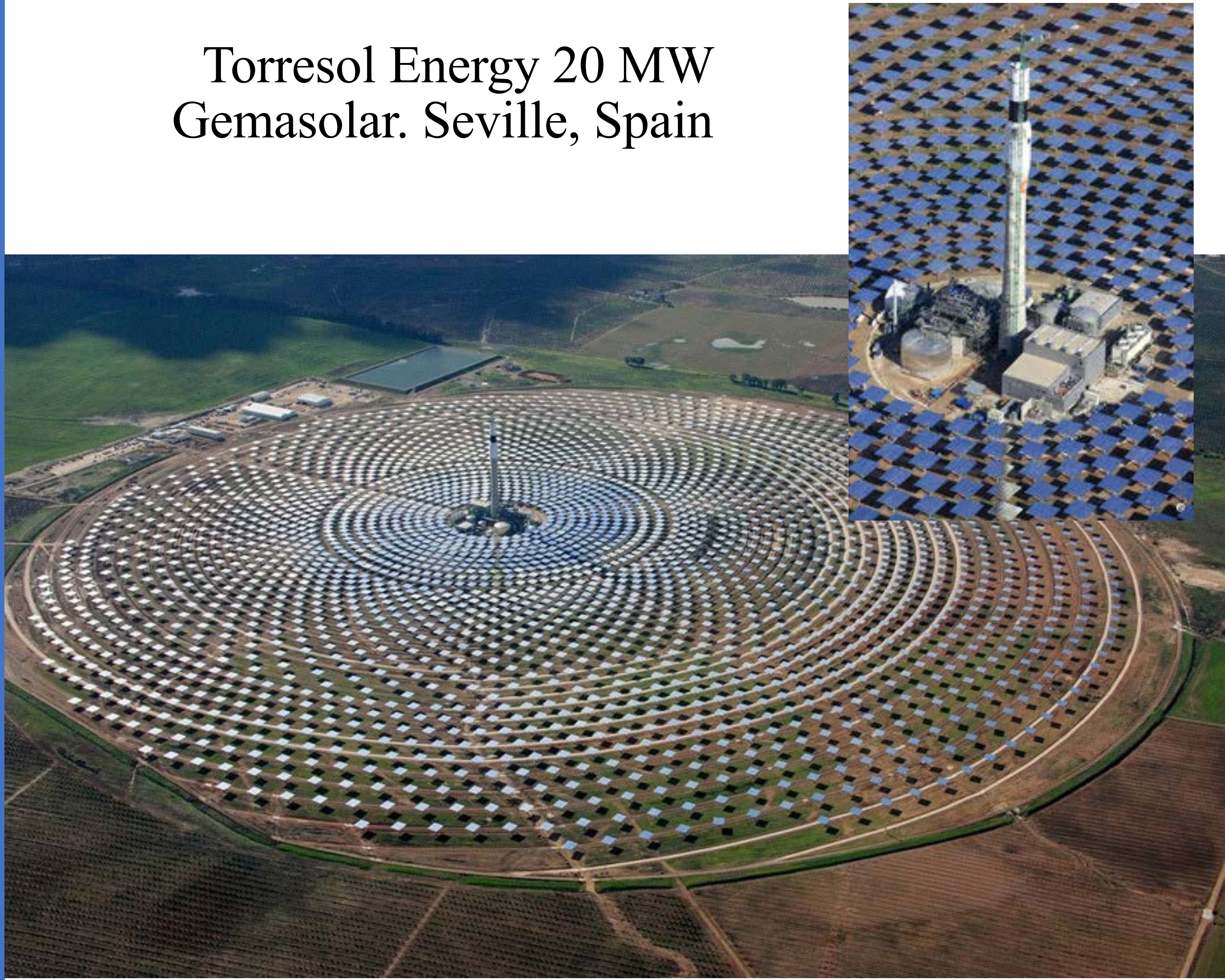


Credits from Renew Economy

How it works: *Solar power towers with integrated storage*

Gen2 Molten Salt State-of-the-Art

Torresol Energy 20 MW Gemasolar. Seville, Spain



- Heat transfer (HTF) and thermal storage (TES) fluid = (Na-K/NO_3);
- Sensible two-tank (565°C, 290°C);
- Power Block = Steam Rankine;
- Alloys used in molten salt loop (pipes, valves, pumps, tank walls, receiver, heat exchanger);

110 MWe Crescent Dunes, Nevada.
10 hours TES

Fast Facts:

- 10 hours of thermal energy storage
- 195-m tall tower
- 1600-acre site
- Hybrid cooling

Crescent Dunes; Tonopah, Nevada

Evolution, progress and challenges of thermal storage in CSP

- Gemasolar and Crescent Dunes 347 SS hot tanks failed after extended service at elevated temperatures (565 °C).
  - Sener-Gemasolar's hot tank (~550°C), had two consecutive fractures.
  - Gemasolar constructed a new tank after the second fracture.
  - Mechanical failure for both plants was reported to be associated with engineering design and implementation issues.
- It has been reported that weldments in 347 SS are prone to fail due to stress relaxation cracking (SRC).
- Post-weld heat treatment (PWHT) after welding 2"-thick plates of 347 SS not performed because following the Code, it is not required.
- Concerns about performing PWHT in the field.

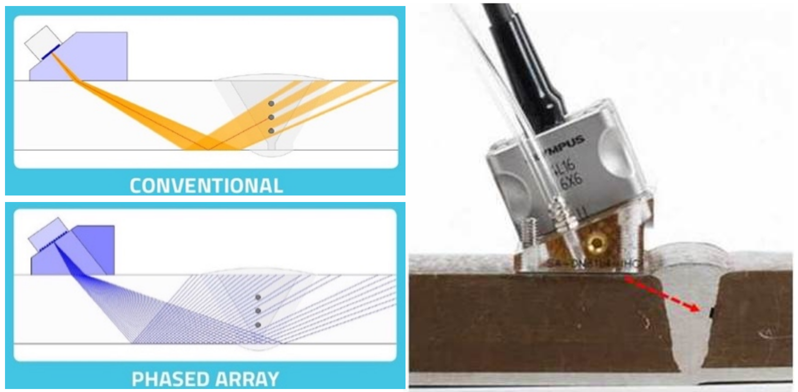
Goals

- Overarching goal is to recommend SRC mitigation protocols to avoid susceptibility to fail through SRC at CSP temperatures:
    - Determine susceptibility of 347SS to fail due to SRC,
    - Evaluate welding protocols employed at commercial scale for tank constructions that could increase SRC susceptibility, and
    - Test new alloys commercially available that are resistant to SRC under the required operating conditions for hot-tank nitrate salt.

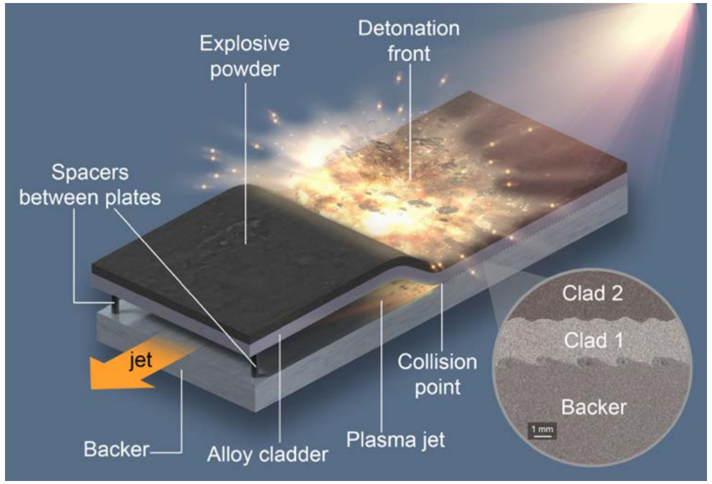
Progress and Opportunity

- SRC may be prevented by:
  - *Performing PWHT,*
  - *Change filler metals (e.g., E309L).*
  - *Use less susceptible wrought alloys (e.g., 316L SS)*
  - *Use appropriate non-destructive evaluations*
  - *Use advanced manufacturing technologies (e.g., metal cladding to decouple corrosion and mechanical strength requirements)*

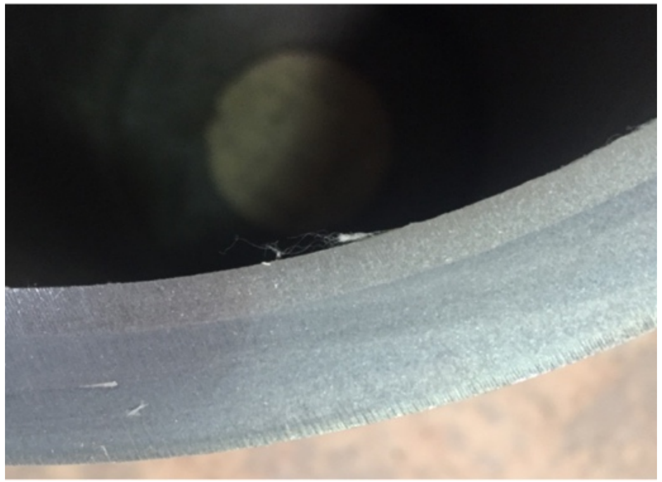
Industrial-scale PWHT with flexible ceramic pads. Credits Heat Ment.



Advantage of phased-array ultrasonic testing (bottom left) compared with conventional ultrasonic testing (top left). Left: Credits Acuren. Right: Credits Olympus.



Mechanism of the explosion-welding cladding. Bond interface microstructure. Courtesy of NobelClad



SS316 cladder on carbon steel pipe from combustion synthesis and centrifugal rotation. Credits from AMS

347H Stainless Steel (Gen2 Hot Tank Alloy)

Nominal alloy composition (wt%) of AISI type 347H stainless steel:

wt %	C	N	Ni	Cr	Mo	Mn	Nb	Si
ASTM A240	0.04-0.1	-	9-13	17-19	-	2	(8 x (C+N))	0.75
Substrate[1]	0.05	0.03	9.1	17.3	0.3	1	0.58	0.5
Weld Metal[2]	0.03	0.03	10.1	19.5	0.2	1.5	0.36	0.5

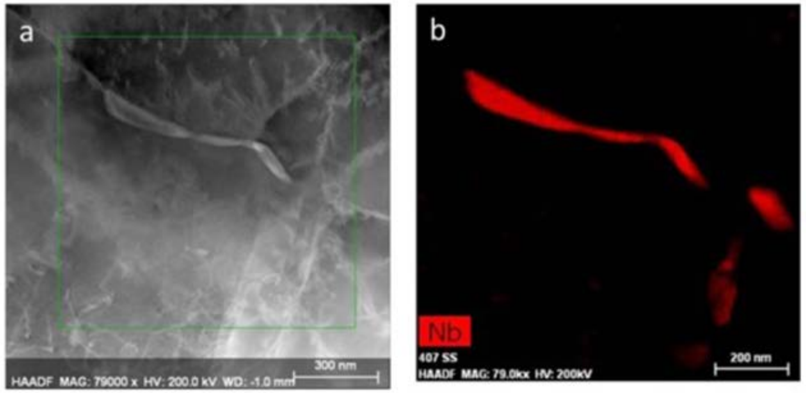
Nb stabilized 347H SS [3]

- Sensitization resistance due to formation of Nb {C,N} over $Cr_{23}C_6$
- High strength at moderately elevated temperature (e.g. 590-650ºC) by Nb {C,N} precipitation strengthening

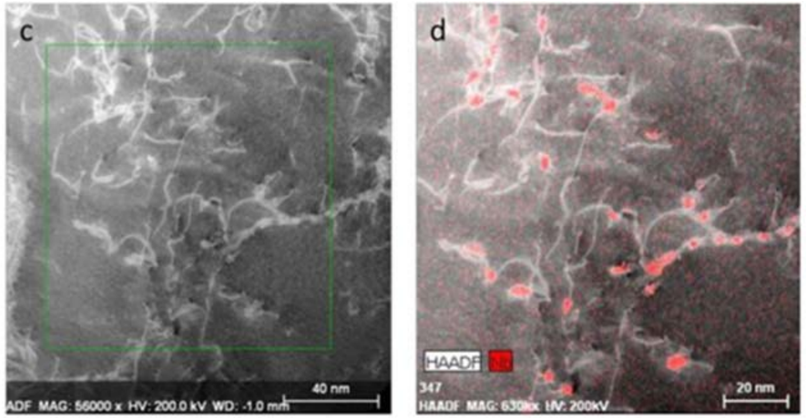
Processing of Plates

- Solution Annealed after hot rolling (1050-1100°C) and water quenched to ambient temp.

Intergranular NbC



Intragranular NbC



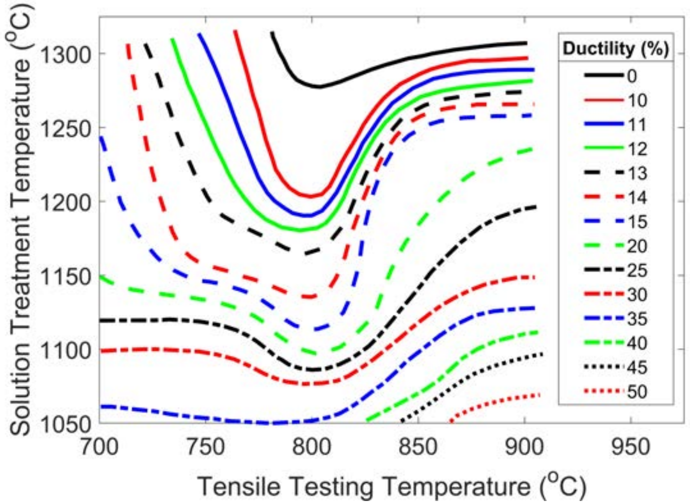
STEM/HAADF images and corresponding Nb elemental maps showing Nb-C precipitation in grain boundaries (a-b) and dislocations within grains (c-d) in as-received material [4]

[1] Composition of alloy used for experiments, provided by Sandmeyer
[2] Excalibur E347-16 SMAW typical all weld metal composition
[3] R.D. Thomas, Jr. and R. W. Messler, WRC 421-Welding type 347 SS-report
[4] B. S. Amirkhiz, S. Xu, J. Liang, and C. Bibby,2016.

Failure Risks in 347 SS Welds with E347

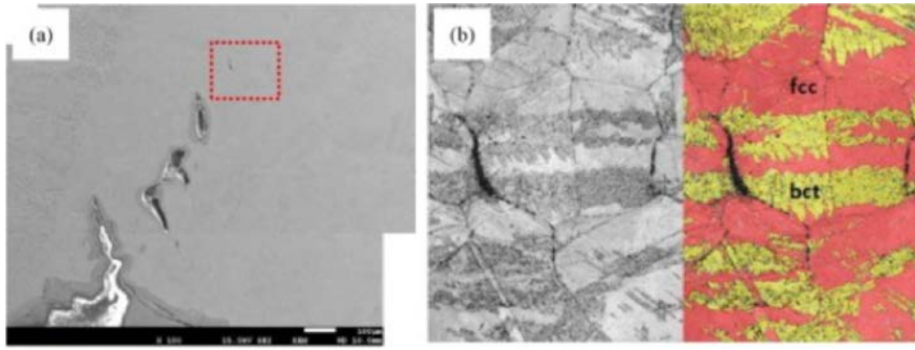
- Partially melted zone (**PMZ**) liquation cracking during welding [1,2]
- Ductility dip cracking in fusion zone (FZ), heat-affected zone (HAZ), and reheated FZ (e.g, multi-pass welds), by elevated temperature grain boundary creep phenomena [3-5]
- Intermediate-temperature embrittlement (e.g. 600 to 900ºC) by formation of sigma phase [7,8]
- "Knifeline" corrosion attack in 347SS welds by dissolution of stabilized carbides and reformation of Cr-rich carbides

Eutectics of Nb rich phases and austenite forming in PMZ along with continuous grain boundary Nb {C,N}



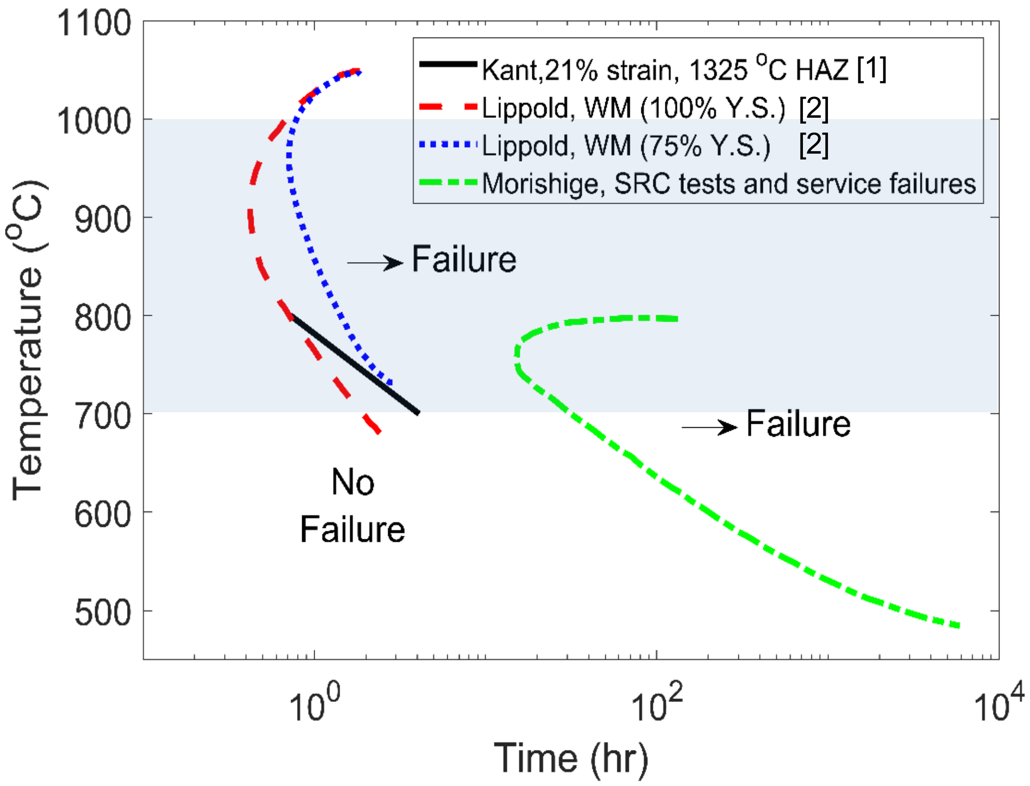
Ductility dip primarily around 800°C with NbC strain age hardening [6]

- Cracking in HAZ associated with transformation induced plasticity (TRIP) [9]



[1] R. W. Messler and L. Li, *Science and Technology of Welding and Joining,*1997.
[2] C.D. Lundin, Welding Journal, 1988.
[3] J. R.D. Thomas, *Welding Journal,* 1984.
[4] D. K. J. Lippold, *Welding Metallurgy and Weldability of Stainless Steels,* 2005.
[5] R.D. Thomas, Jr. and R. W. Messler, WRC 421-Welding type 347 SS-report
[6] K. J. Irvine, et al, *Journal of Iron and Steel Institute,* 1960.
[7] K. X. Guan, X;, Xu, H.; Wang, Z. , Nuclear Engineering and Design, 2005.
[8] M. A. Ghalambaz, M.; Eslami, A.; Bahrami, A., Case Studies in Engineering Failure Analysis, 2017.
[9]H.S. Lee et al. *Engineering Failure Analysis,* 2015.

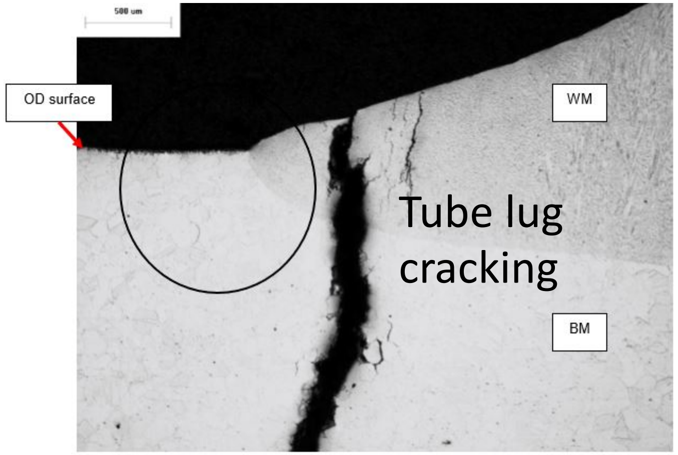
Stress Relaxation Cracking in 347 SS Welds



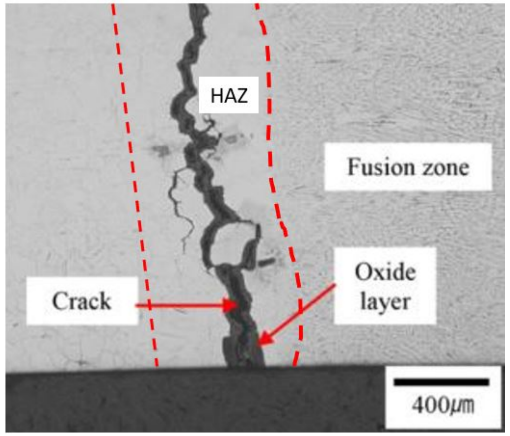
Niobium carbonitrides are reported to be precipitated out in the region of 500-1100˚C, but most active between 700-1000˚C [2].

- Stress relaxation cracking (SRC), as a form of reheat cracking, is the most probable crack type when no PWHT is performed.
- SRC could be promoted by precipitation hardening within the grain interior due to Nb (C,N) precipitation and strain localization in the precipitate free zone (PFZ) during stress relaxation.

[3]



Ex. SRC failure in superheat tubes by Xcel Energy

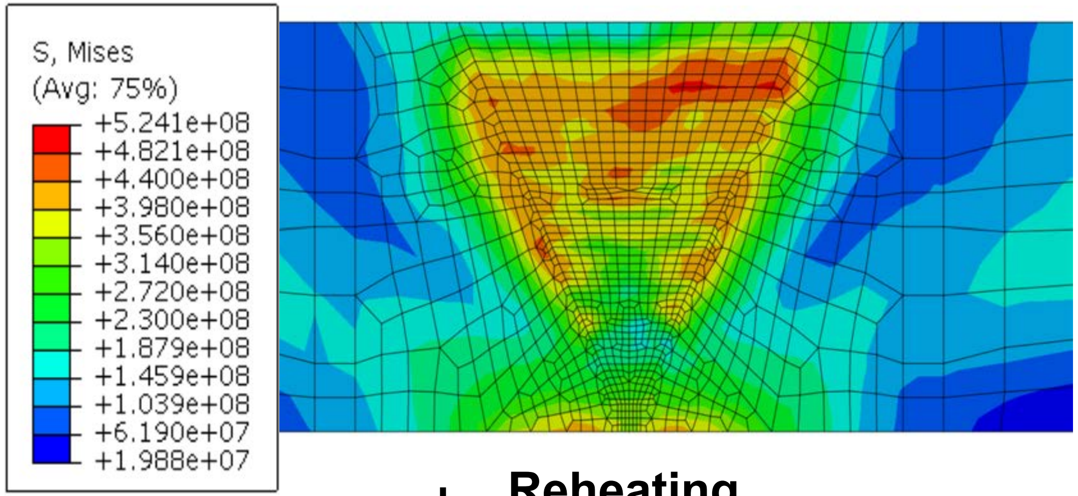


Ex. SRC failure after 5 months in service (595°C) [4]

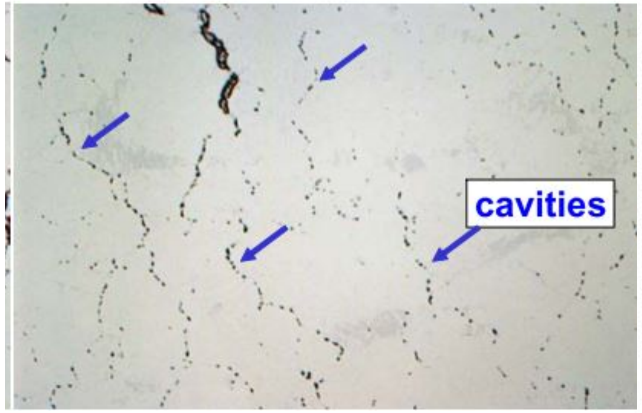
[1] R. Kant and J. N. DuPont, *Welding Journal,* vol. 98, pp. 29-49, 2019.
[2] D. K. J. Lippold, *Welding Metallurgy and Weldability of Stainless Steels*, ed: John Wiley and Sons, Inc., 2005.
[3] .N. Morishige, M. Kuribashi, H. Okabayashi, and T. Naiki, Third International Symposium of the Japan Welding Society, 1978.
[4] H.-s. Lee, et al, *Engineering Failure Analysis,* vol. 57, pp. 413-422, 2015.

Stress Relaxation Cracking Characteristics

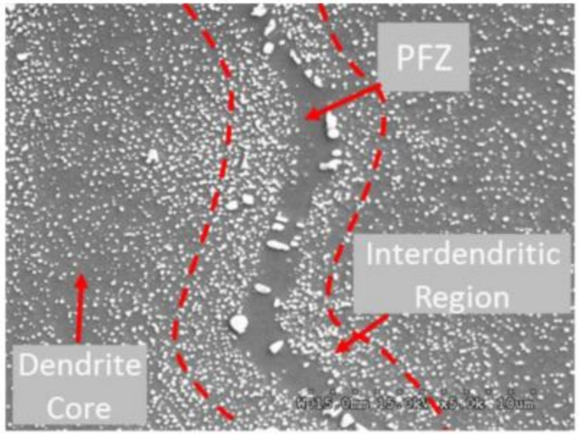
Weld-induced Residual Stress



+ Susceptible Microstructure

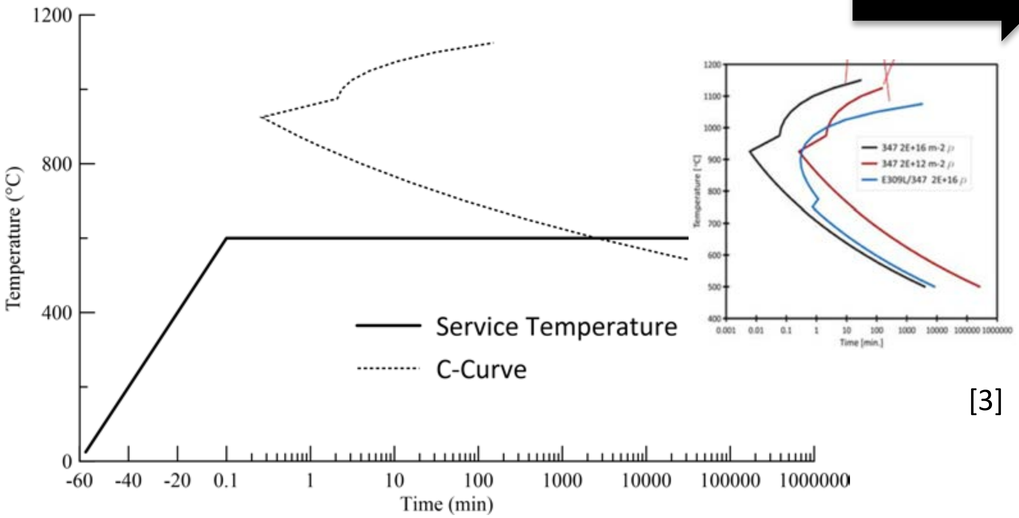


347H cavity formation ahead of crack [1]



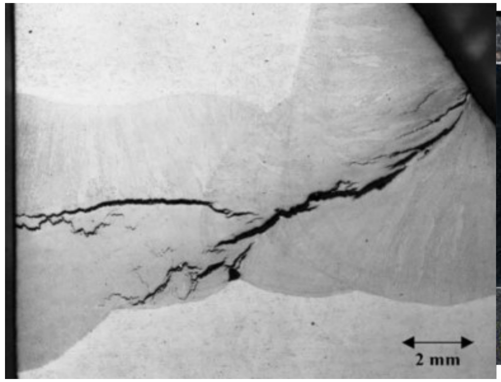
γ' precipitation and PFZ in 740H WM [2]

+ Reheating



[3]

CRACKING!



[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*, 2005.

Potential Mitigation Solutions

- **For existing tanks:**
  - Stress reduction through post weld heat treatment (PWHT) while avoiding SRC and formation of Cr-carbides during cooling.
- **For tanks being manufactured with 347H SS:**
  - Alternative filler metals (e.g., E16Cr-8Ni-2Mo)
  - Control of residual stress by optimizing joint geometry design and welding procedure
  - Use high deposition-rate low heat-input processes
  - PWHT
- **For future tanks**:
  - Alternative base metals (e.g., NUCL 167 SPH 316L w/ B) and filler wires
  - Advanced manufacturing technologies (e.g., cladded plates)

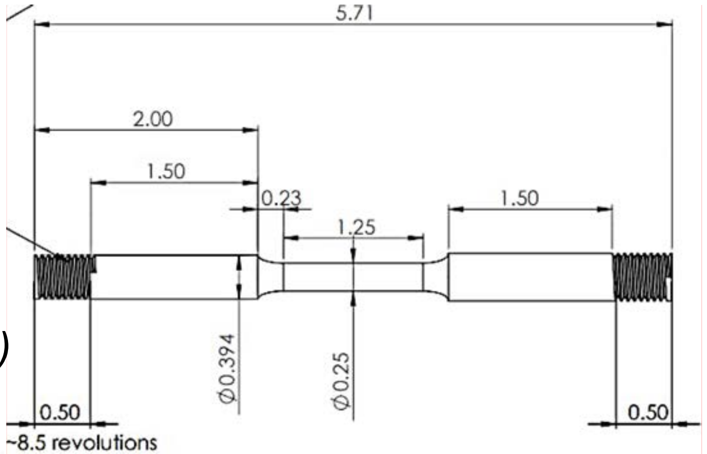
Project Goals and Approach

- **Overarching goal**: Determine mitigation protocols to avoid failure through stress relaxation cracking (SRC) at the current Gen2 CSP nitrate hot tanks.
- **Approach**: Investigate crack susceptibility of 347H SS and other alloys of interest under welding and post-weld heat treatment (PWHT) procedures, and CSP operational conditions, using
    - Welding experiments
    - Gleeble thermo-mechanical physical simulations
    - Finite element modeling (FEM)
    - Metallurgical characterizations
    - Thermodynamic calculations

Gleeble Reheat Crack Test Methodology

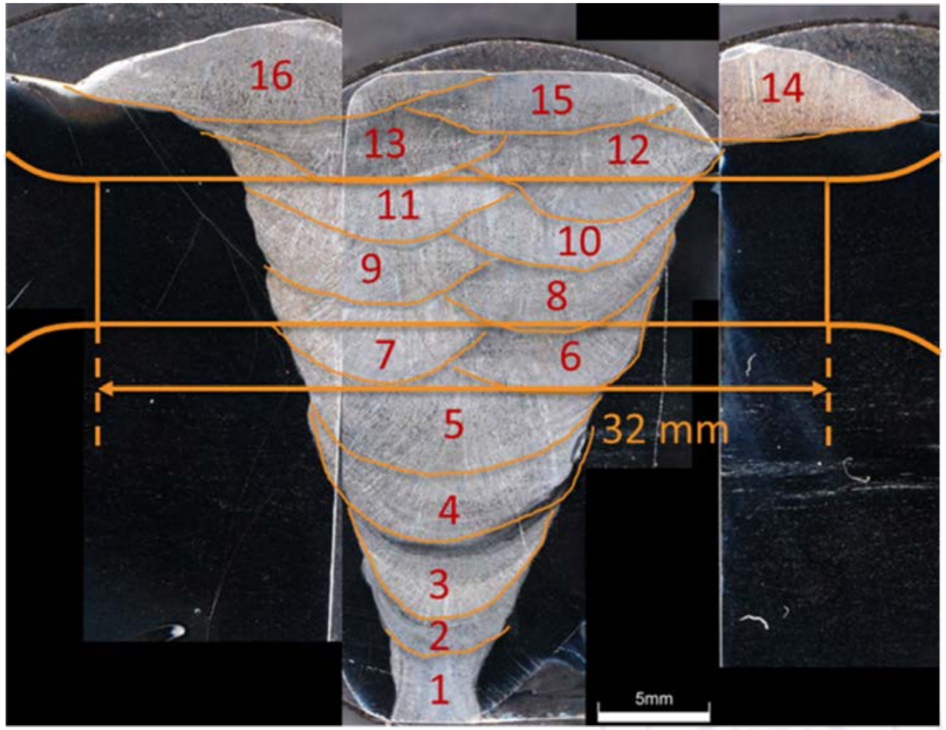
- **Objective:** Determine reheat cracking susceptibility and critical pre-stress/strain to failure in 347H SS HAZ and weld metals, respectively, as a function of temperature.

- **Three main variables**:
  1. HAZ peak temperature: 1335, 1275, 1150°C
  2. Pre-strain/stress: 0.01 strain (250 MPa), 0.025 strain (300 MPa), 0.04 strain (335 MPa) , 0.05 strain (350 MPa), 0.08 strain (415 MPa), 0.1 strain (450 MPa) and 0.174 strain (600 MPa);
  3. Reheat temperatures
     - 750-1050°C

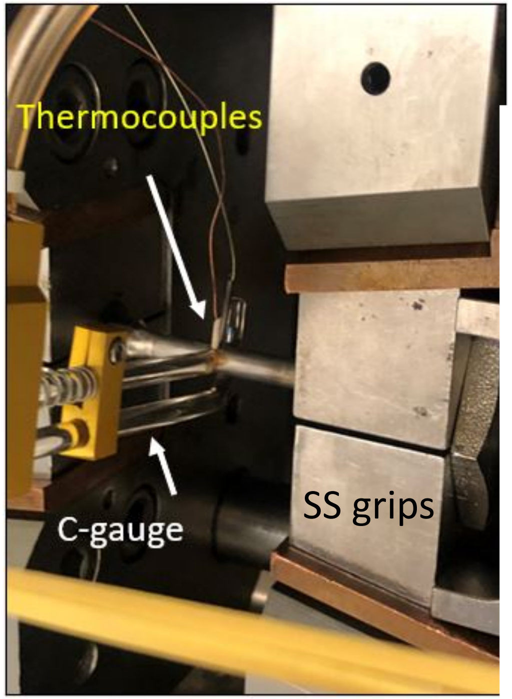


ASTM E8 Sub-size tensile specimen (mm)

1" thick 347H SS weld using E347-16



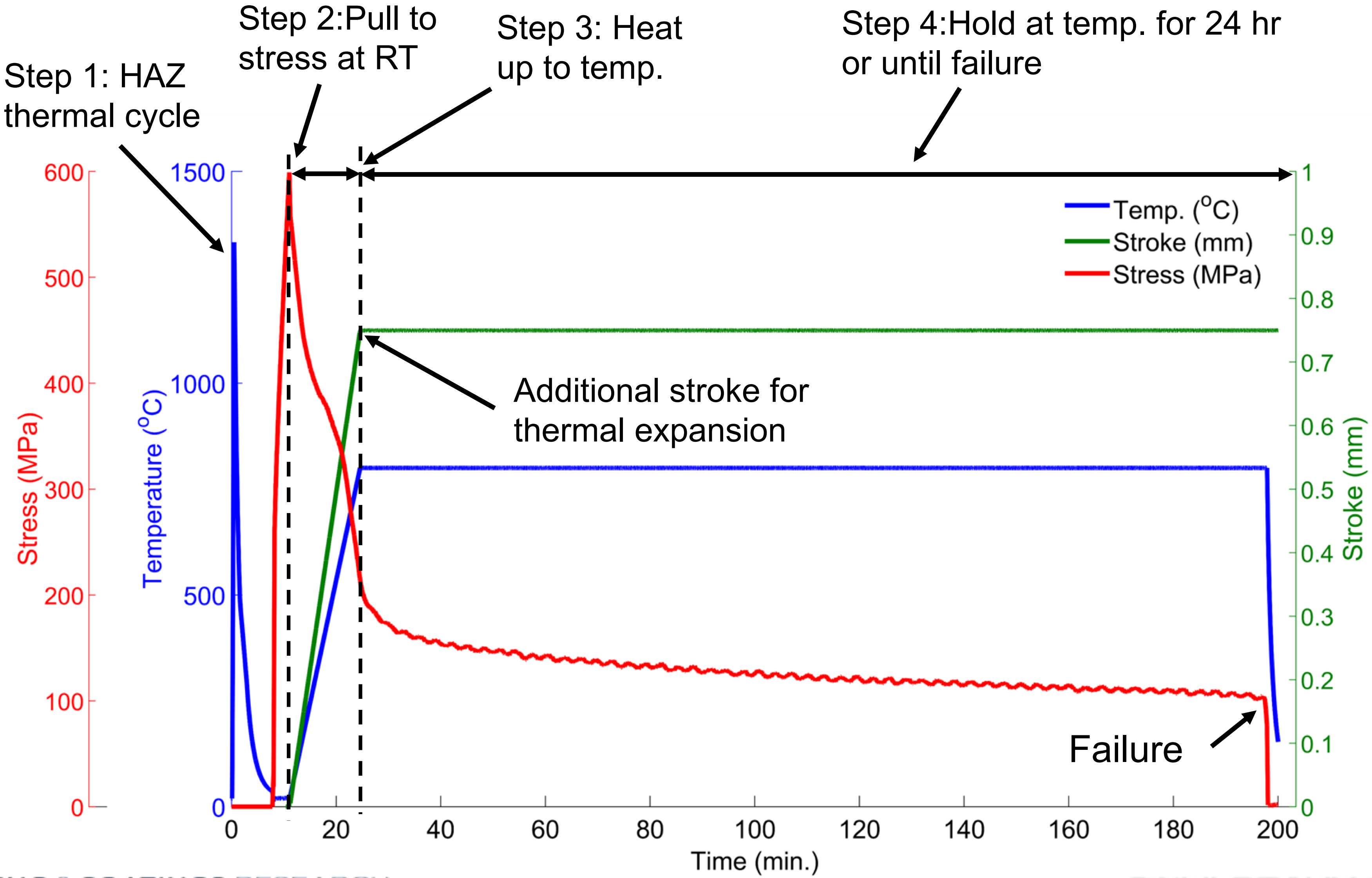
Gleeble Reheat Crack Test Steps



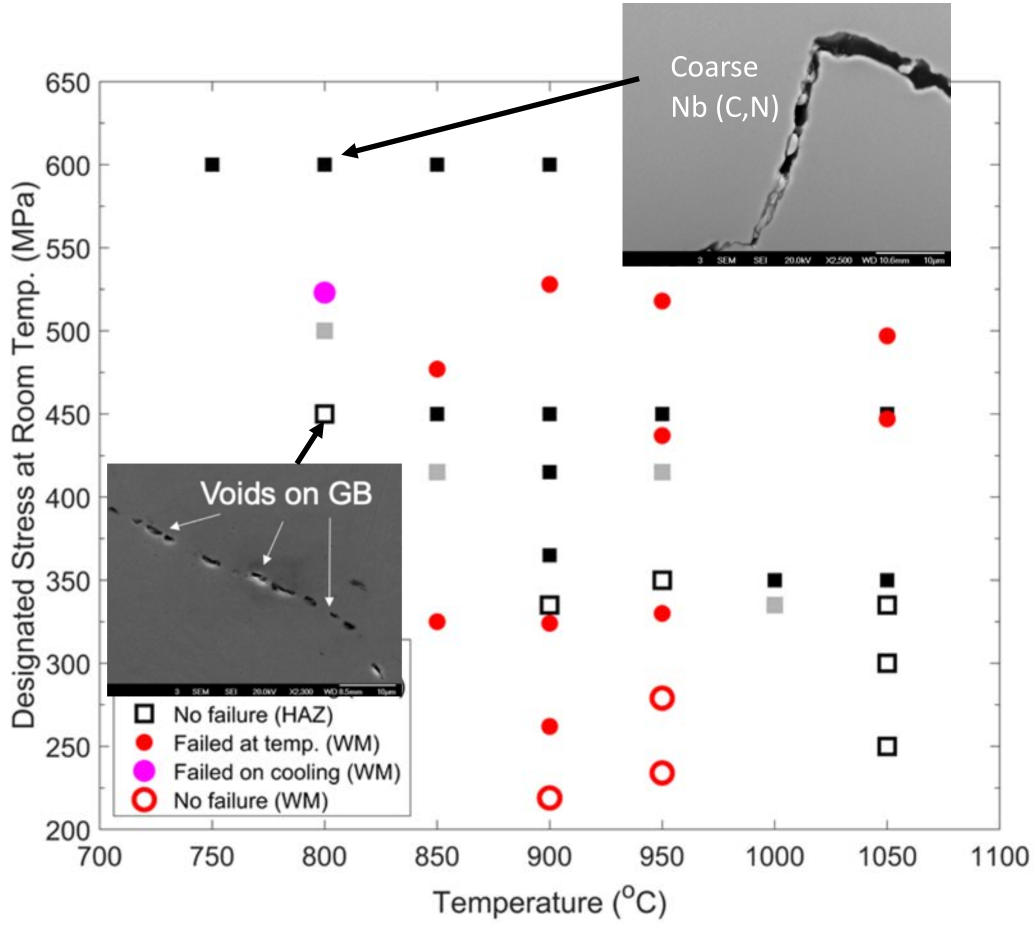
C-gauge used to measure true plastic strain.

$$\varepsilon = 2\ln\left(\frac{d_o}{d_o + \Delta d}\right)$$

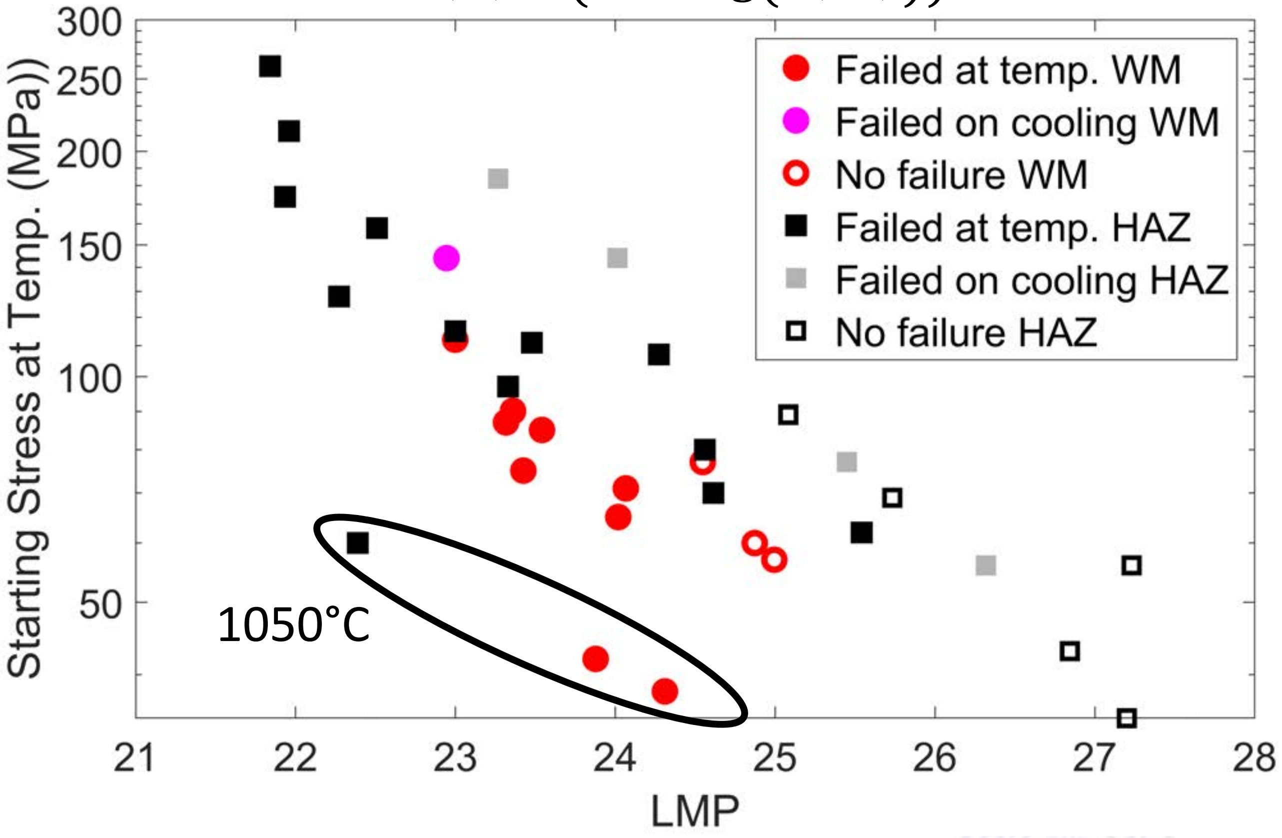
$$\sigma = \frac{F}{\pi * \frac{(\Delta d + d_o)^2}{4}}$$



SRC Susceptibility: HAZ vs. WM



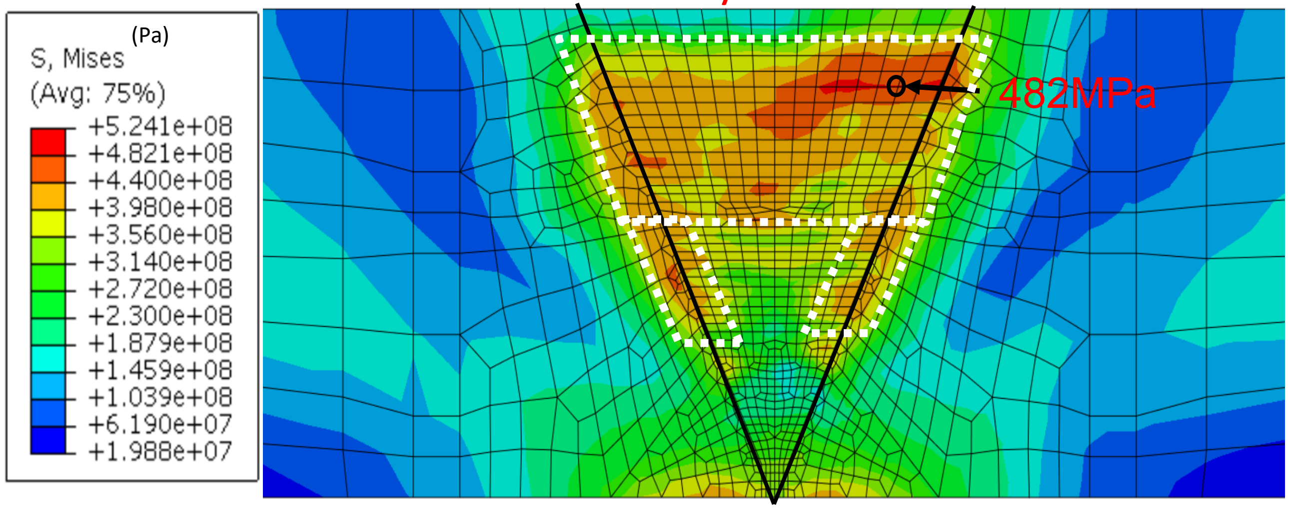
LMP= $T\ (K) * \left(C + \log\left(t(hr)\right)\right)$, C=20



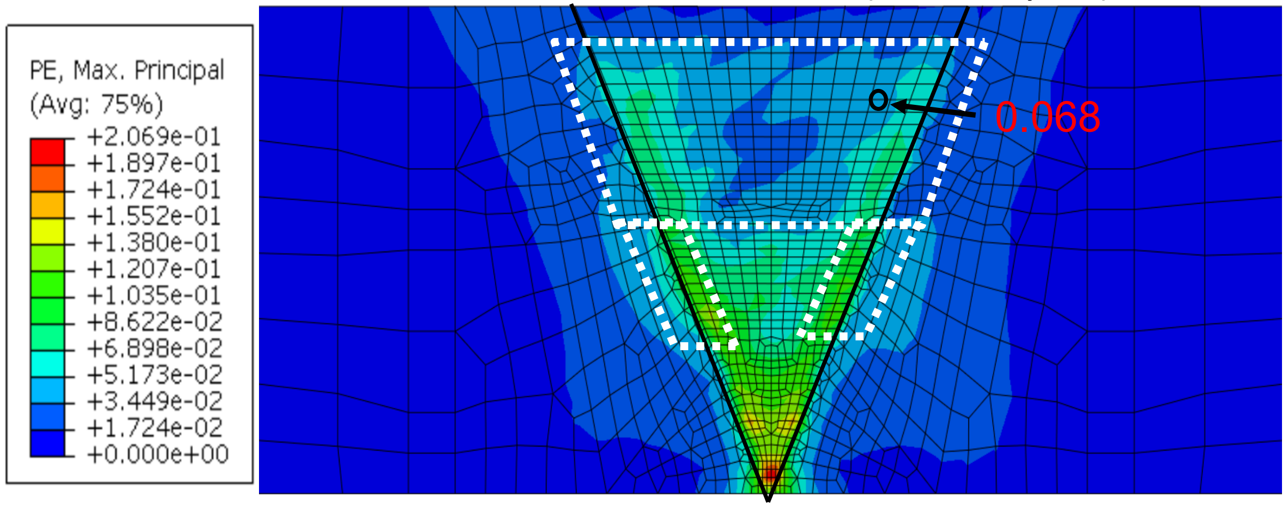
- WM E347-16 is more susceptible to SRC in comparison to the 347H SS HAZ

FE Analysis of Failure Susceptibility

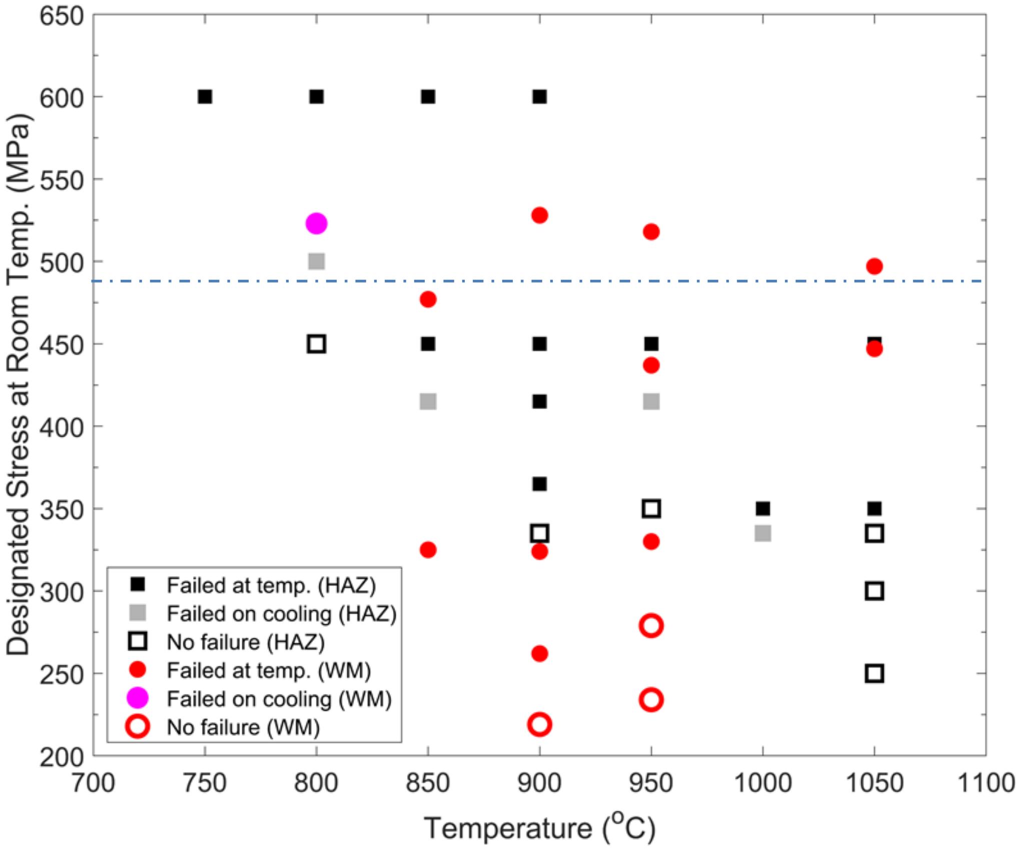
Likely area for failure



Von Mises Stress field (Unclamped)



Plastic strain field (Unclamped)



WM generally more susceptible due to generally higher stresses and with a lower stress threshold compared to HAZ at 900 and 950°C

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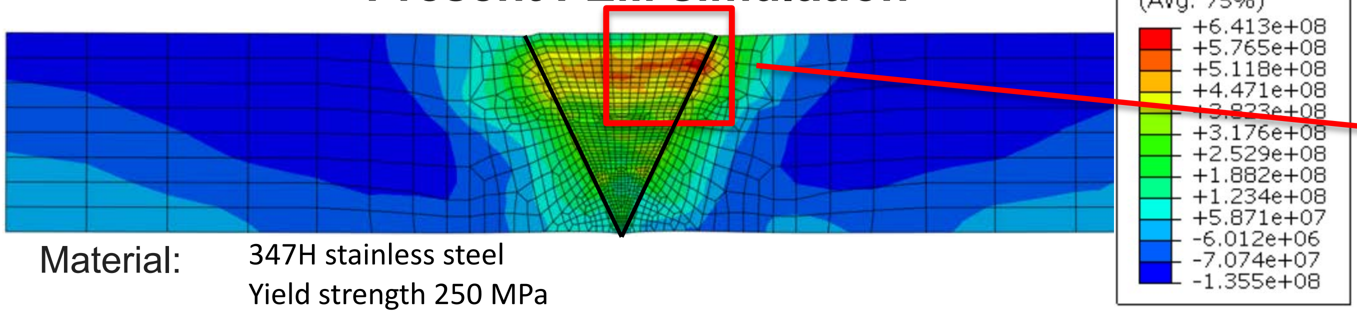
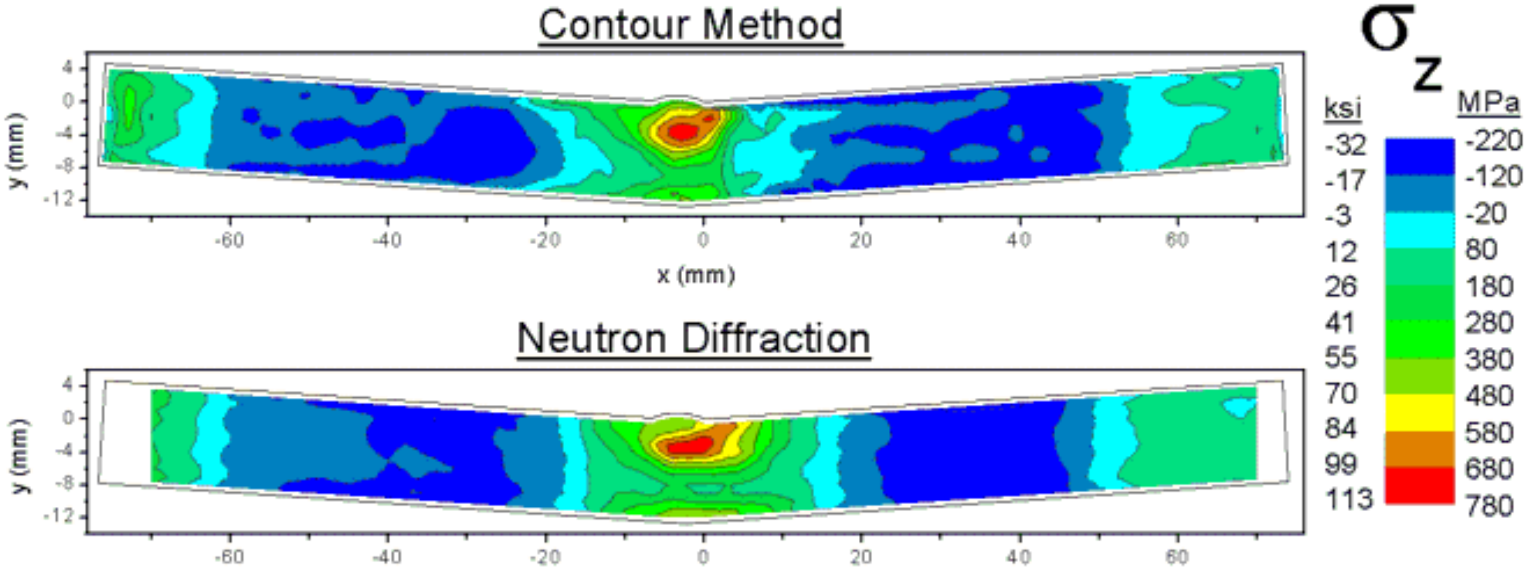
Comparison to Literature

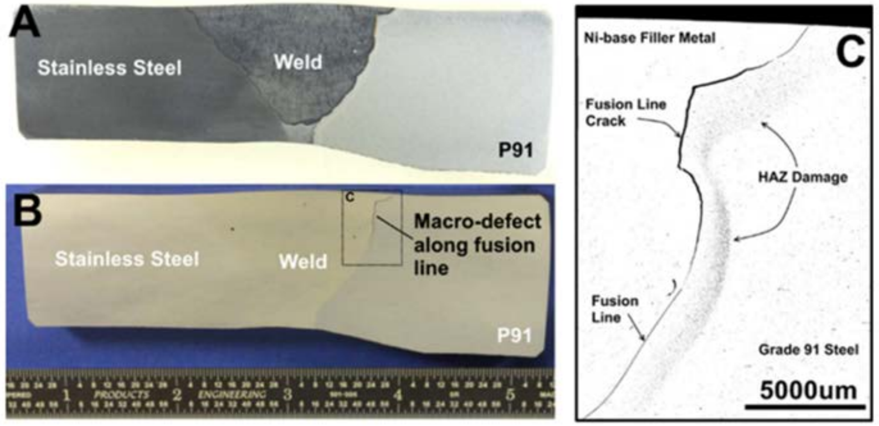
Present FEM simulation



Material: 347H stainless steel
Yield strength 250 MPa

Material: BS 4360 grade 50D- low carbon steel
Yield strength 305 MPa





Example of failure along the fusion boundary in a DSW with P91 and SS [2]

- Locations of failure are subsurface in a single v groove after being at service at 565℃ for approximately 125k hours (14 years) – when examined
- A good agreement with literature based stress patterns in thick, multi-pass welds

1. Prime, Michael B., et al. *Experimental Mechanics* 44.2 (2004): 176-184.
2. Sean Orzolek, John Dupont, John Siefert, (2020). Metallurgical and Materials Transactions A 51(5): 2222-2238.

Conclusions

- The critical threshold residual stress/strain as a function of temperature for reheat cracking was identified for the weld metal and HAZ of 347H through Gleeble simulation. The E347-16 WM is demonstrated to be more susceptible to SRC than 347H HAZ.
- FE analysis in combination with the Gleeble results indicated failure preferentially occur in the subsurface region near top passes with high tensile stress/strain.
- The thresholds obtained from Gleeble testing in combination with FEM predictions can assist to determine: (1) the optimum PWHT conditions while avoiding SRC to occur during PWHT taking into consideration of plate thickness; and (2) improved joint geometry design (e.g., double-V groove with alternating weld pass sequence for thick welds).
- *Future work: Optimize cost-effective, thickness-dependent, localized PWHT procedures and investigate for feasible non-destructive evaluation (NDE) at commercial scale for hot tanks in Gen2 CSP.*

1. *"Susceptibility of 347H Stainless Steel Thick Welds to Reheat Cracking and Mitigation Solutions", T. Pickle, Y. Hong, J. Vidal, Z. Yu. 2021*
2. *"Finite Element Simulation of Welding and Post Weld Heat Treatment in Stainless Steel 347H Plate:. Y. Hong, T. Pickle, J. Vidal, Z. Yu.2021*

Acknowledgements

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

- Lincoln Electric for providing GTAW and SMAW consumables

- BRAHMA Inc. for guidance on welding procedures of 2” thick plate

- Sarah Harling and Karsten Anderson for welding assistance