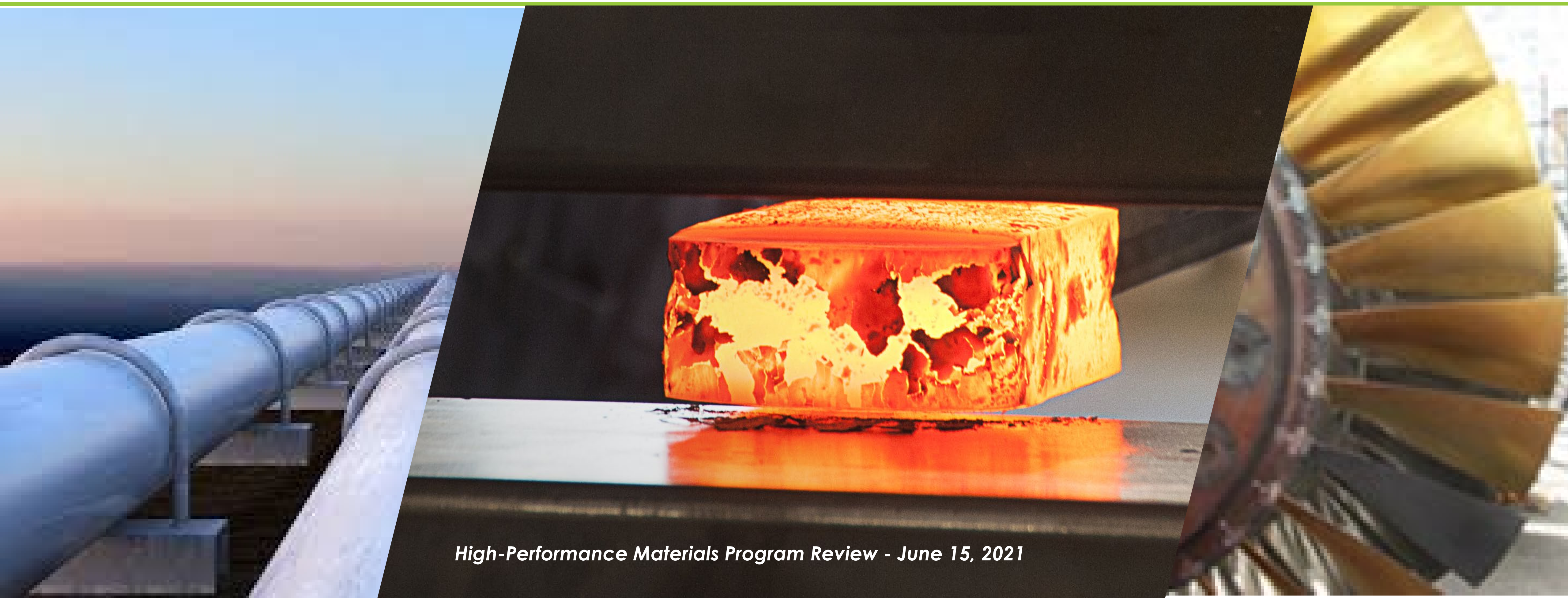
Materials Performance in sCO_2 Power Cycles

Advanced Alloy Development FWP Task 12

Ömer Doğan
Research and Innovation Center



High-Performance Materials Program Review - June 15, 2021

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Authors and Acknowledgements

Sajedur Akanda[1], Kyle Rozman[1,2], Jeff Hawk[1], Richard P. Oleksak[1,2], Ömer N. Doğan[1]

[1]National Energy Technology Laboratory, 1450 Queen Ave SW, Albany, OR 97321, USA

[2]NETL Support Contractor, 1450 Queen Ave SW, Albany, OR 97321, USA

Contacts: omer.dogan@netl.doe.gov
richard.oleksak@netl.doe.gov

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Supercritical CO_2 Power Cycles

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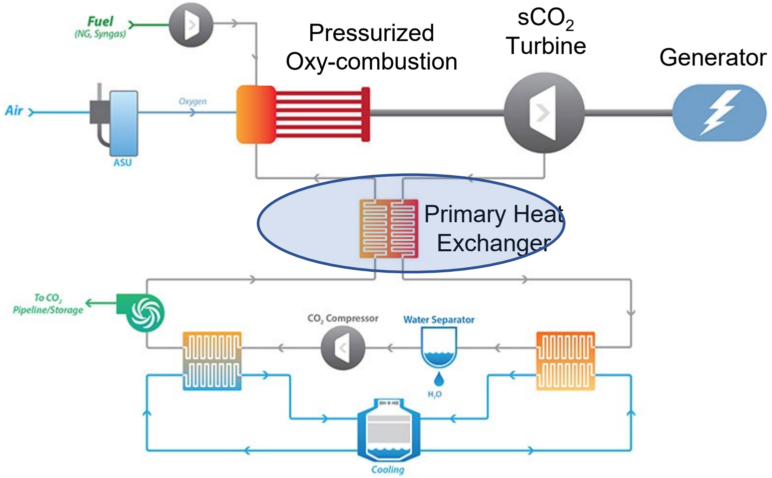
Direct-fired sCO_2 cycle



Properties of sCO_2 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

Materials are enablers for deployment of sCO_2 power cycles

Materials Challenges in sCO_2 power cycles:

- Materials perform in harsh environments (High T, P, and complex chemistry)
- Lack of data for materials performance
- Availability of cost-effective materials
- Manufacturing processes for components are not established for advanced materials

Materials Performance in Supercritical CO_2 Power Cycles

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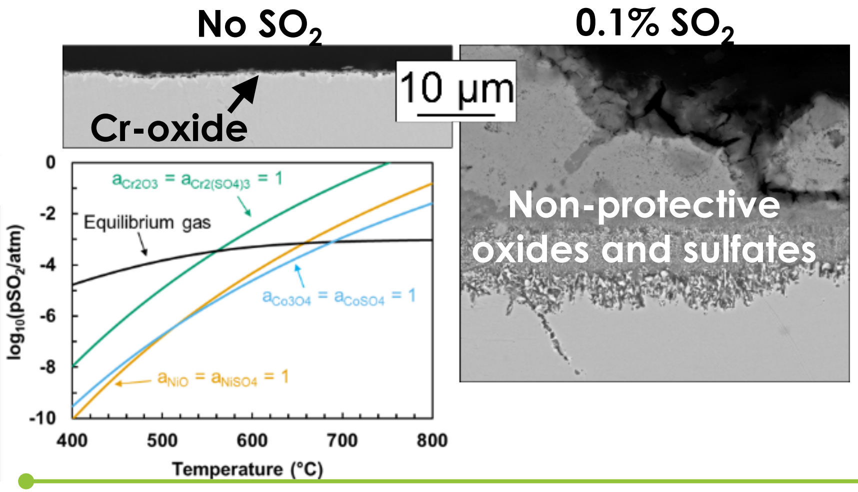
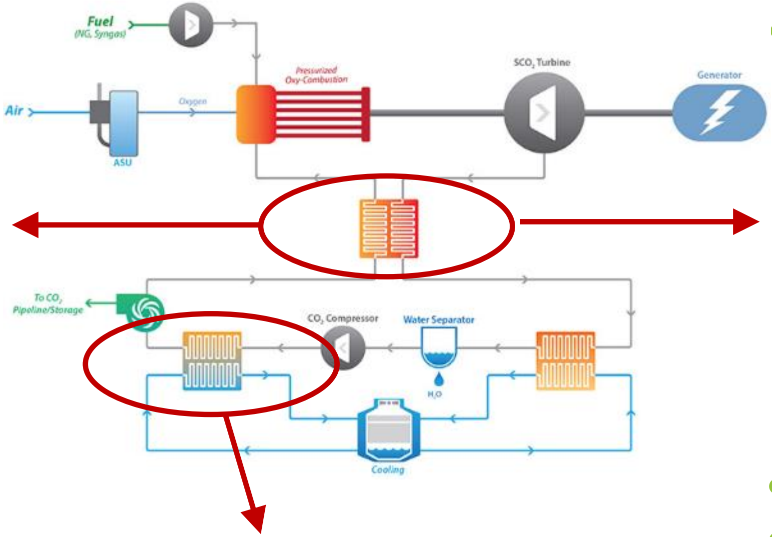
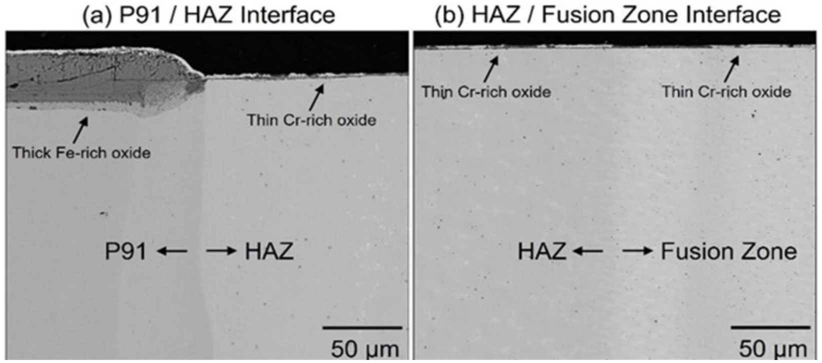
HIGH-TEMPERATURE OXIDATION OF STEELS AND SUPERALLOYS

Effects of impurities and pressure

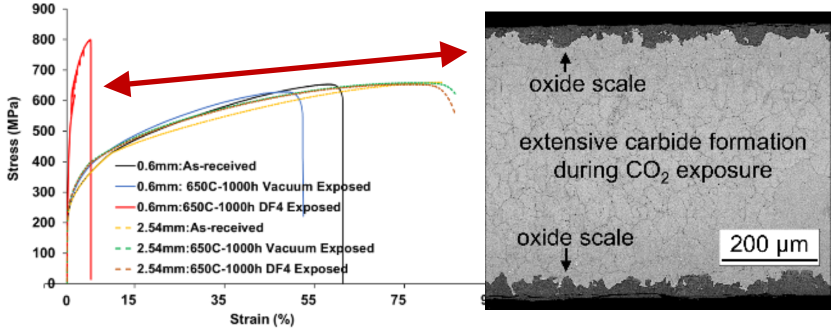




JOINING

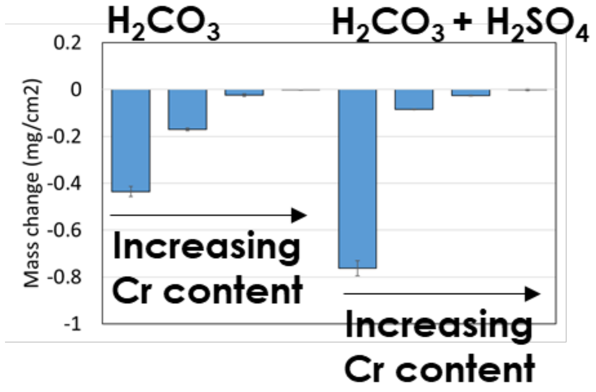


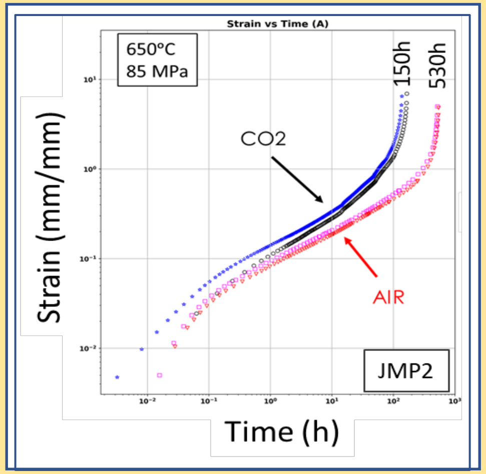
LINKING OXIDATION BEHAVIOR AND MECHANICAL DEGRADATION



LOW-TEMPERATURE CORROSION

Identifying low-cost steels resistant to acidic condensates



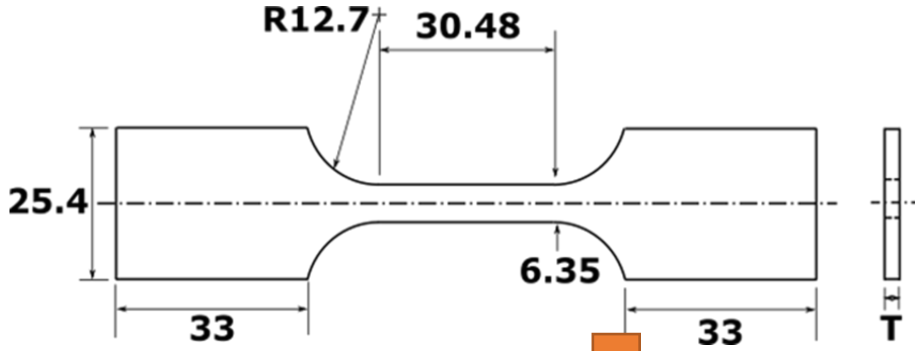


Current Effort

Impact of CO_2 on:

- ✓ creep
- ✓ creep-fatigue

Effect of Direct sCO_2 Conditions on Mechanical Performance of 9 Cr Steels



Thickness
0.5 mm
2.5 mm

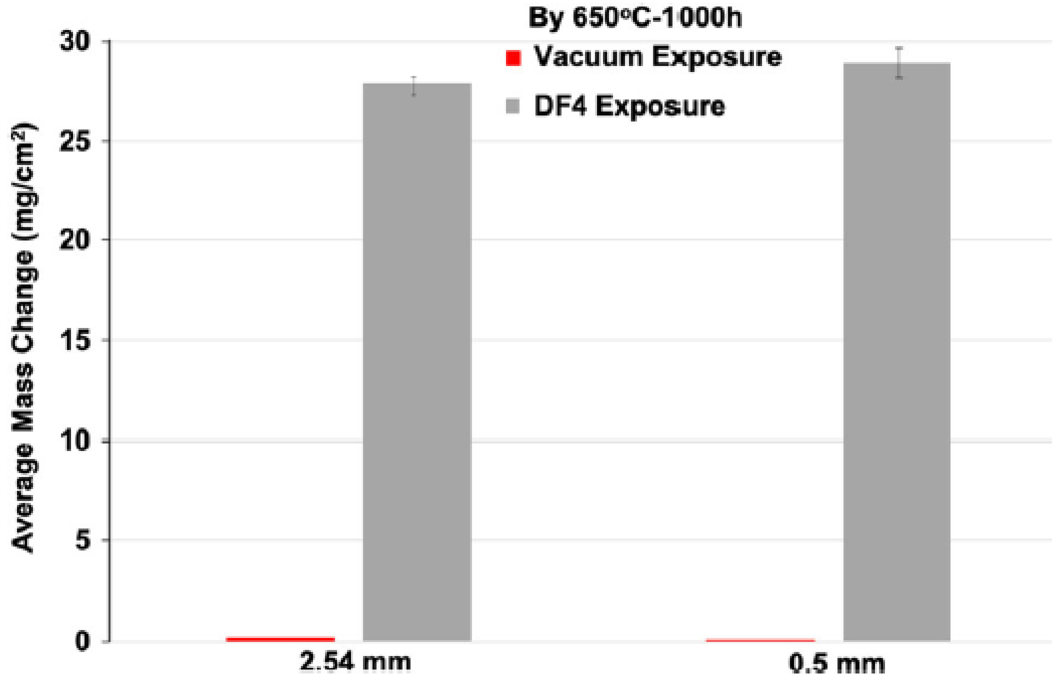
				Grade 91					
Fe	Cr	C	Mn	Mo	Ni	V	Si	Nb	N
Bal.	8.37	0.09	0.45	0.90	0.09	0.22	0.33	0.07	0.05

As-received
Normalized at 1038C for 4 h
Tempered at 788C for 1.5h

DF4 Exposure
1 bar flowing gas ($95\%CO_2+4\%H_2O+1\%O_2$) at 650°C for 1000 hours

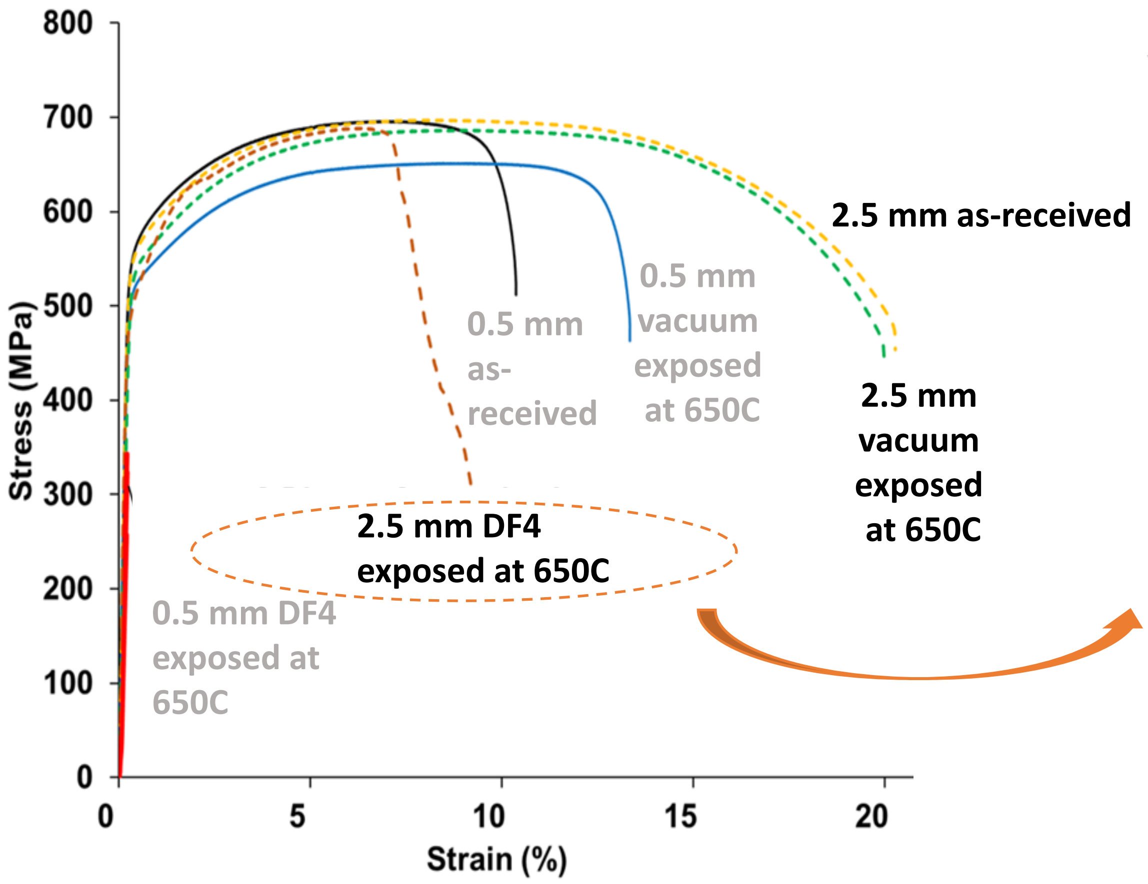
Vacuum Exposure
at 650°C for 1000 hours

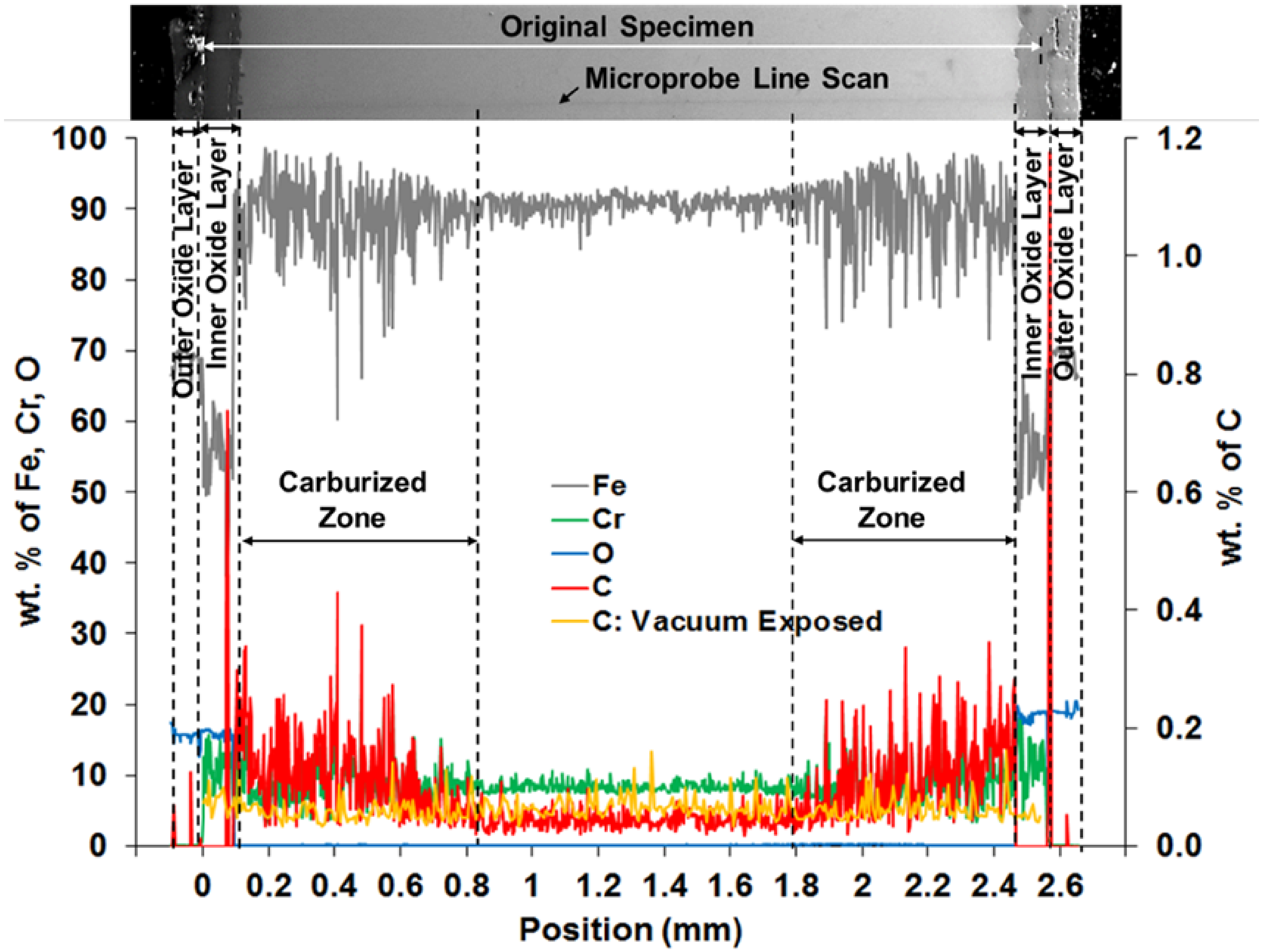
Tensile testing
Room temperature
Strain rate of $4 \times 10^{-5}\ s^{-1}$



Effect of Direct sCO_2 Conditions on Mechanical Performance of 9 Cr Steels

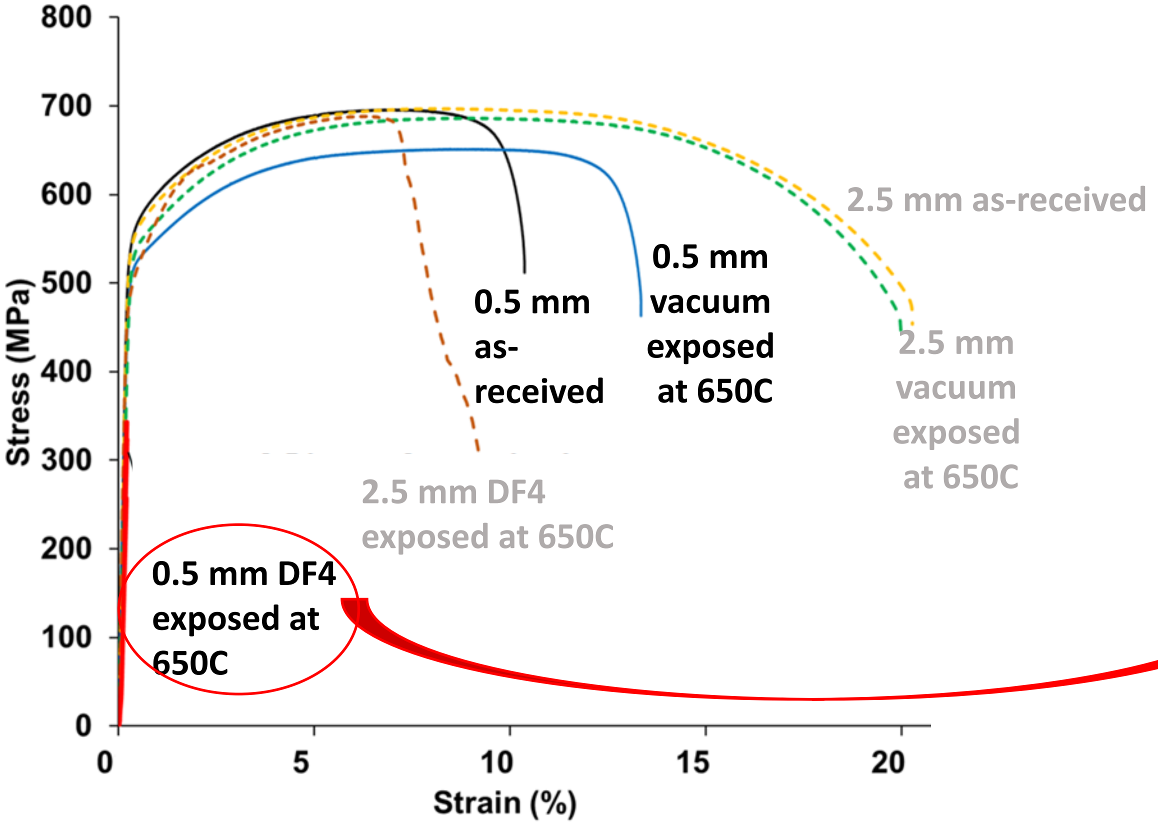
2.5 mm thick specimen after exposure to DF4

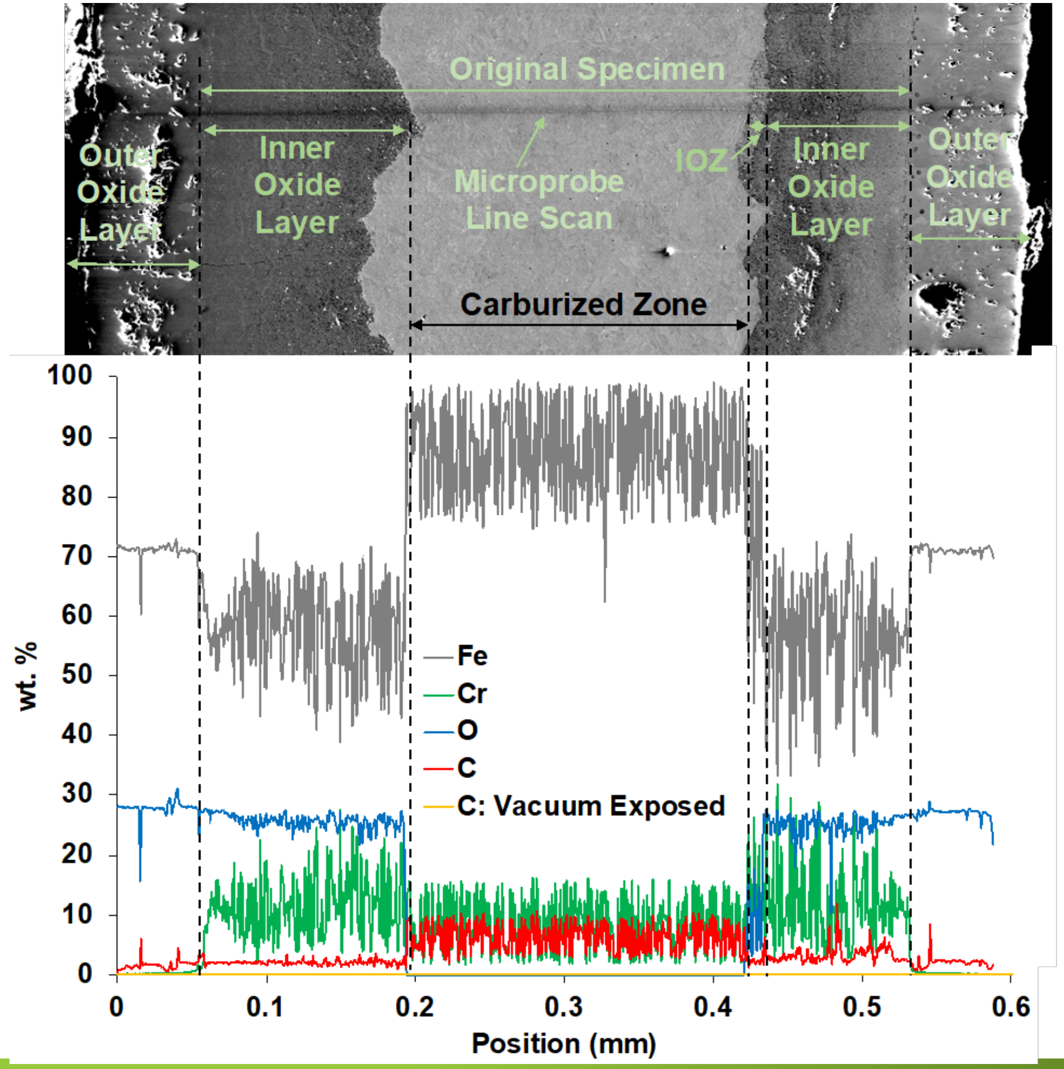




Effect of Direct sCO_2 Conditions on Mechanical Performance of 9 Cr Steels

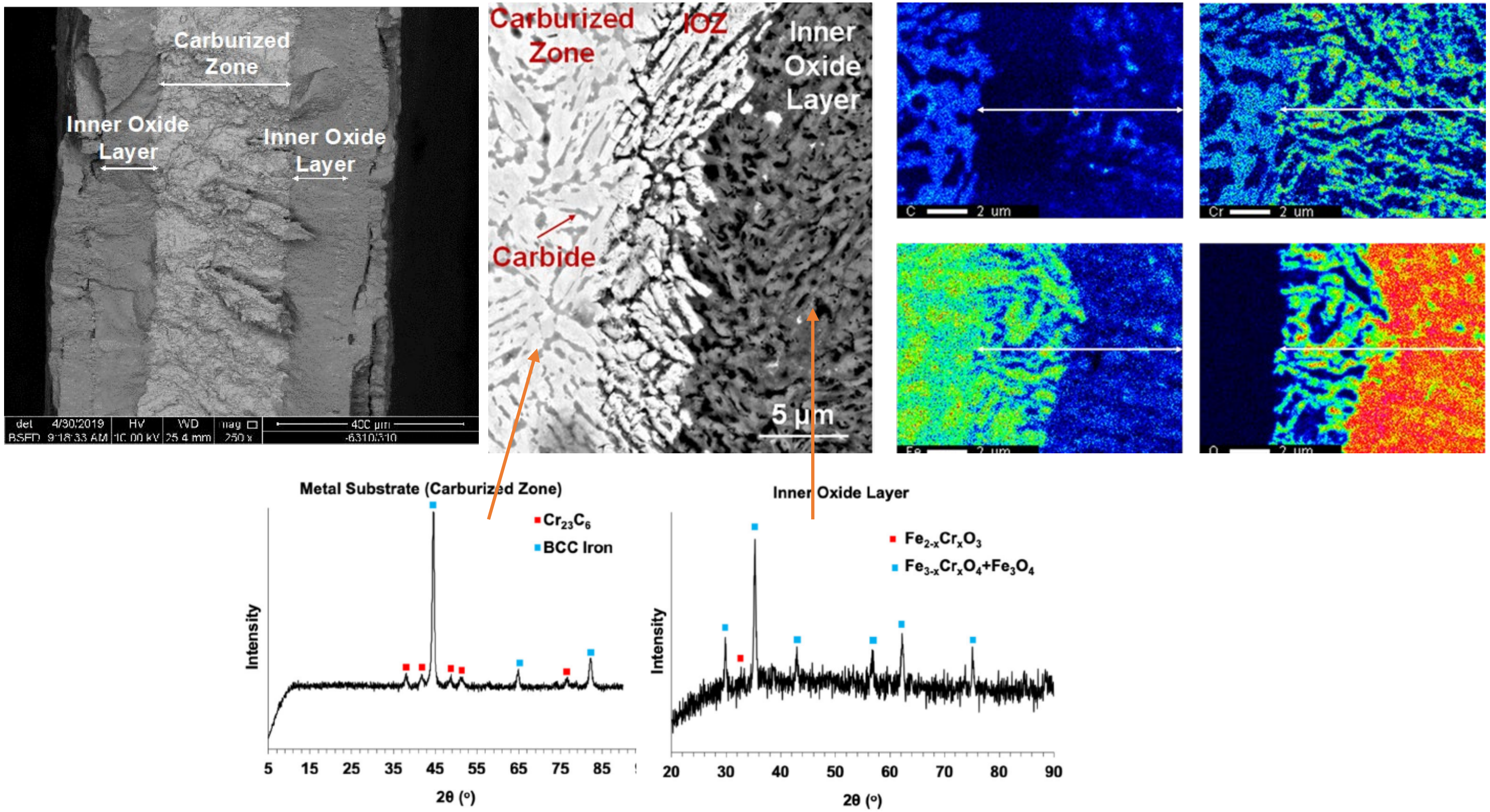
0.5 mm thick specimen after exposure to DF4





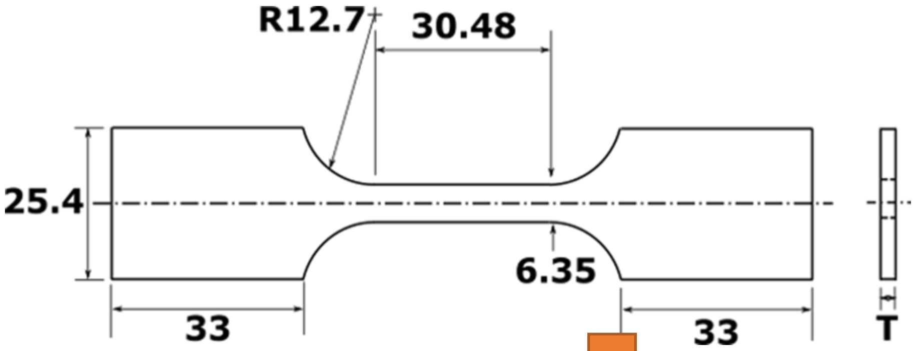
Effect of Direct sCO_2 Conditions on Mechanical Performance of 9 Cr Steels

0.5 mm thick specimen after exposure to DF4



- Duplex oxide scale formation
- CO2 transport to the oxide-metal interface
- Oxidation of Cr and Fe and C deposition at the oxide-metal interface
- Diffusion of C into the metal and formation of Cr rich carbides (M23C6)
- Growth of inner oxide into the alloy
- Conversion of Cr rich carbides to Cr-rich oxides
- C liberation and diffusion further into the alloy
- C saturation and deposition of C in the oxide scale
- Breakaway oxidation

Effect of Direct sCO_2 Conditions on Mechanical Performance of Austenitic Steels



Thickness
0.6 mm
2.5 mm

As-received
Annealed at 1065C

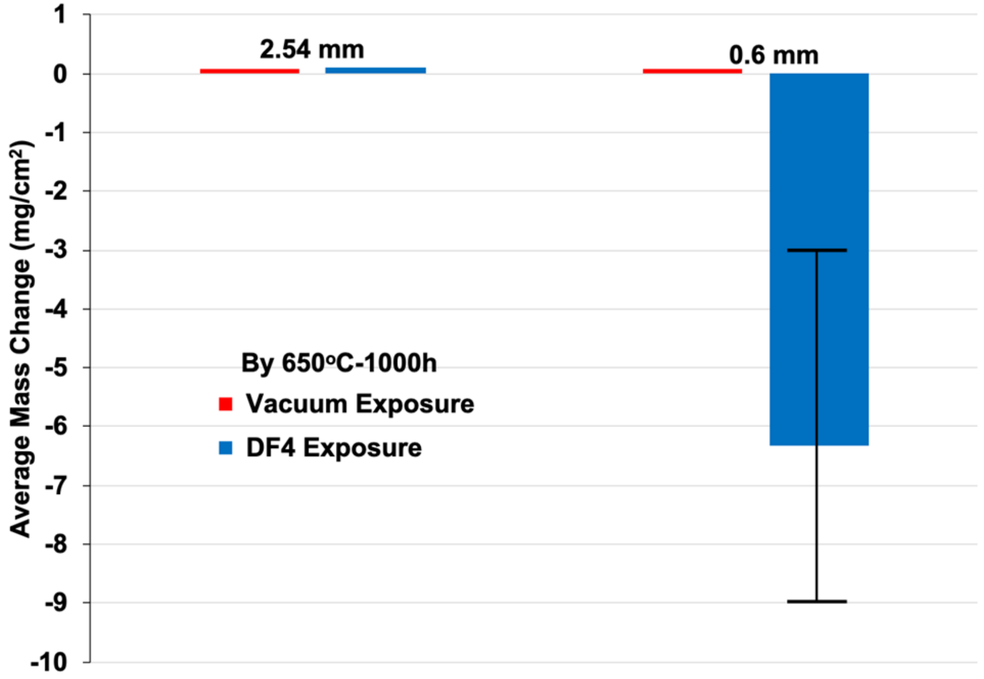
DF4 Exposure
1 bar flowing gas ($95\%CO_2+4\%H_2O+1\%O_2$) at 650°C for 1000 hours

Vacuum Exposure
at 650°C for 1000 hours

Tensile testing
Room temperature
Strain rate of $4x10^{-5}$ s^{-1}

347H

Fe	Cr	Ni	Mn	Si	Nb	Cu	Co	Mo	C
Bal.	17.3	9.0	1.5	0.4	0.6	0.4	0.2	0.4	0.05



S.R. Akanda, *Corrosion Science* (2021) in review

Effect of Direct sCO_2 Conditions on Mechanical Performance of Austenitic Steels

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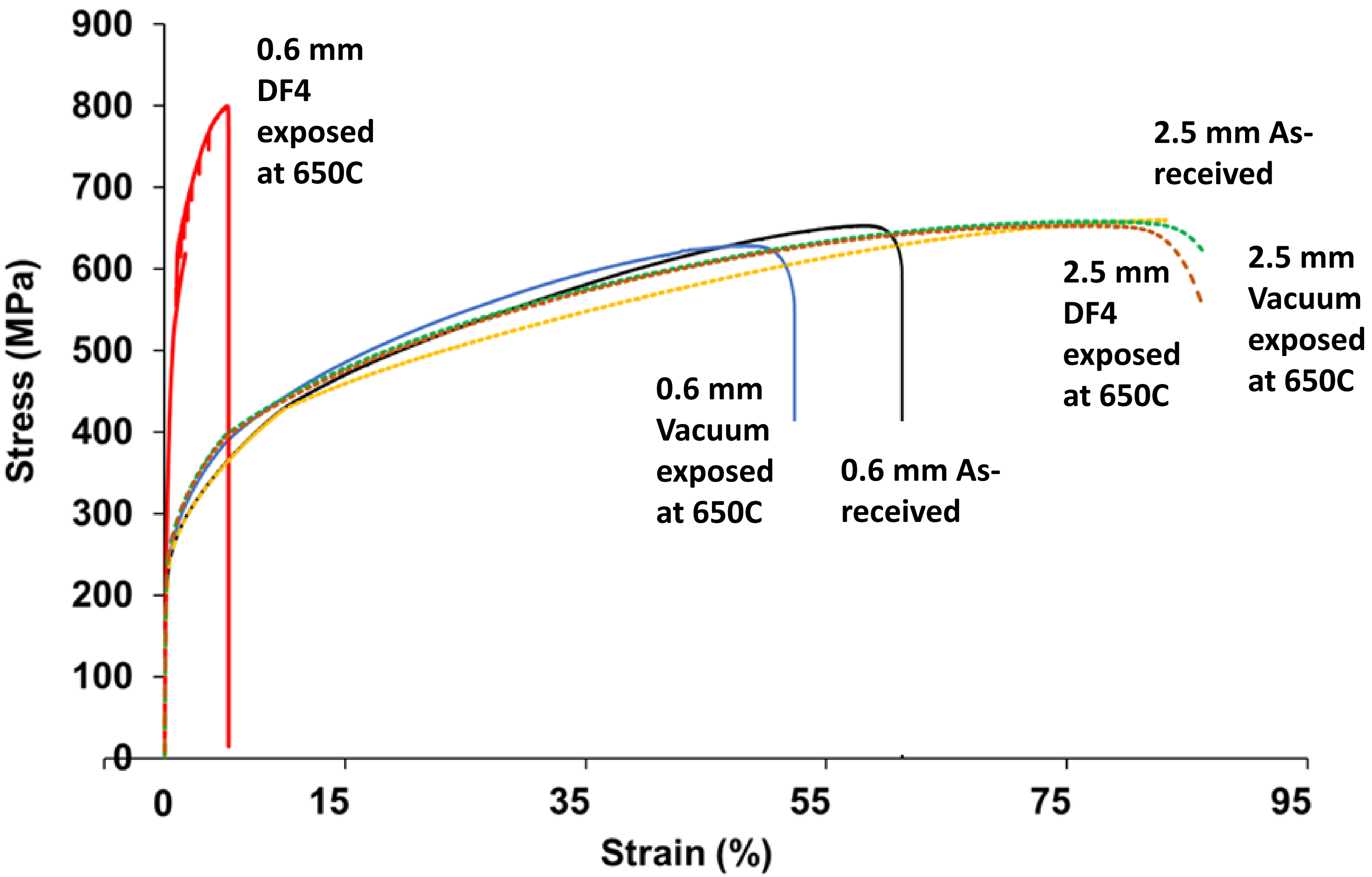
347H



- 2.5 mm thick 347H formed a protective chromia scale, resulting in no mechanical degradation.
- **0.6 mm thick 347H failed to form chromia, resulting in extensive carburization and embrittlement.**

Effect of Direct sCO_2 Conditions on Mechanical Performance of Austenitic Steels

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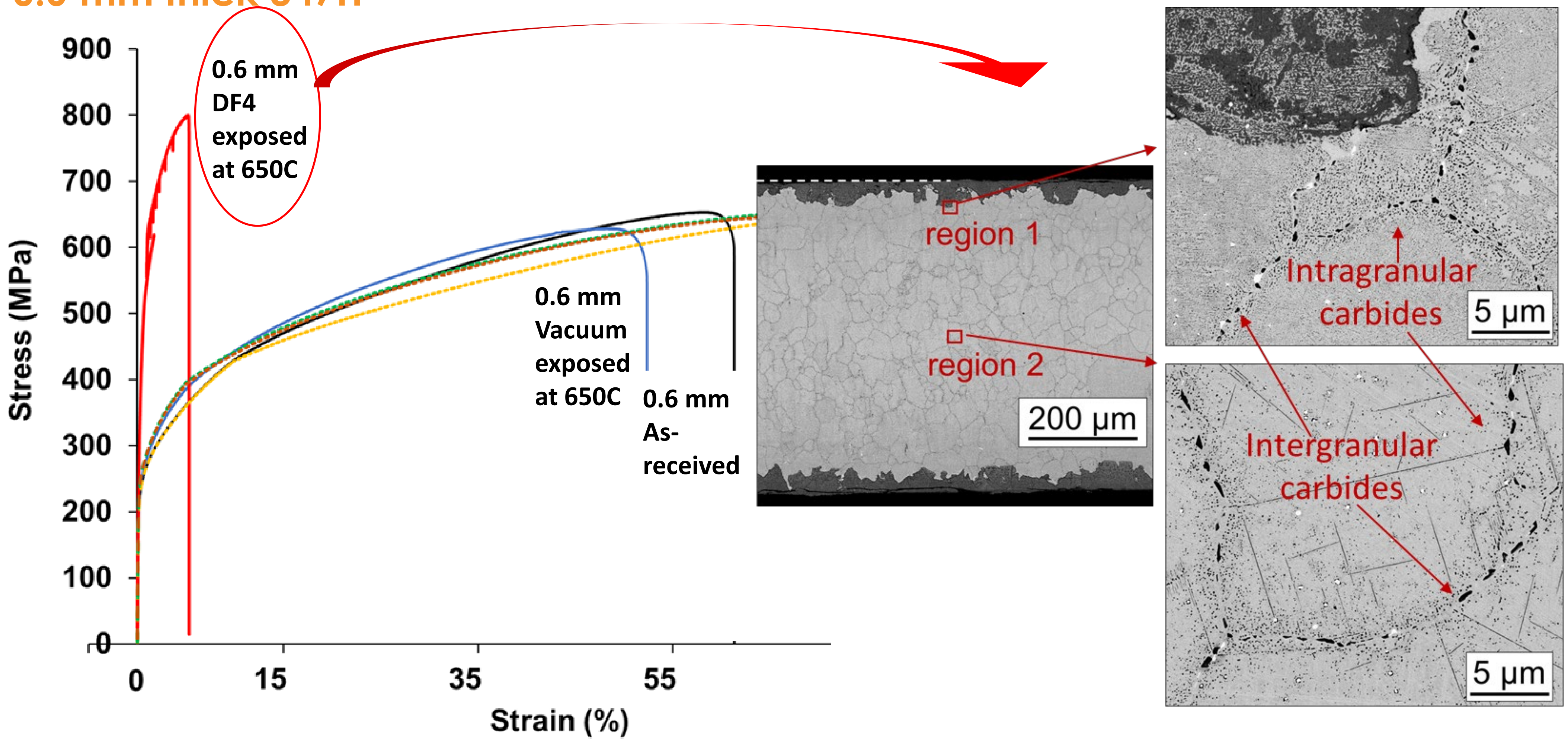
0.6 mm thick 347H



- Steels containing less than 18%Cr cannot be used in thin wall applications (compact heat exchangers) for direct sCO_2 power cycles.
- Higher Cr steels will need to be tested.

Environmental Creep Testing of Steels in CO_2

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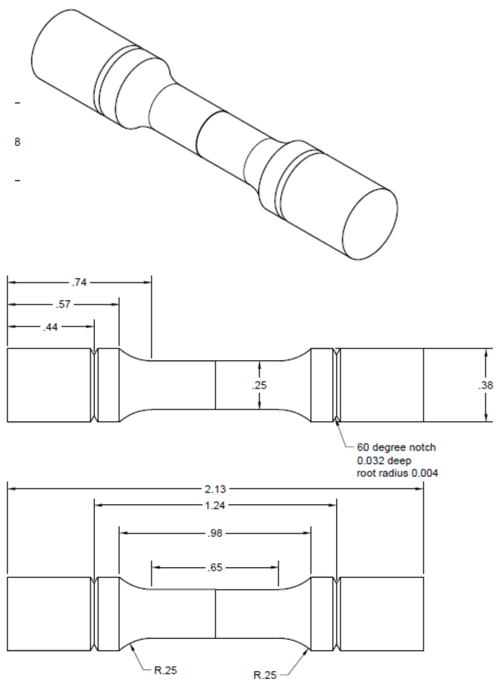
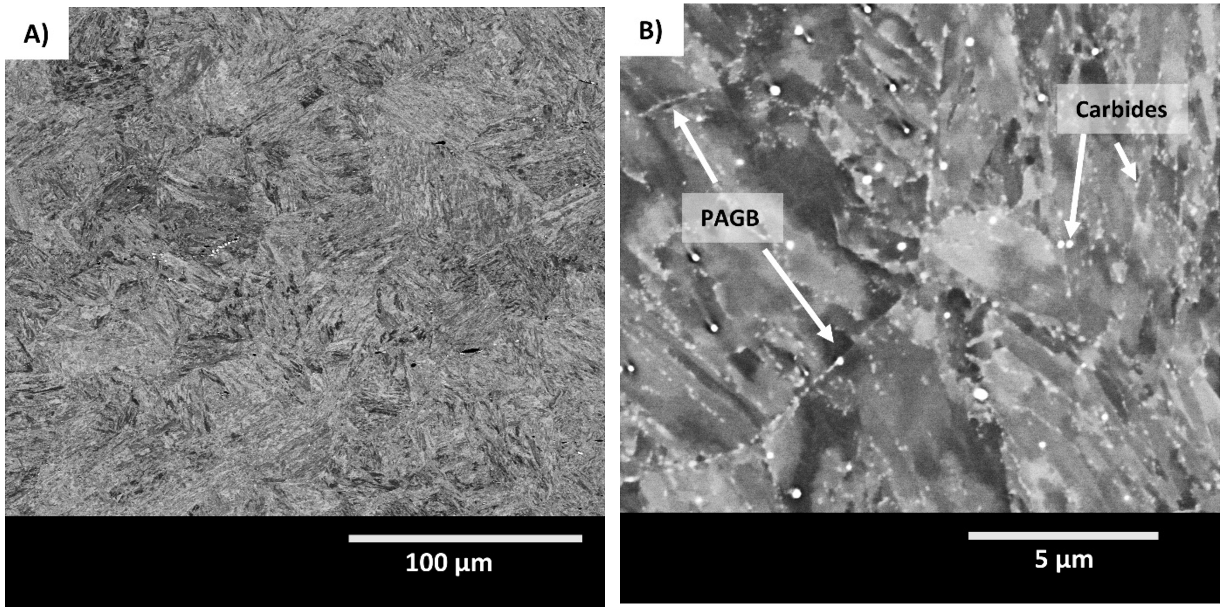
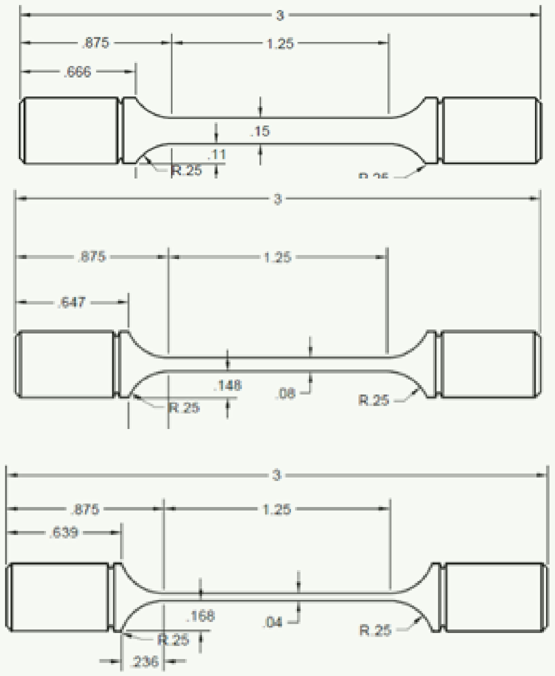
					MARBN							
Fe	Cr	Co	W	Mn	Ta	V	Ni	Mo	Nb	C	N	B
Bal.	9.08	2.93	2.90	0.51	0.35	0.20	0.18	0.10	0.06	0.15	0.02	0.01



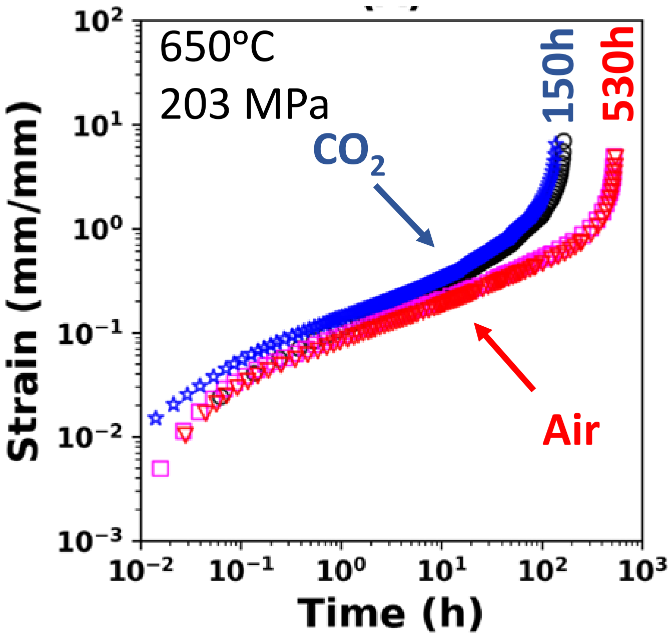


347H SS specimens with three thicknesses are being tested in air and CO_2

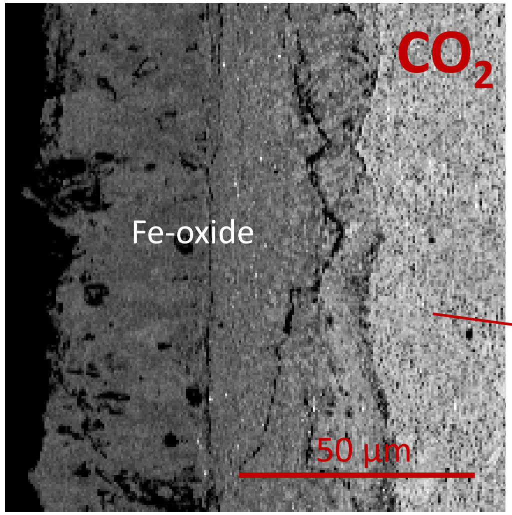


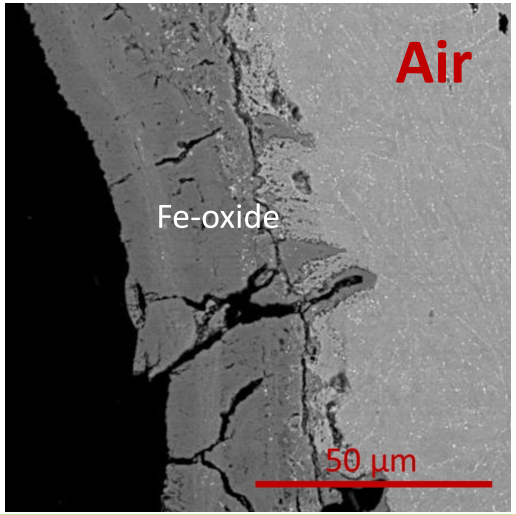
Environmental Creep Testing of Steels in CO_2

MARBN Ferritic-Martensitic 9Cr steel

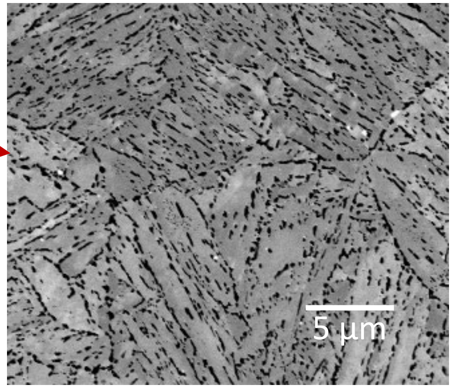


Reduced creep life in CO_2 relative to air at 650 °C





Steel carburization in CO_2 enables crack propagation via carbide network



Task 12 Milestones and Recent Publications

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Milestones

03/31/2022	**Determine the effect of environment on the creep behavior of thin-section components of Fe alloys in sCO_2 power cycles.**
03/31/2022	Identify an alloy that is at least 30% less expensive than 18Cr-10Ni grades (e.g., 347H) and shows comparable oxidation performance in sCO_2 power cycle environments at temperatures ≤ 450°C.

- Effect of Specimen Thickness on the Degradation of Mechanical Properties of Ferritic-Martensitic P91 Steel by Direct-fired Supercritical CO_2 Power Cycle Environment, S.R. Akanda, R.P. Oleksak, R. Repukaiti, K.A. Rozman, Ö.N. Doğan,*Metall Mater Trans A* (2021) 52 (1) 82-93. https://doi.org/10.1007/s11661-020-06065-9.
- High-Temperature Oxidation of Transient-Liquid Phase Bonded Ni-Based Alloys in 1 bar and 250 bar Carbon Dioxide, C.S. Carney, R.P. Oleksak, M. Kapoor, G.R. Holcomb, , Ö.N. Doğan, *Materials at High Temperatures* (2020) 37 (6) 445-461. https://doi.org/10.1080/09603409.2020.1818046.
- Tensile Deformation Behavior of a Dissimilar Metal Weldment of P91 and 347H Steels, S.A. Akanda, R.W. Wheeler, K.A. Rozman, J. Rider, Ö.N. Doğan, M.L. Young, J.A. Hawk, *Strain* (2020) https://doi.org/10.1111/str.12366.
- Temperature-Dependence of Corrosion of Ni-Based Superalloys in Hot CO2-Rich Gases Containing SO2 Impurities, R.P. Oleksak, J.H. Tylczak, G.R. Holcomb, Ö.N. Doğan, *JOM (2020).*
- High temperature oxidation of steels in CO2 containing impurities, R.P. Oleksak, J.H. Tylczak, G.R. Holcomb, Ö.N. Doğan, *Corrosion Science* (2020).

Status and Summary

- Ni alloys demonstrate good corrosion properties in direct sCO_2 environment; however, identifying steels that can work at appropriate temperature range is important for cost reduction. So far, our work on steels shows that:
- Steels containing >12 wt% Cr perform well in direct sCO_2 environments.
- 9Cr steels perform poorly in direct sCO_2 conditions due to high rates of oxidation and carburization, resulting in severe embrittlement.
- Steels containing less than 18% Cr (such as 347H, 316) likely cannot be used in thin wall applications (compact heat exchangers) for direct sCO_2 power cycles. Higher Cr steels will need to be tested.
- Reduced creep life of 9Cr steels in CO_2 was demonstrated in environmental creep test setup.