Advanced Alloys in Supercritical CO_2 Power Cycles

FWP 1022406 –Advanced Alloy Development

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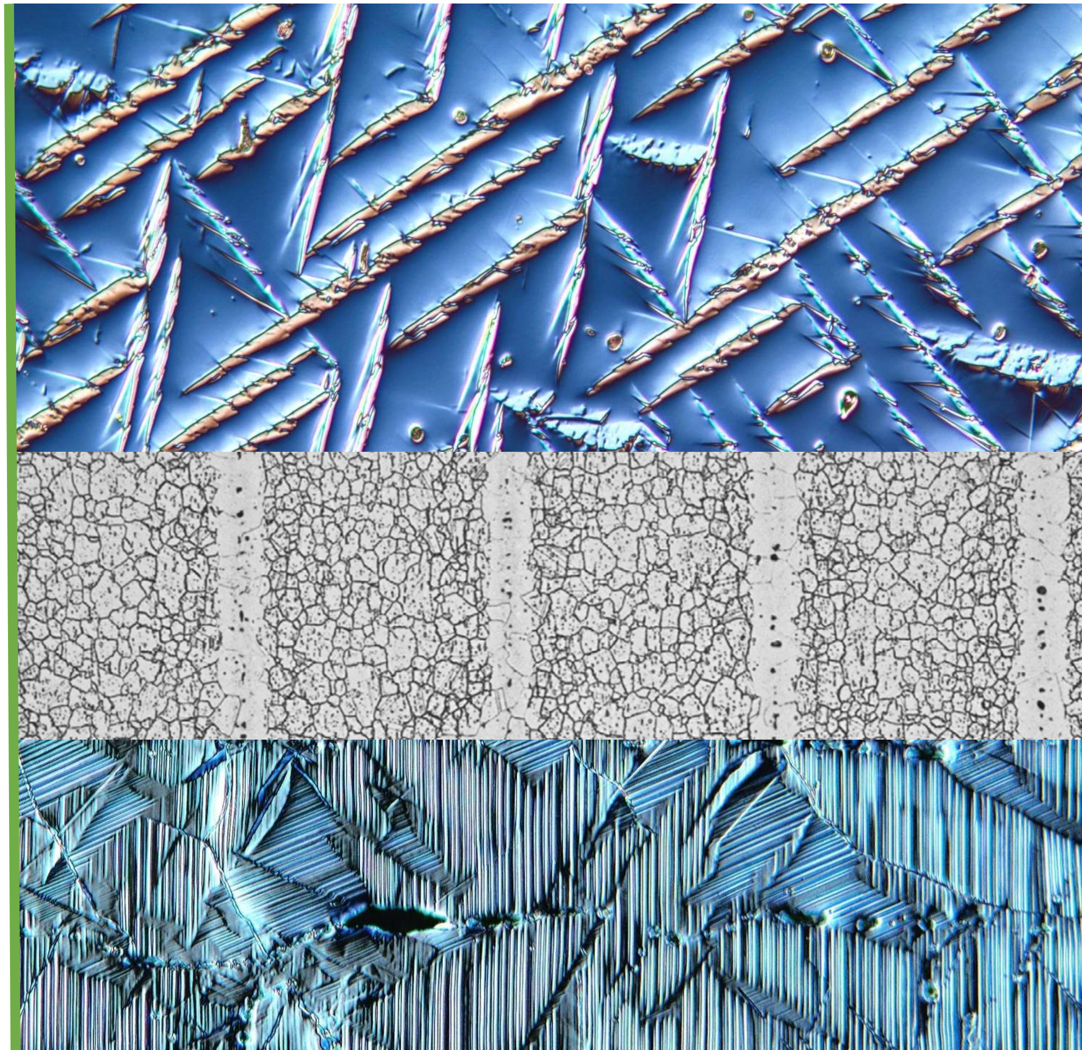

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U.S. DEPARTMENT OF ENERGY

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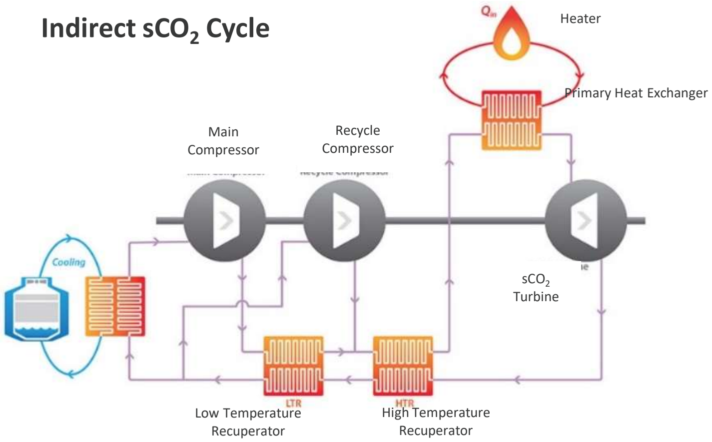
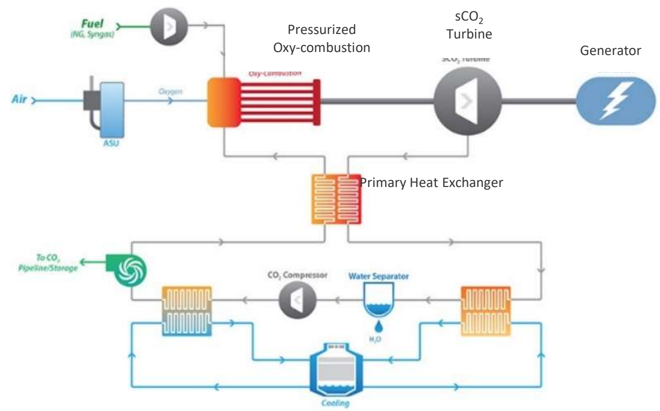
Supercritical CO_2 Power Cycles

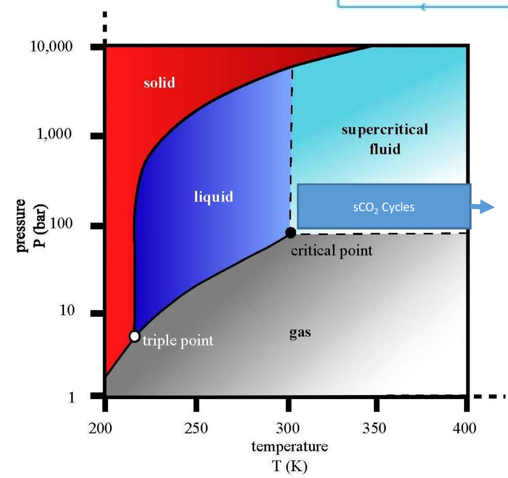
Indirect sCO_2 Cycle

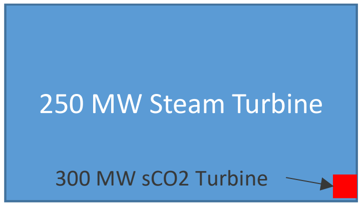


Direct sCO_2 Cycle



Properties of sCO2 Cycles	Impact
No phase change (Brayton Cycle)	Higher efficiency
Recompression near liquid densities	Higher efficiency
High heat recuperation	Higher efficiency
Compact turbo machinery	Lower capital cost
Simple configurations	Lower capital cost
Dry/reduced water cooling	Lower environmental impact
Storage ready CO_2 in direct cycles	Lower environmental impact

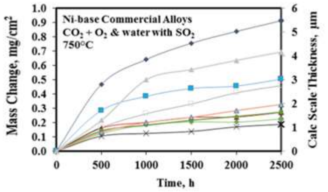


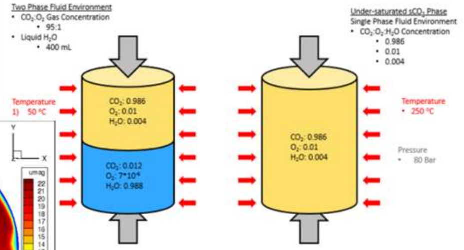


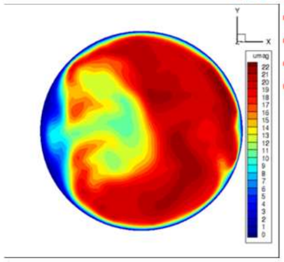
Supercritical CO_2 Power Cycles

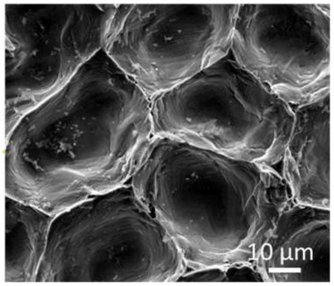
Materials Research at NETL

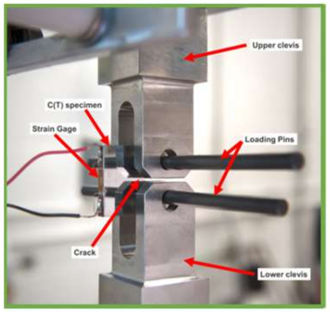
- **High-temperature oxidation in direct sCO_2 power cycles**
- **Low-temperature corrosion in direct sCO_2 power cycles**
- Effect of sCO_2 cycle environments on mechanical properties
- **Erosion in components of sCO_2 power cycles**
- Materials issues in manufacturing compact heat exchangers
- **Mechanical and chemical stability of joined materials in sCO_2**
- Additive manufacturing of heat exchangers with new geometries





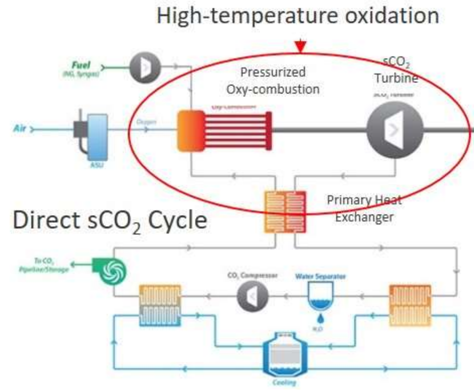


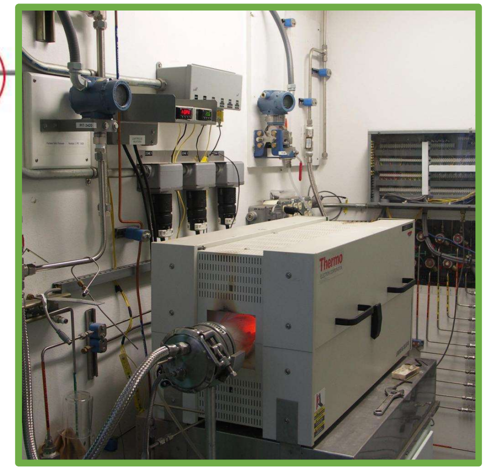


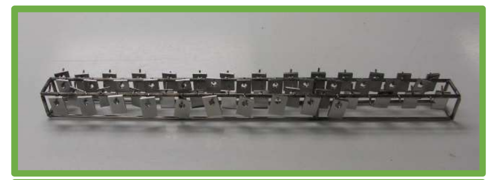


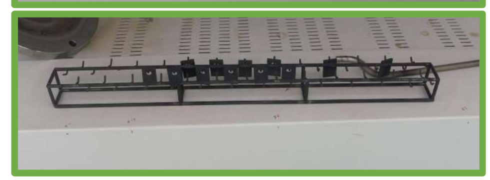
High-Temperature Oxidation in Direct sCO_2 Power Cycles

- **Importance**
  - Corrosion resistance of available structural materials need to be determined to built demonstration and future commercial sCO_2 power plants in a cost effective way.
- **Scope**
  - Evaluating A-USC alloys (both Ni-based and Fe-based) for their high-temperature oxidation performance in direct sCO_2 power cycle environments
- **Progress to Date**
  - Ni alloys (740H, 282, 625, 617, 230, 600, 718) and steels (347H, 304H, 310S, P91, P22) were tested at 750°C and 550°C, respectively, in atmospheres (1 bar) simulating natural gas-fired and coal-fired direct sCO_2 power cycles.
  - Model alloys (Ni-xCr, Fe-22Cr-xSi, Fe-22Ni-22Cr-xSi, Fe-Cr-xSi) were also exposed in the direct cycle environments to study the effect of alloying elements (Cr and Si) on oxidation.
- **FY18 Expected Accomplishments**
  - High-pressure (~200 bar), high-temperature (>700°C) oxidation tests in $sCO_2+H_2O+O_2$ will begin.
  - Oxidation rates of the exposed alloys (1 bar and 200 bar) will be reported.
  - Oxidation mechanisms of the exposed alloys will be defined.









R.P. Oleksak, et al.., *Corrosion Science* (2017)
R.P. Oleksak, et al.., *Oxidation of Metals* (2017)

High-Temperature Oxidation in Direct sCO_2 Power Cycles

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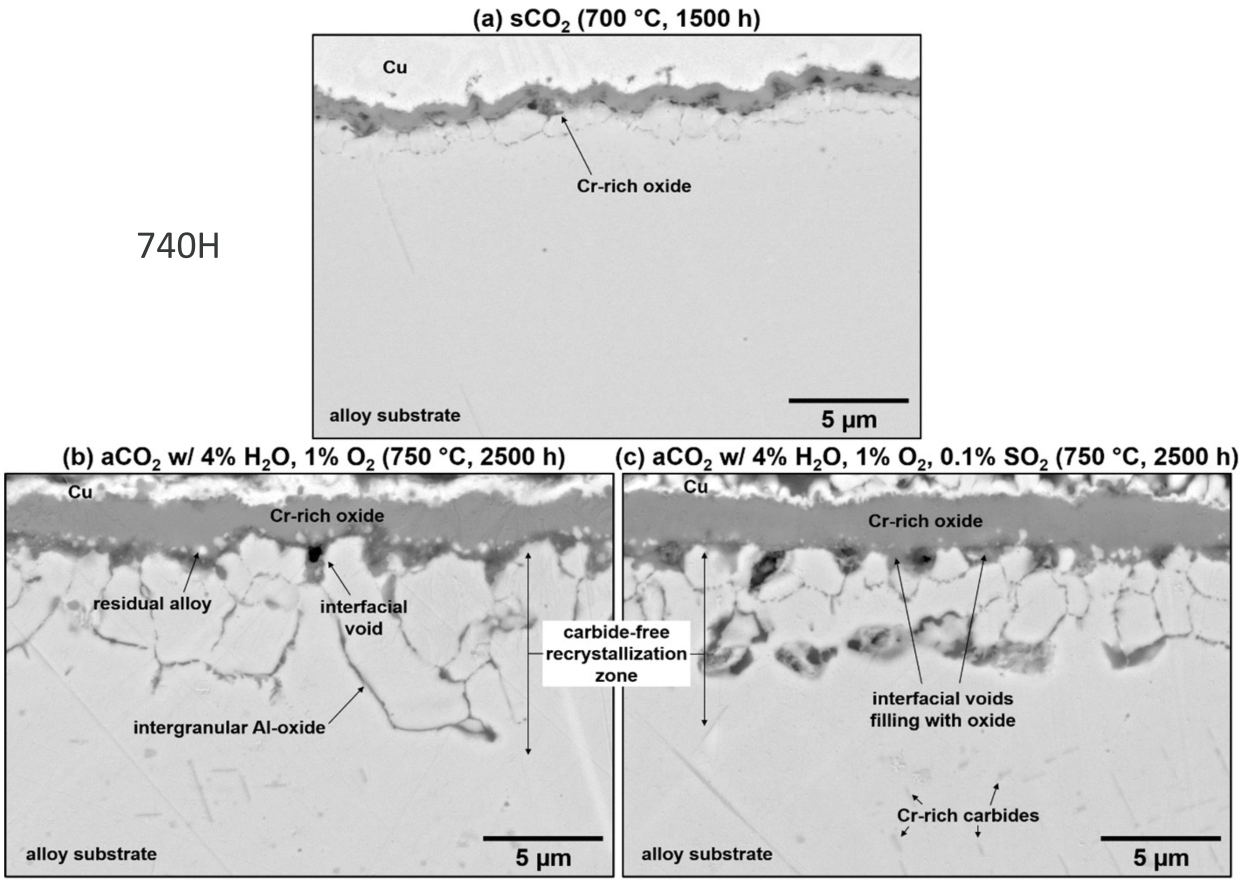
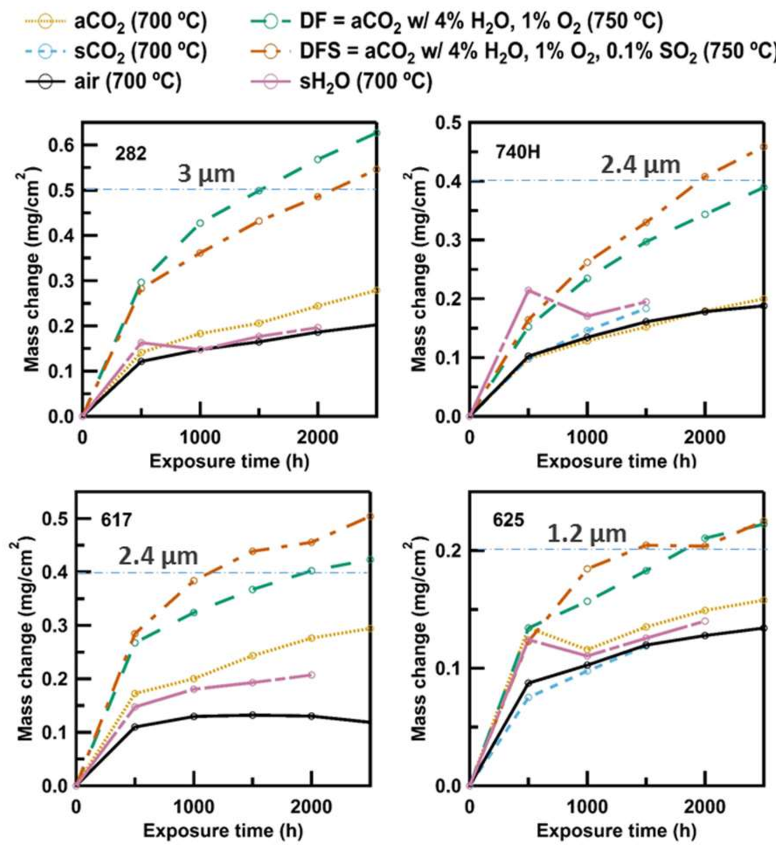
740H





R.P. Oleksak et al., *JOM (2018)*
J.H. Tylczak et al., *6th International Symposium on Supercritical CO2 Power Cycles (2018)*

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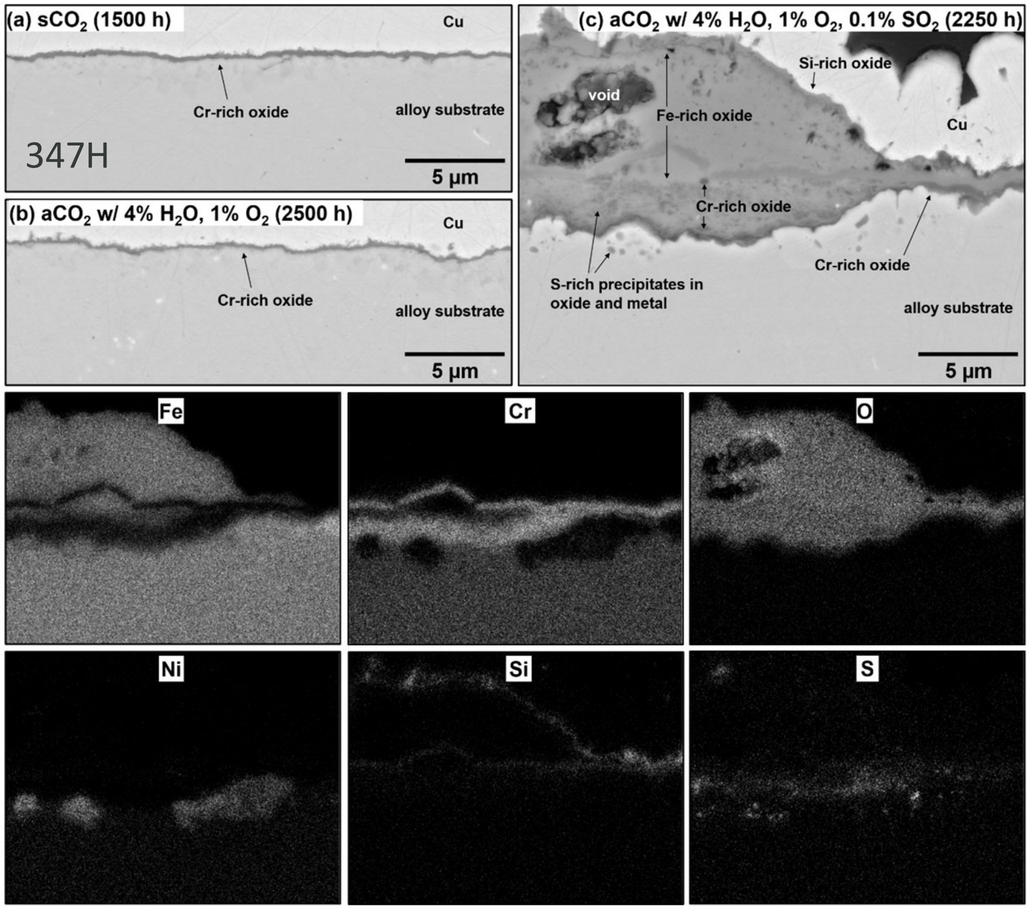
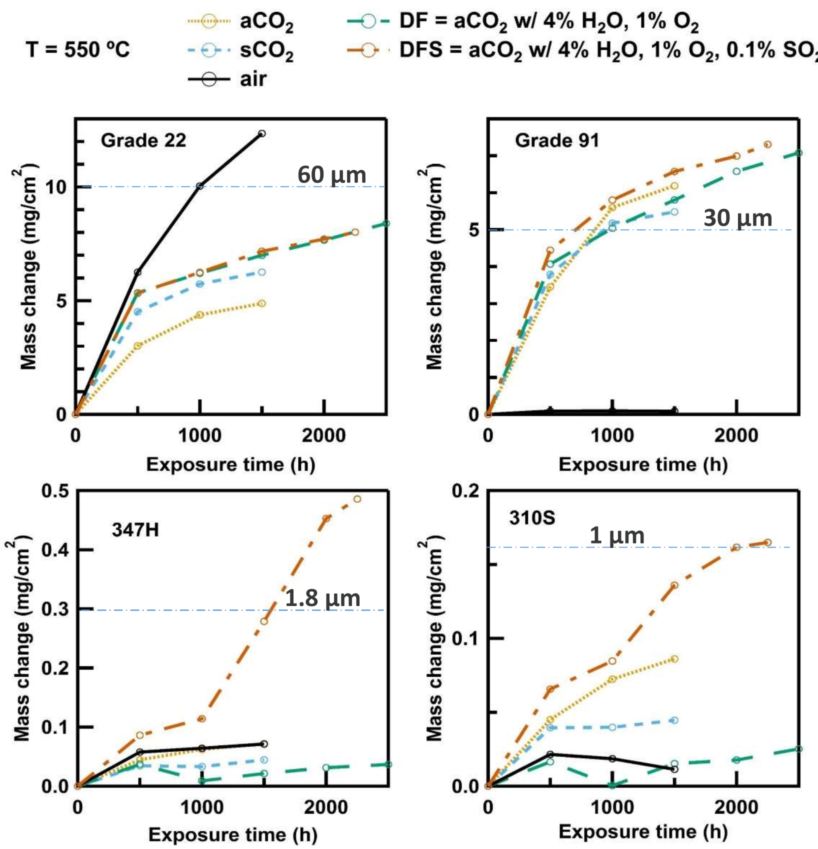
High-Temperature Oxidation in Direct sCO_2 Power Cycles





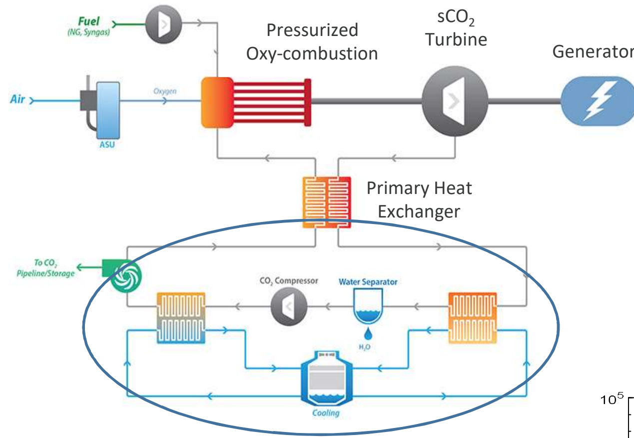
R.P. Oleksak et al., *JOM (2018)*
J.H. Tylczak et al., *6th International Symposium on Supercritical CO2 Power Cycles (2018)*

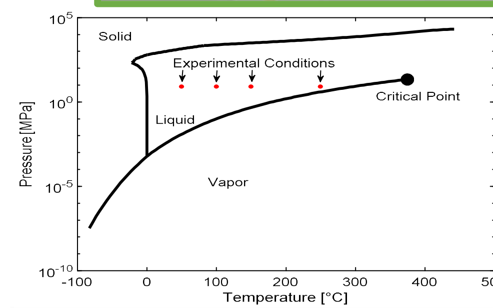
Summary – High-Temperature Oxidation in Direct sCO_2 Power Cycle Conditions

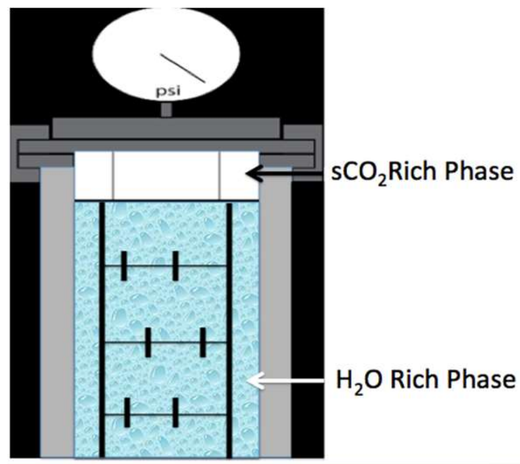
- Fe and Ni based alloys were exposed to conditions intended to simulate the direct fired sCO_2 cycles
- Tests included gas streams (CO_2+H_2O+O_2) with and without SO_2 additions
- No sulfur effect was observed on Ni alloys. Some sulfur compounds were observed on stainless steels
- Ni based solution strengthened alloys generally showed less mass gain than the age hardenable alloys

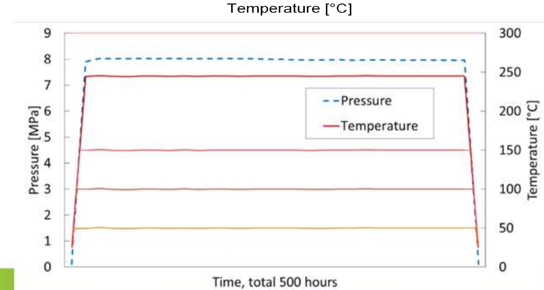
Low-Temperature Corrosion in Direct sCO_2 Power Cycles

- **Importance**
  - Low-temperature components of the 25 MW Net Power demonstration plant (natural gas-fired direct cycle) is being built using an austenitic stainless steel. This task investigates whether a lower Cr (less expensive) steel could be used instead.
- **Scope**
  - An experimental investigation of corrosion resistance of Grade 91 and 347H steels in condensed water saturated with CO_2 (Carbonic acid).
- **Progress to Date**
  - A series of autoclave coupon exposure tests simulating the environment of low-temperature recuperators and coolers in a direct sCO_2 cycle power plant have been performed
  - Due to high corrosion rates of Grade 91 steel in water saturated with CO_2, it is concluded that unlike in the steam cycles, lower Cr steels are not suitable for low-temperature components of direct sCO_2 cycle plants. 347H performed well in the same environment.
- **FY18 Expected Accomplishments**
  - In coal-fired direct sCO_2 cycle power plants without pre-combustion sulfur removal, sulfuric acid can condense in the cooler parts of recuperator. Corrosion of stainless steels due to sulfuric acid condensation will be investigated.

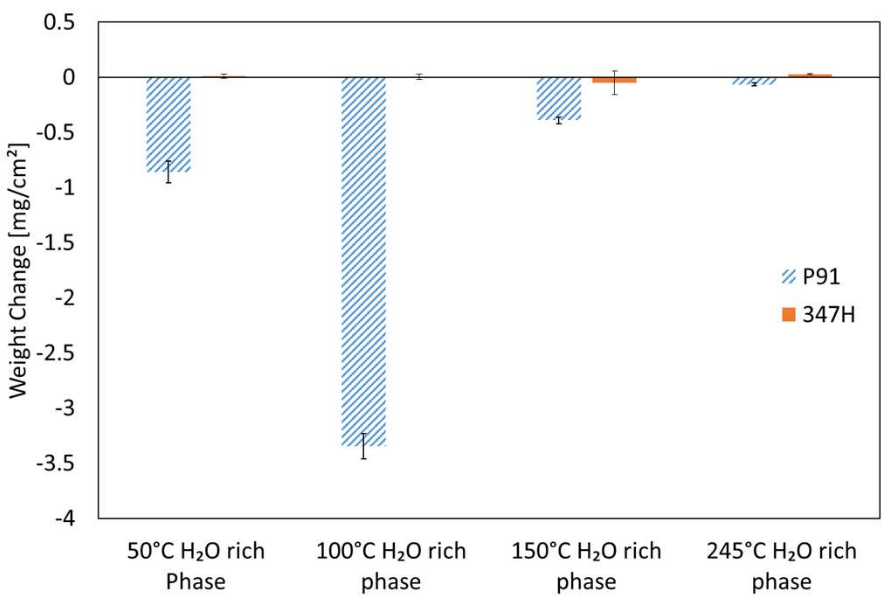


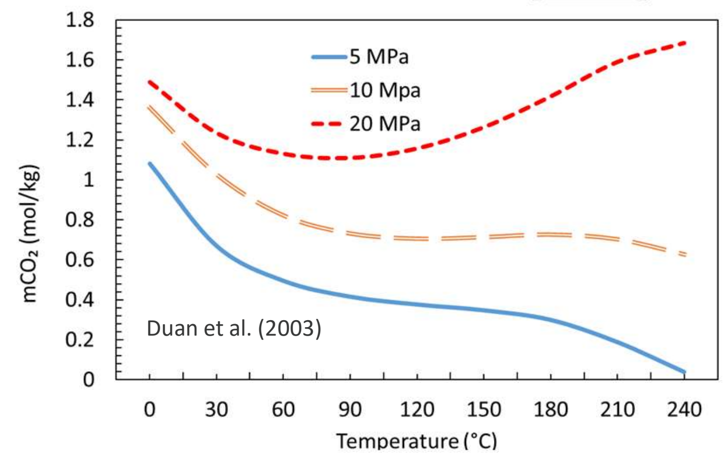


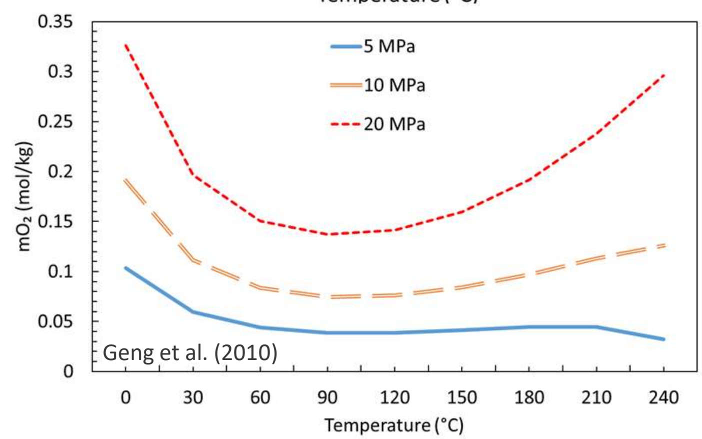




Low-Temperature Corrosion in Direct sCO_2 Power Cycles







R. Repukaiti et al., *6th International Symposium on Supercritical CO2 Power Cycles (2018)*
R. Repukaiti et al., *Corrosion 2018*

Low-Temperature Corrosion in Direct sCO_2 Power Cycles

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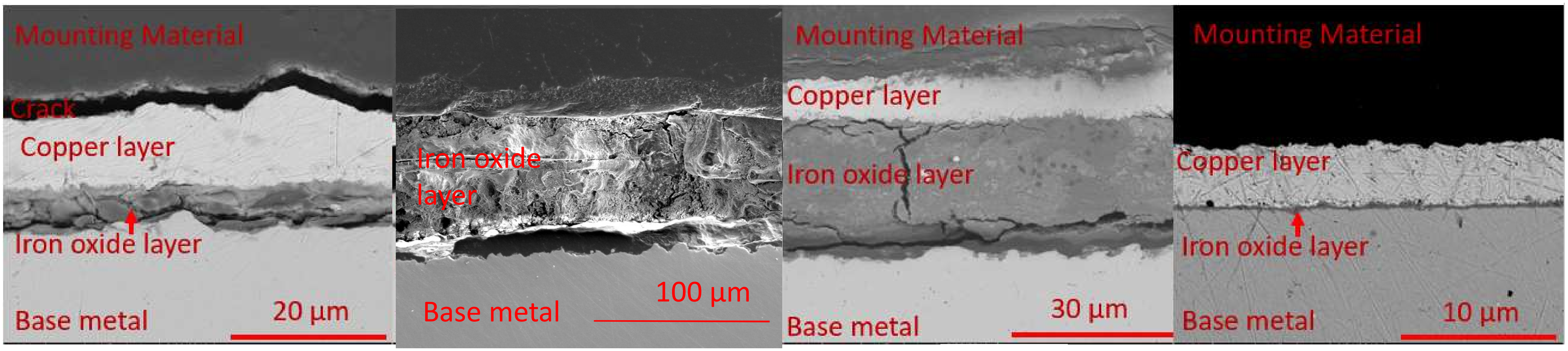


50°C 100°C 150°C 245°C

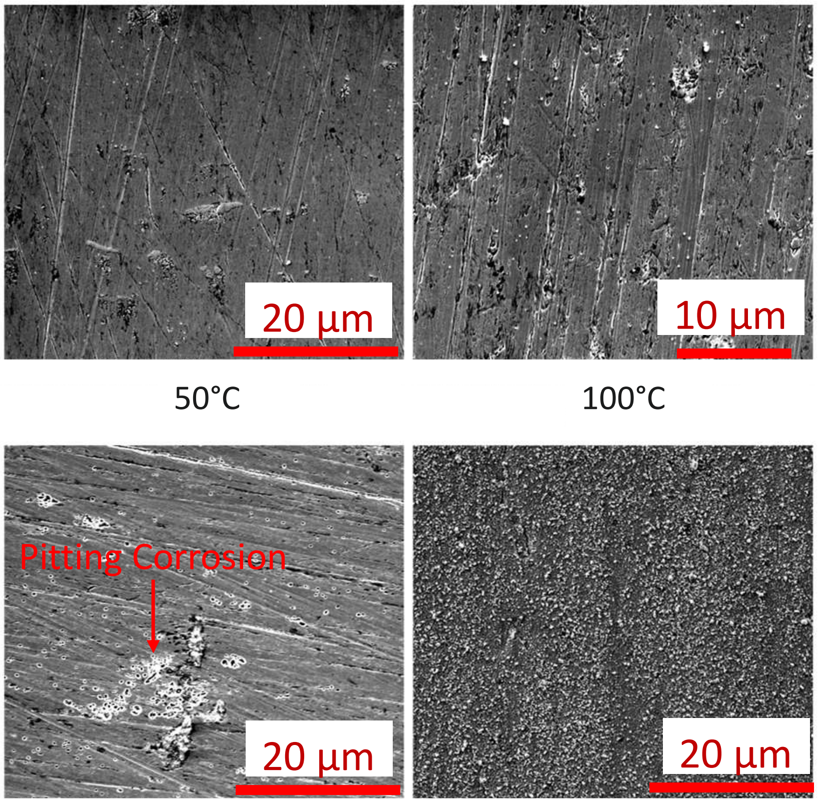
50°C	100°C	150°C	245°C
Fe_2O_3	Fe_2O_3	Fe_2O_3	Fe_2O_3
$FeO(OH)$	Fe_3O_4	Fe_3O_4	Fe_3O_4
Fe_3O_4			

XRD Analysis of P91 Corrosion Products

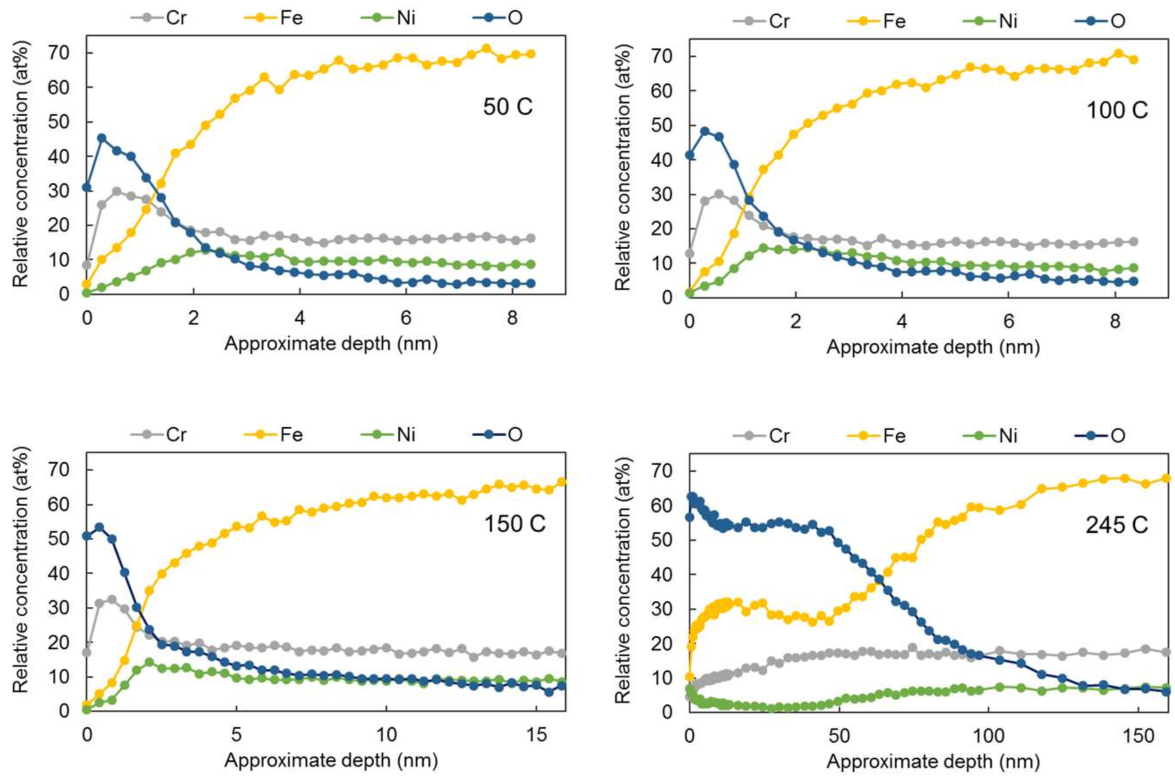
R. Repukaiti et al., *6th International Symposium on Supercritical CO2 Power Cycles (2018)*
R. Repukaiti et al., *Corrosion 2018*

Low-Temperature Corrosion in Direct sCO_2 Power Cycles

347H Stainless Steel



50°C | 100°C | 150°C | 245°C



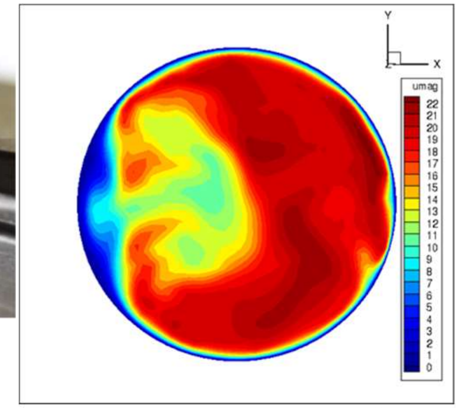
R. Repukaiti et al., *6th International Symposium on Supercritical CO2 Power Cycles (2018)*
R. Repukaiti et al., *Corrosion 2018*

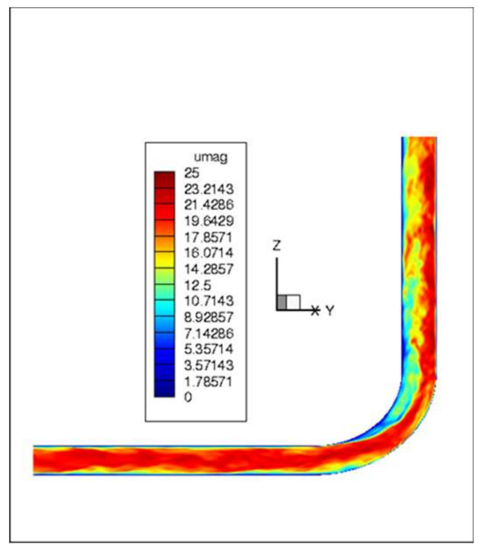
Summary – Low-Temperature Corrosion

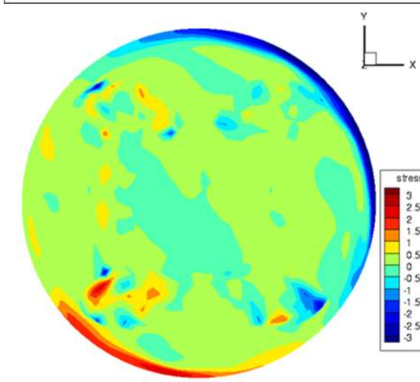
- Residual corrosion products on the Grade 91 coupons were identified as Fe_2O_3 and Fe_3O_4, while 347H coupons showed minimal mass change and very thin passive layers.
- Lower Cr steels such as Grade 91 may not be suitable for the low / intermediate temperature components in the direct sCO_2 power cycles.
- We will evaluate higher Cr steels that are less costly than austenitic stainless steels.

Erosion in Components of sCO_2 Cycles

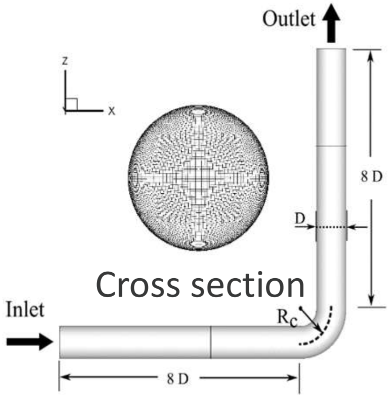
- **Importance**
  - This work will establish:
    - Whether erosion might be a significant problem in sCO_2 power cycles
    - An understanding of erosion mechanism
    - A guidance for an experimental work which might be implemented if erosion is shown to be a problem.
- **Scope**
  - Large eddy simulations are performed at different Reynolds numbers to determine magnitude of oscillating shear stresses and the effect of heat transfer in a 90 degree bend pipe in order to identify the potential causes of the erosion.
- **Progress to date**
  - Oscillating shear stresses on pipe wall were investigated for Reynolds numbers of 5000, 27,000, 45,000, 70,000 and 95,000.
- **FY18 Expected Accomplishments**
  - Begin a finite element model to study effect of oscillating shear stresses on the pipe wall material.
  - Introduce hard particles into the sCO_2 flow and examine their effect on the component walls.





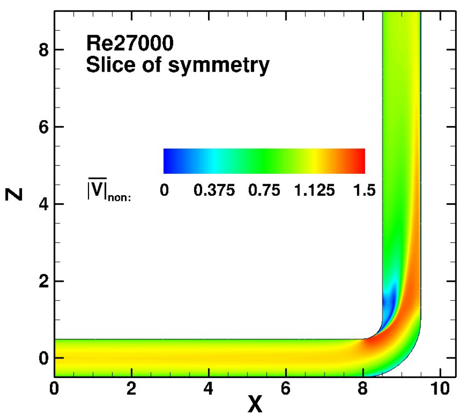


Erosion in Components of sCO_2 Cycles

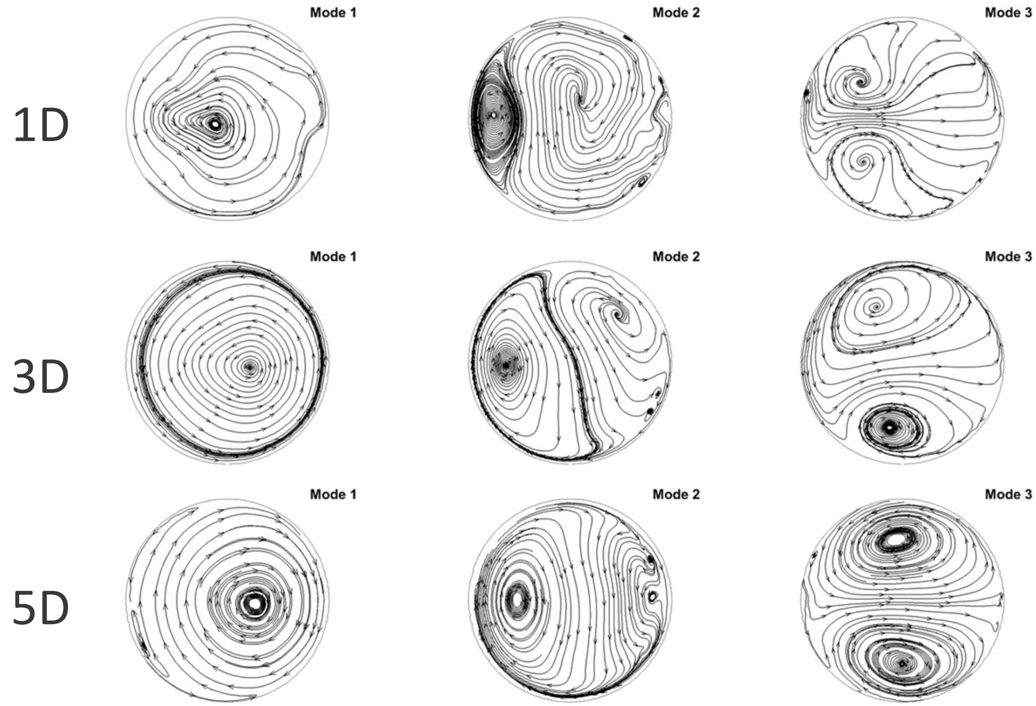


- Large-eddy simulation (LES) is implemented using a highly validated, efficient and predictive solver, which is fully parallel and uses finite volume method.

Geometry and cross section of the pipe



- Mean streamwise velocity becomes higher at the inner wall at 30 degree angle;
- At 90 degree, the maximum velocity shifts towards the outer wall.



Erosion in Components of sCO_2 Cycles

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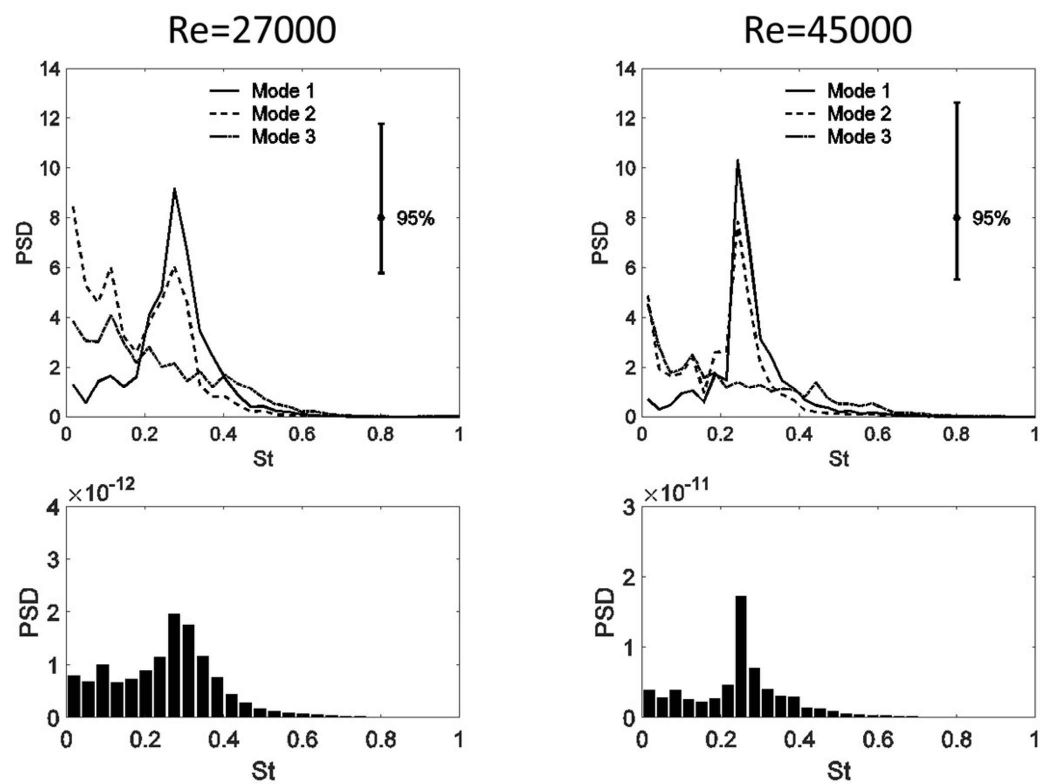

Spectra of shear stress (down) and secondary flow patterns (up), indicating they are highly correlated.

The oscillation of the secondary flow patterns directly causes the oscillation of the shear forces, which could possibly result in the erosion on the pipe surface.

X. He et al., *6th International Symposium on Supercritical CO2 Power Cycles (2018)*

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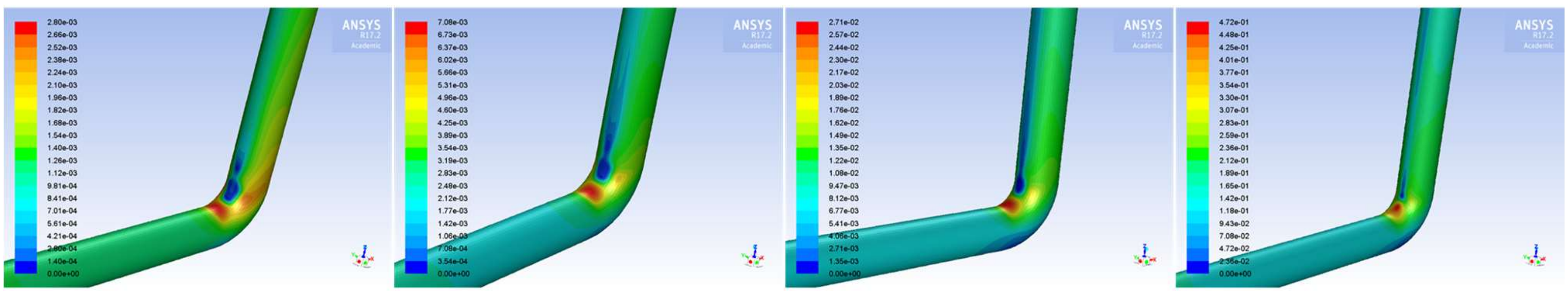
Estimation of the shear force for the real sCO_2 power plant

- In the real sCO_2 power cycle pipe lines, the Reynolds number can go as high as about 15 million. It is necessary to estimate the magnitude of the oscillating shear force on the wall to see if it can actually cause the erosion;
- For such high Reynolds number flows, the computational costs for LES would be enormous. As a result, RANS model is used to estimate the mean value of the shear forces.



Re=27000 Re=45000 Re=95000 Re=500000

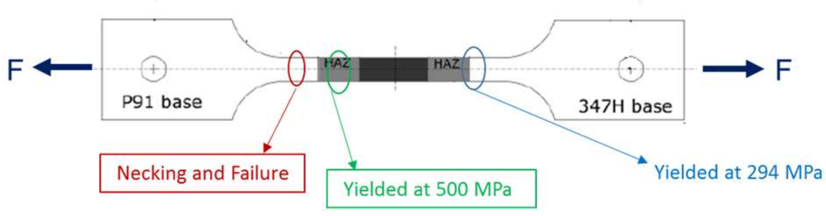
- Although more detailed analysis is needed, the shear force at Re=15M is likely to be responsible for the breakdown of the oxide scale on the inner surface of the pipe, causing the erosion.

Summary – Erosion in sCO_2 Power Cycle Components

- Performed large-eddy simulations for turbulent flows through pipe bends a range of Reynolds numbers between 5000 and 100,000;
- Swirl switching phenomenon was observed downstream of the bend for Re = 27,000. Similar phenomenon is expected for higher Re cases;
- The swirl switching is highly correlated with the shear force on the wall. This has the potential to cause fatigue and erosion of oxide scale on pipe wall;
- Effect of hard particles entrained in sCO_2 flow will also be investigated.

Mechanical and Chemical Stability of Welded Alloys in sCO_2

- **Importance**
  - High-temperature components (piping, recuperators, turbines) in sCO_2 cycles are typically joined together by welding. Although the goal is to form a monolithic structure, depending on the alloy composition and microstructure, the interface region (weld, heat affected zone) of the joined structure usually have a microstructure different from the parent alloy. This can be a source of mechanical and/or chemical instability for the structure in the sCO_2 environments.
- **Scope**
  - Effect of sCO_2 on the welded structures will be investigated and documented. The investigation involves making the joined structures, exposing them to sCO_2, evaluating their properties, and modeling the mechanical behavior.
- **Progress to Date**
  - Ten (10) similar and dissimilar metal welds (8”x6”x1” plates) were produced by GTAW.
  - Mechanical behavior (tensile, indentation) of welded structures is being modeled.
  - Effect of sCO_2 on welded regions is being investigated on P91-347H dissimilar metal weld.
- **FY18 Expected Accomplishments**
  - More similar and dissimilar metal welds exposed to sCO_2 will be evaluated.

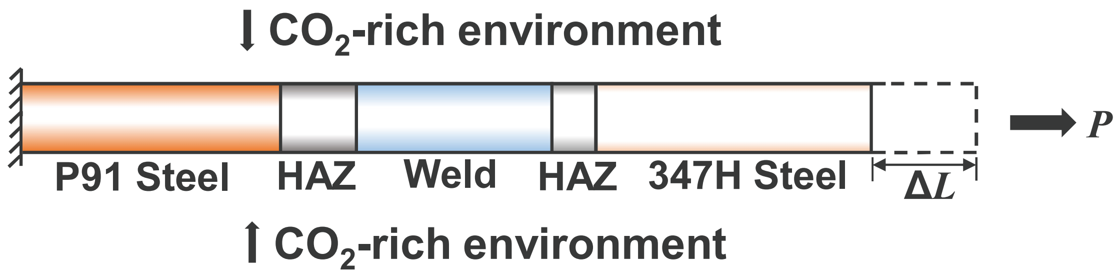


At Edison Welding Institute (EWI)

By Gas Tungsten Arc Welding (GTAW).

With Post Weld Heat Treatment.

Performance of welds under load

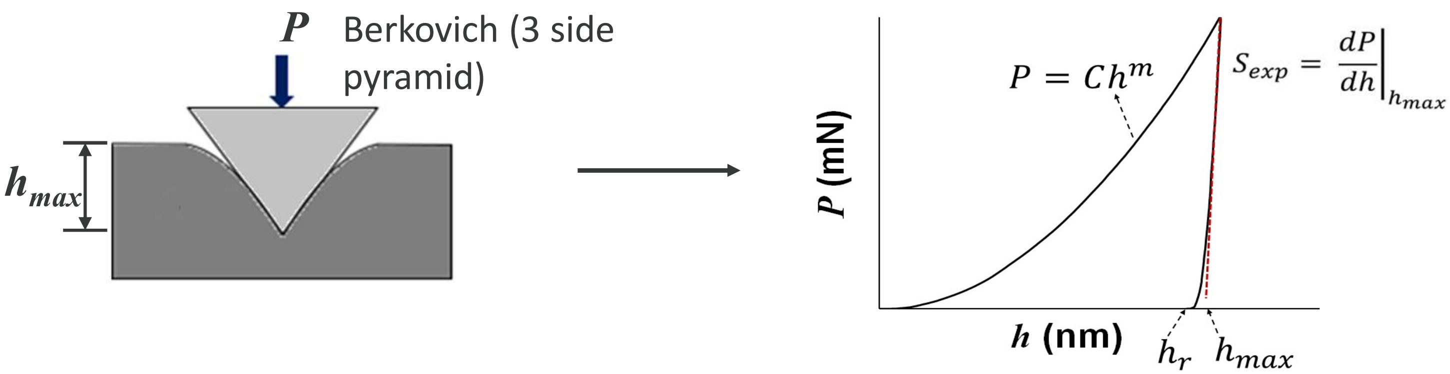


***GOAL :** Development a framework to study the effect of environment on the global deformation behavior of dissimilar metal-welds.*

Framework

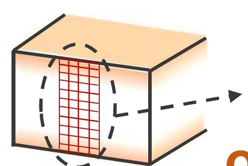
- E, σ_y, n from Nano-indentation and Tensile Test
  - As-received
  - Vacuum Exposed
  - Pure/impure CO_2 Exposed
- Input E, σ_y, n in a 3D FE Tensile Model

Nano-indentation Test



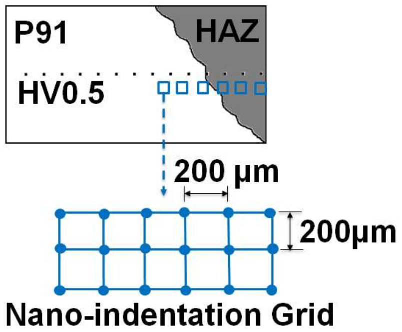
C, S_{exp}, h_r, h_{max} → Input → A set of semi-empirical equations → Numerical Solution → Hardness, H; Elasticity, E; Yield Strength, σ_y; Hardening, n

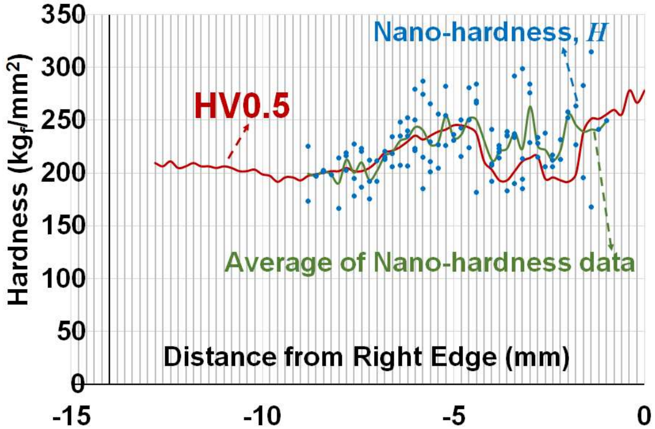
Advantage: ***Can capture the local mechanical property.***

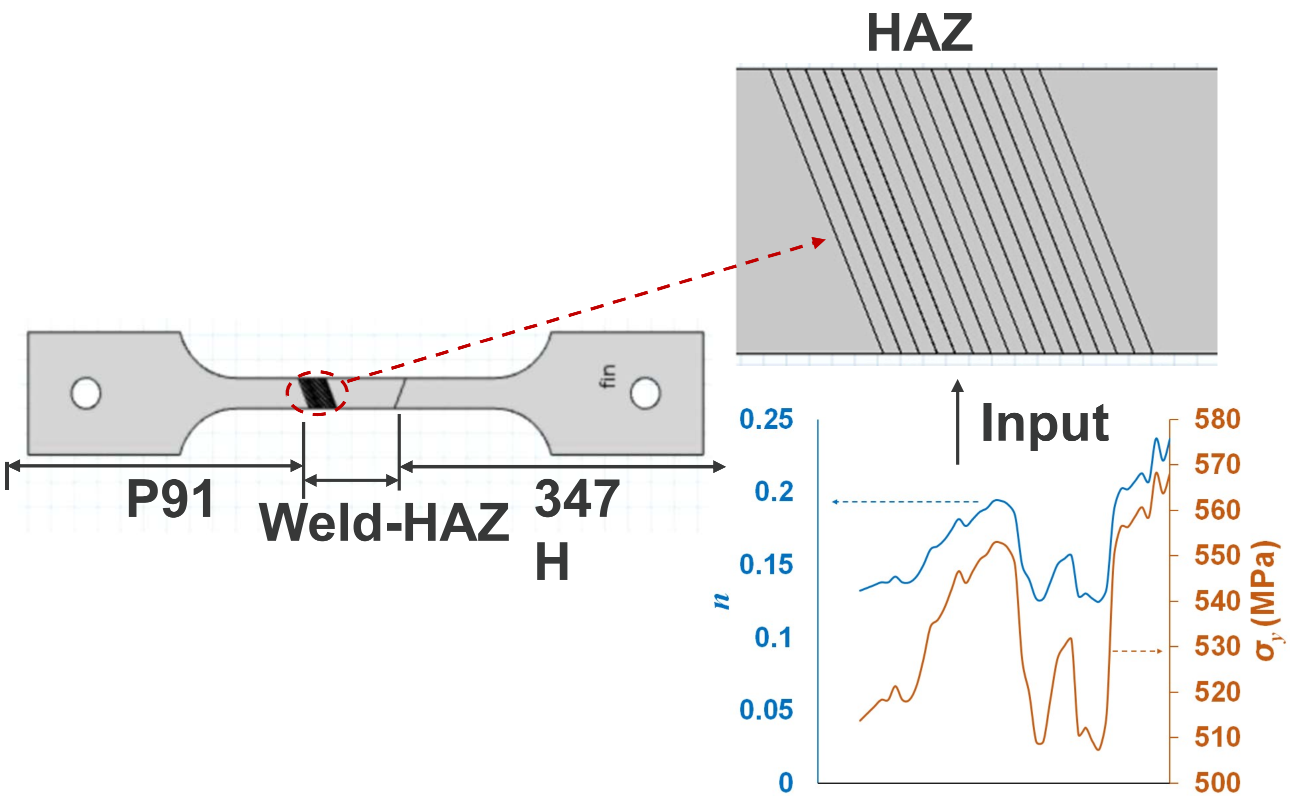


Nano-indentation Test Grid on carburized cross-section.

Nano-indentation Test to Capture the Mechanical Properties of HAZ

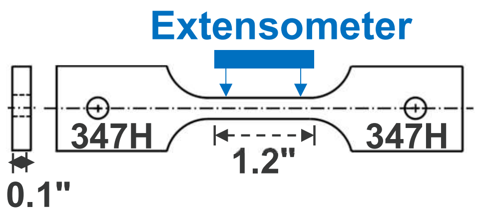




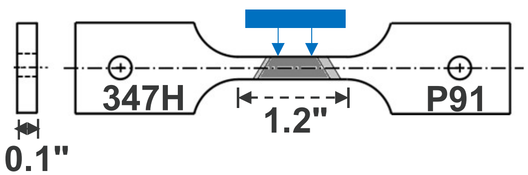


Obtained from Nano-indentation Test

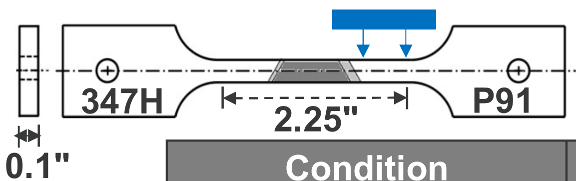
Room Temperature Tensile Test Results



Condition	E (GPa)	n	σ_y (MPa)
As-Received	217.94 ± 39.02	0.391 ± 0.0066	232.92 ± 4.92
CO_2+4%H_2O+1%O_2, 650C-1000h Exposed	193.31 ± 9.67	0.3628 ± 0.0041	256.68 ± 5.41



Condition	E (GPa)	n	σ_y (MPa)
As-Received	186.26 ± 24.79	0.114 ± 0.03	491.19 ± 20.68
CO_2+4%H_2O+1%O_2, 650C-1000h Exposed	176.76 ± 0.488	0.1589 ± 0.0336	587.84 ± 4.42

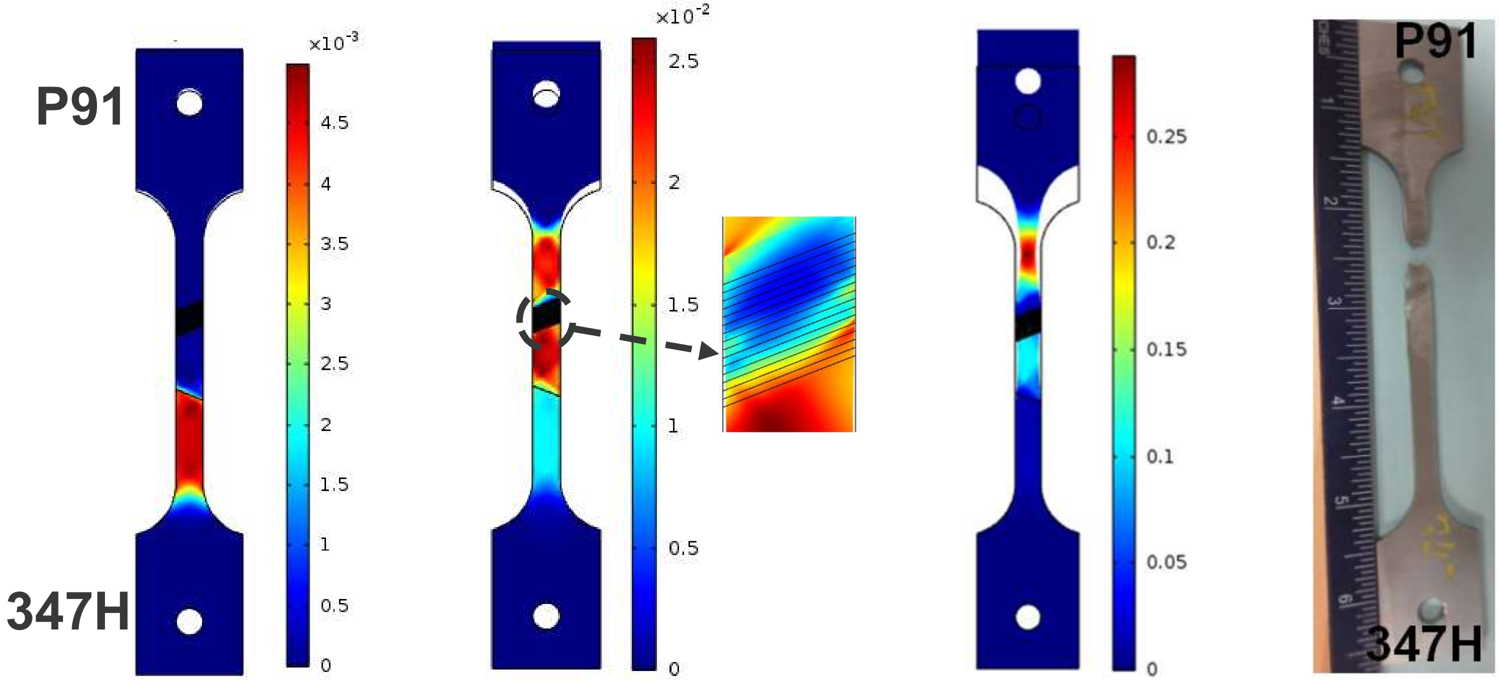


Condition	E (GPa)	n	σ_y (MPa)	% Area Reduction	Failure Location
As-Received	249.03 ± 4.32	0.125 ± 0.0023	488.93 ± 4.18	66.3 ± 5.93	P91
CO_2+4%H_2O+1%O_2, 650C-1000h Exposed	167.73 ± 16.79	0.1616 ± 0.0036	406.16 ± 2.80	38 ±9.3	P91

FE Simulation Results of P91-347H Weld Couple

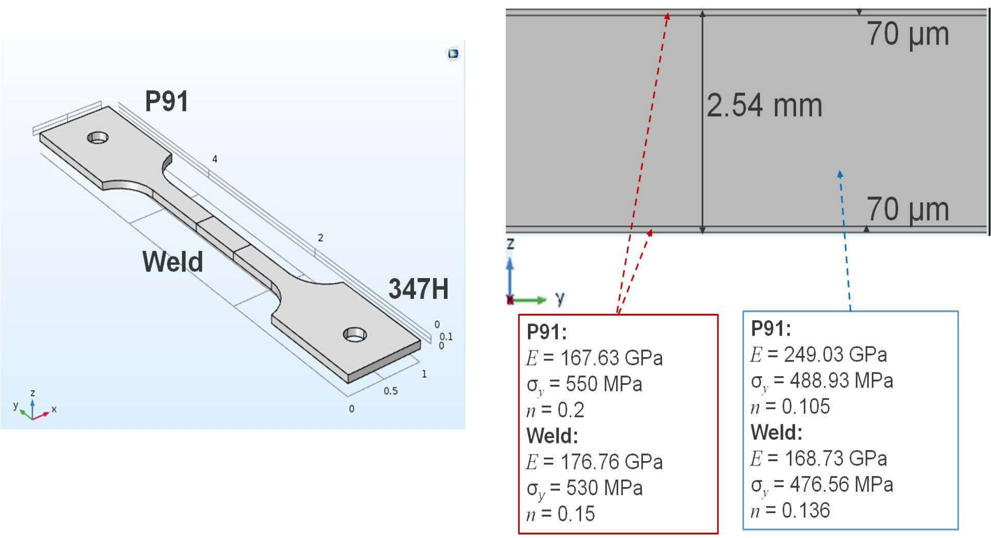
Plastic Strain Distribution at:

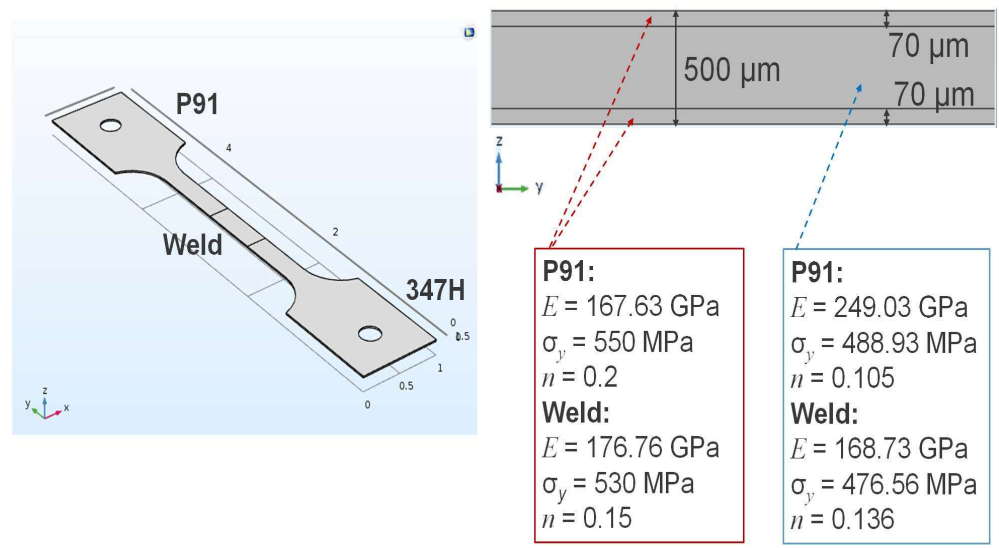
Δ =0.3 mm **Δ =1.1 mm** **Δ =4.5 mm**



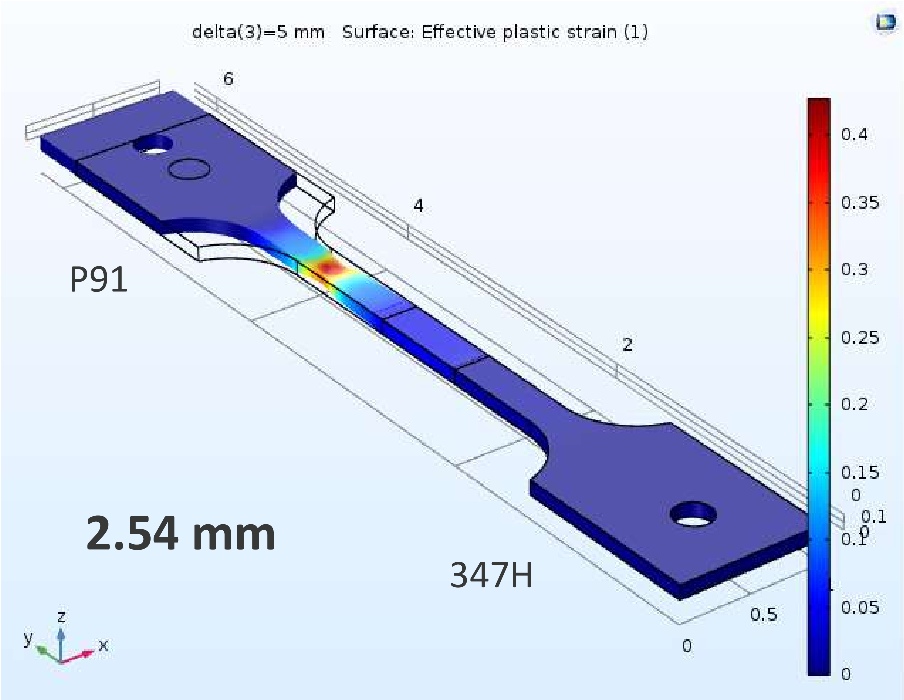
Failure location is on P91 from both FE simulation and tensile test.

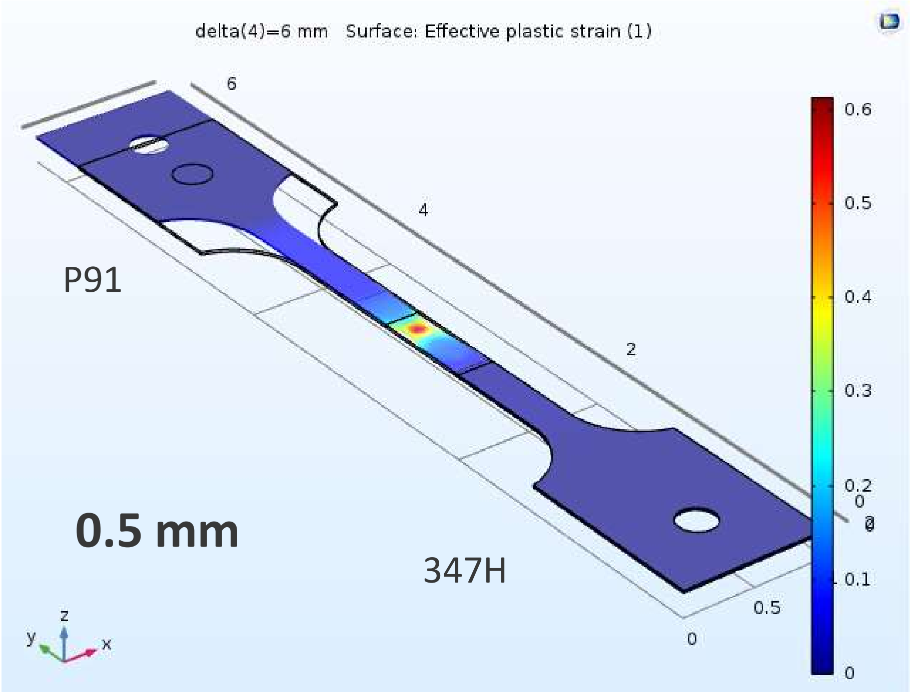
FE Simulation of Surface Modified P91-347H Weld Couple





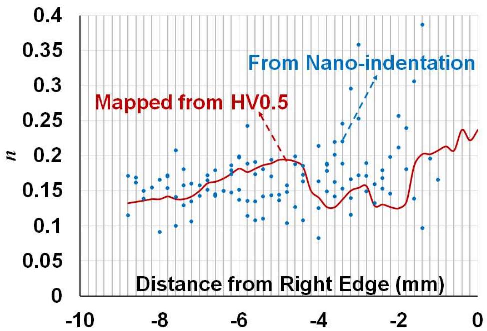
FE Simulation of Surface Modified P91-347H Weld Couple



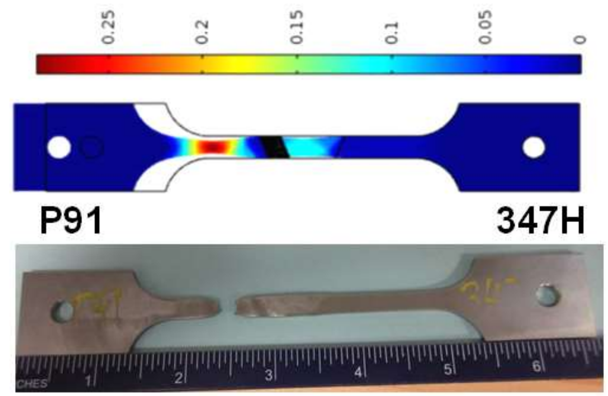


3D FE Simulation suggests that thin sheet specimen of 500 μm may behave differently than thick specimen of 2.54 mm (0.1") due to internal carburization.

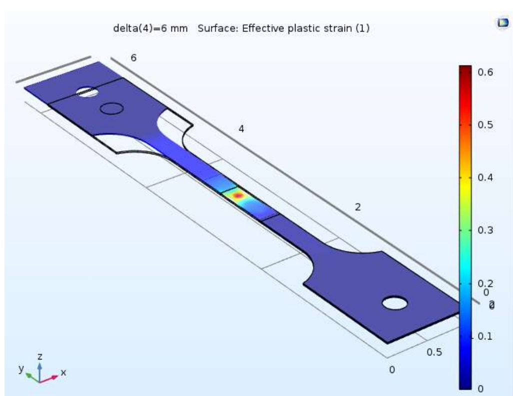
Summary – sCO_2 Effect on Dissimilar Metal Welds



As-received HAZ-P91 property variation is captured by nano-indentation.



2D FE Simulation predicts failure location successfully.



3D FE Simulation suggests that thin sheet specimens may behave differently than thick specimens under tensile load due to corrosion/carburization.

Supercritical CO_2 Power Cycles

Materials Research at NETL

- **High-temperature oxidation in direct sCO_2 power cycles**
- **Low-temperature corrosion in direct sCO_2 power cycles**
- Effect of sCO_2 cycle environments on mechanical properties
- **Erosion in components of sCO_2 power cycles**
- Materials issues in manufacturing compact heat exchangers
- **Mechanical and chemical stability of joined materials in sCO_2**
- Additive manufacturing of heat exchangers with new geometries