DoE Award No. DE-FE31819

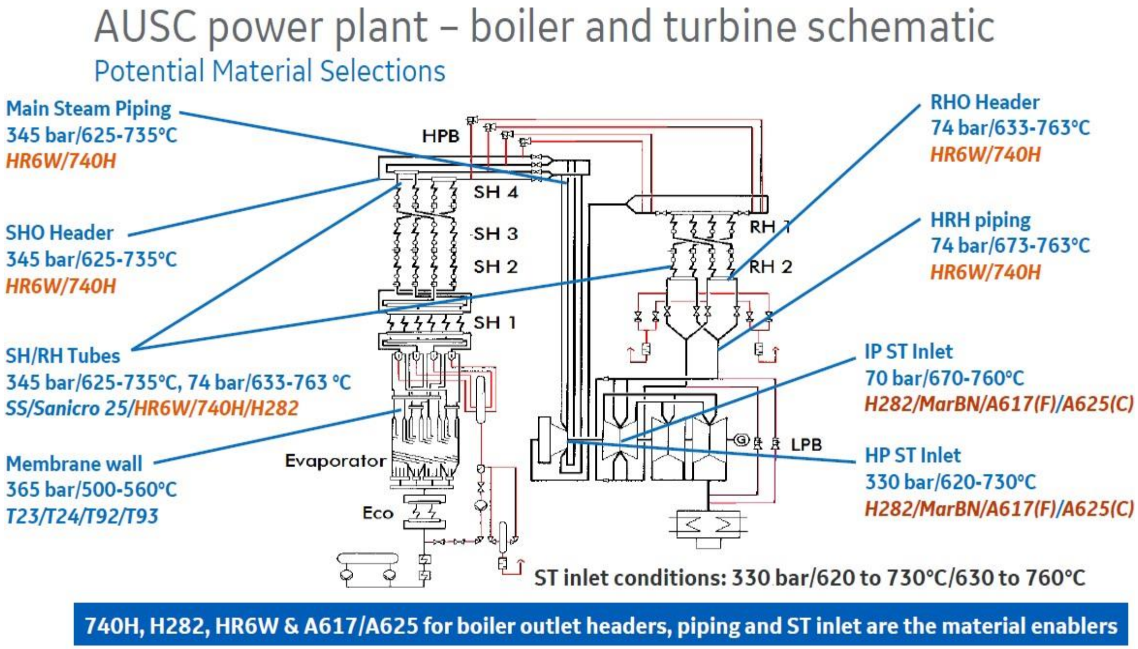
Additively Manufactured Graded Composite Transition Joints (AM-GCTJ) for Dissimilar Metal Weldments in Advanced Ultra-Supercritical Power Plant

Xingbo Liu[1], Wenyuan Li[1], Kostas Sierros[1], Bai Cui[2], Zhili Feng[3], Yanli Wang[3], Changjie Sun[4], Haiyang Qian[5]

[1]West Virginia University; [2]University of Nebraska – Lincoln; [3]Oak Ridge National Laboratory; [4]GE Research; [5]GE Power,

May 9, 2022

DMWs in A-USC and HRSG



GE Steam: A-USC Mock Header

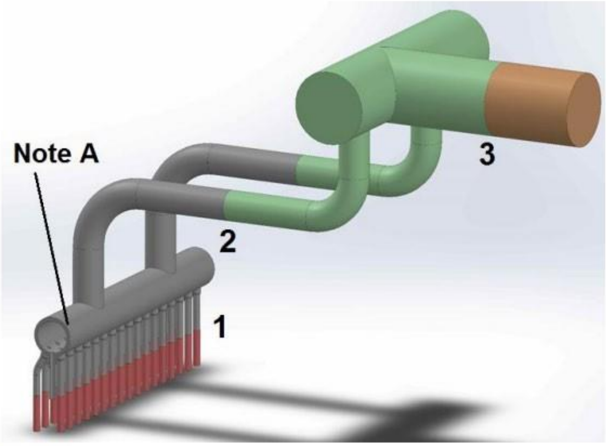


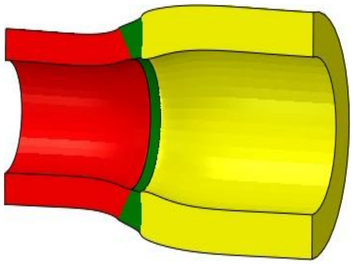
Figure 3-1
HRSG configuration highlighting potential DMW locations (1: tubing internal to the HRSG setting; 2: link piping; 3: outlet piping.)

Program on Technology Innovation: Guidelines and Specifications for High Reliability Fossil Power Plants—Best Practice Guideline for Manufacturing and Construction of Grade 91 Steel to Austenitic Stainless Steel Dissimilar Metal Welds 3002007221 Final Report, December 2017

DMW:

1. Grade 91 – Austenitic Stainless Steel
2. Ni based alloy – Austenitic Stainless Steel

Mismatch of coefficient of thermal expansion and **thermal cycling:**



DMW with sharp material transition

- Mismatch of coefficient of thermal expansion between different materials lead to high strain range along the interface during thermal transients.
- Increasing demand in industry for flexible operation of steam boilers and more cycling capability of HRSGs.

Higher cycling requirements in power industry:

- Steam Boilers: A sample required number of cycles for a new unit

	Total # of cycles of 25 years
Cold Start	455
Warm Start	910
Hot Start	4550

- HRSGs: Typical required number of cycles for a cyclic operating CCPP

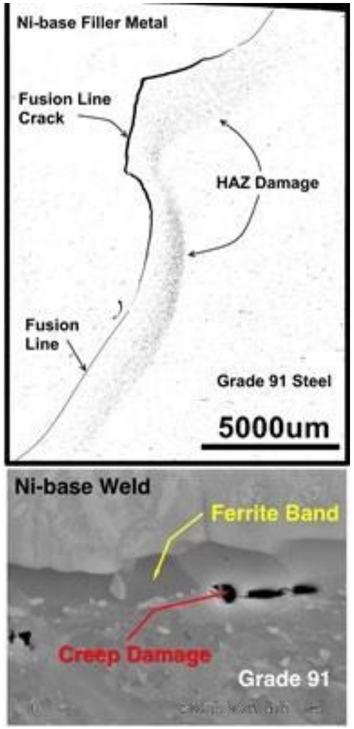
	Total # of cycles of 25 years
Cold Start	250
Warm Start	1250
Hot Start	4250

Current Dissimilar Metal Welds (DMWs)

Failures in DMWs @ the fusion boundary between Grade 91 and nickel based filler metal, often accompanied with considerable damages in the HAZ of Grade 91

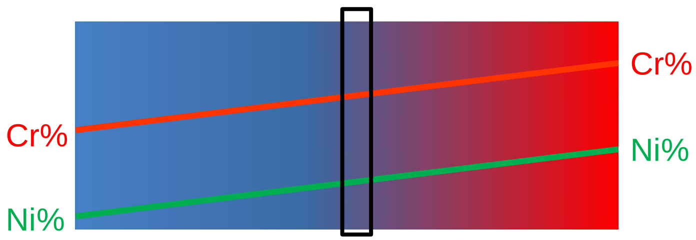
HT exposure during PWHT or service causes carbon diffusion from the ferritic matrix toward the austenitic matrix. Leads to the formation of a carbon-depleted soft zone on the ferritic side and nucleation/growth of carbides on the ASS side that have very high hardness.

Under imposed residual, external, and thermal stresses caused by the CTE mismatch between different alloys of the DMW, creep and/or creep fatigue cracks can occur along the fusion boundary and HAZ.



AM-Graded Transition Joints (GTJs)

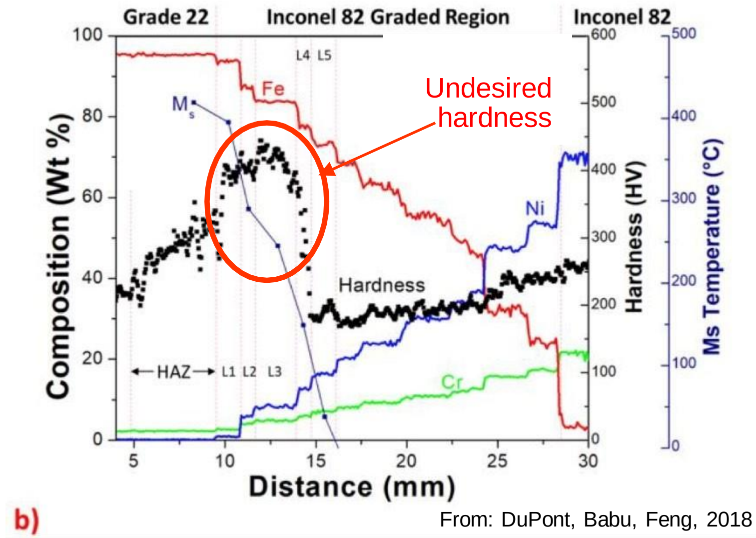
"Conventional" melting based AM



Grade 91
0.08C-9Cr-1Mo-0.4Ni

0.08C-14Cr-4Ni-0.5Mo:
microstructure?

SS304
0.08C-18Cr-8Ni



From: DuPont, Babu, Feng, 2018

- "Conventional" AM (wire or powder) approach melts alloys A&B completely together
  - A critical issue is the continuous transition in composition creates complex and often undesired microstructure

Advantages of AM-GCTJ

- Solid-state Process, composites material” transition with constituents of known chemistry (such as P91, SS304, A282) mixed in controlled proportion
    - •Solved the critical drawbacks of undesired/unpredictable phases/microstructure in conventional AM approach to fabricate the transition joint
- 100% smooth transitions
- Welding happens at A-A, and B-B, no DMWs
- Minimize scale-up issues expected to manufacture large quantity of joints

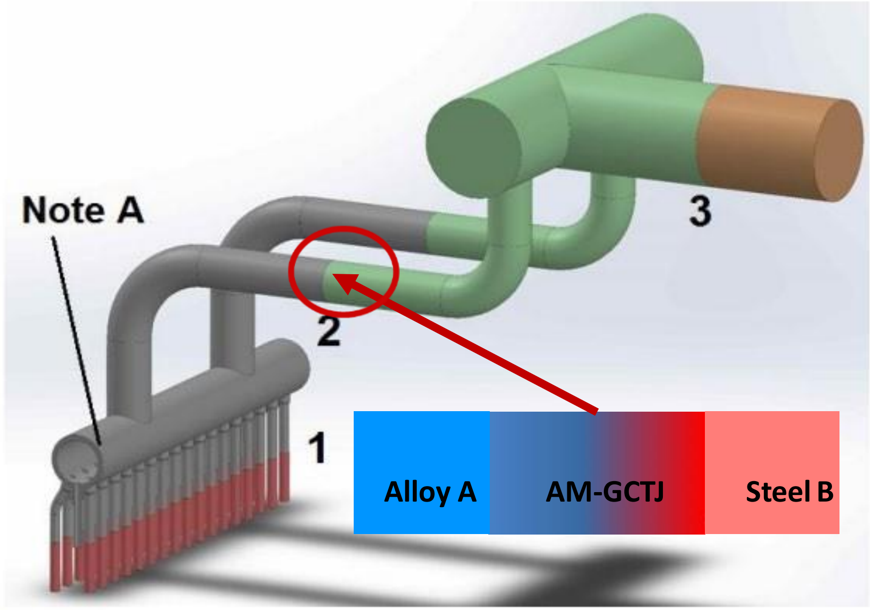


Figure 3-1
HRSG configuration highlighting potential DMW locations (1: tubing internal to the HRSG setting; 2: link piping; 3: outlet piping.)

Illustration of DM weld in power plants

* U.S. Patent Appl. No. 62/704,965 – Method to Produce an Additively Manufactured-Graded Composite Transition Joint

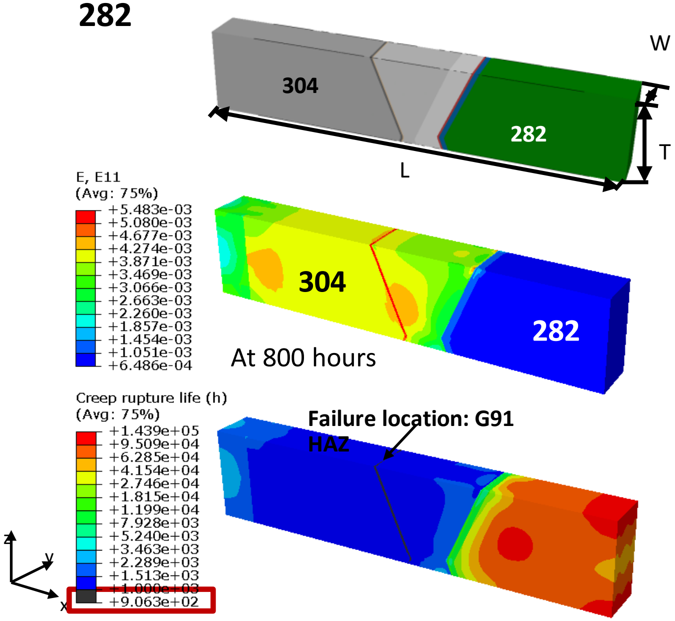
PROJECT OBJECTIVES – PHASE I

(1) To develop and demonstrate at the lab-scale the additively manufactured graded composite transition joints (AM-GCTJ) for dissimilar metal weldments (DMW) in next generation advanced ultra-supercritical (A-USC) coal-fired power plants, that can significantly improve the microstructural stability, creep and thermal-mechanical fatigue resistance, as compared with their conventional counterparts;

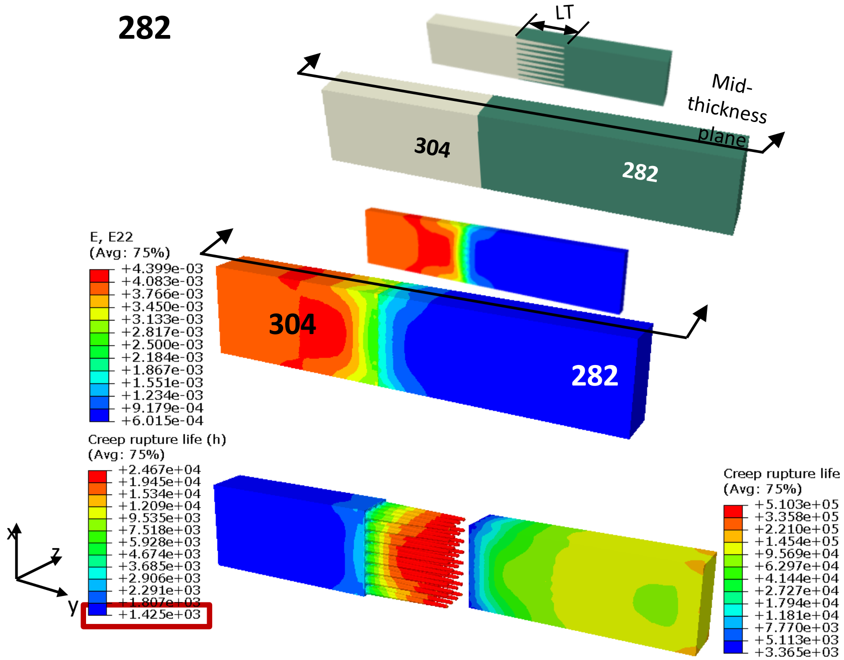
(2) To manufacture and test the components with AM-GCTJ, to advance the technology readiness level to TRL-7, and manufacturing readiness level to MRL 6-7, for targeted commercial applications identified by GE Steam Power, the primary industry partner of the project team

ICWE Model Guided Design - Creep

- **DMW of 304 and 282**



- **AM-GCTJ of 304 and 282**



- Dimensions of test specimens (unit: inch)

	L	W	T	LT
DMW	5	0.5	1.0	
AM-GCTJ	5	0.5	1.0	1.0

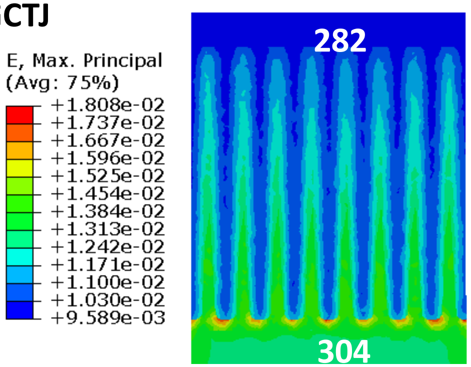
- AM-GCTJ exhibits improved creep resistance

	Creep life (h)	Failure location
DMW	906.3	HAZ of 304
AM-GCTJ	1425.5	Base material of 304

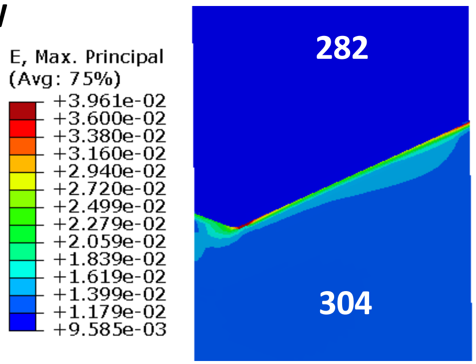
Prediction of Creep Strain Accumulation and Rupture Life of SS 304 - 282 joints at 700 °C and 120 MPa

ICWE Model Guided Design - Thermal Fatigue

- **AM-GCTJ**

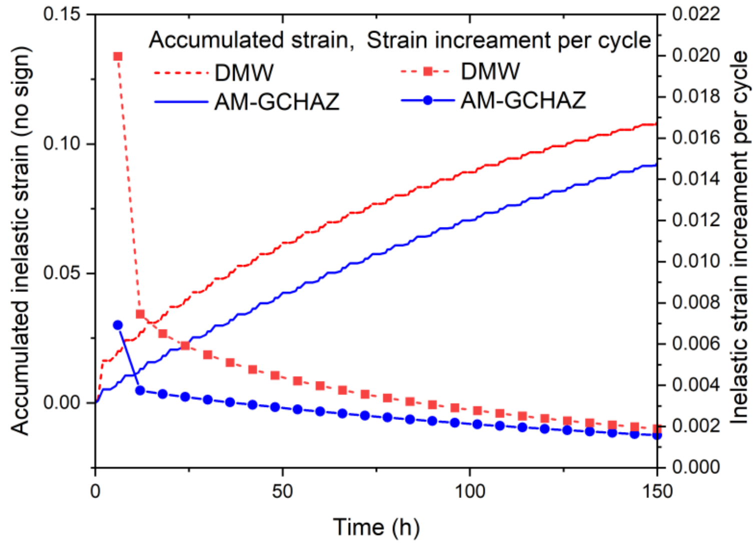


- **DMW**



Strain at 25th thermal cycle, temperature at 700°C

Thermal fatigue load:
Temperature ranges between room T and 700 °C, with 2 hours of loading, holding, and unloading

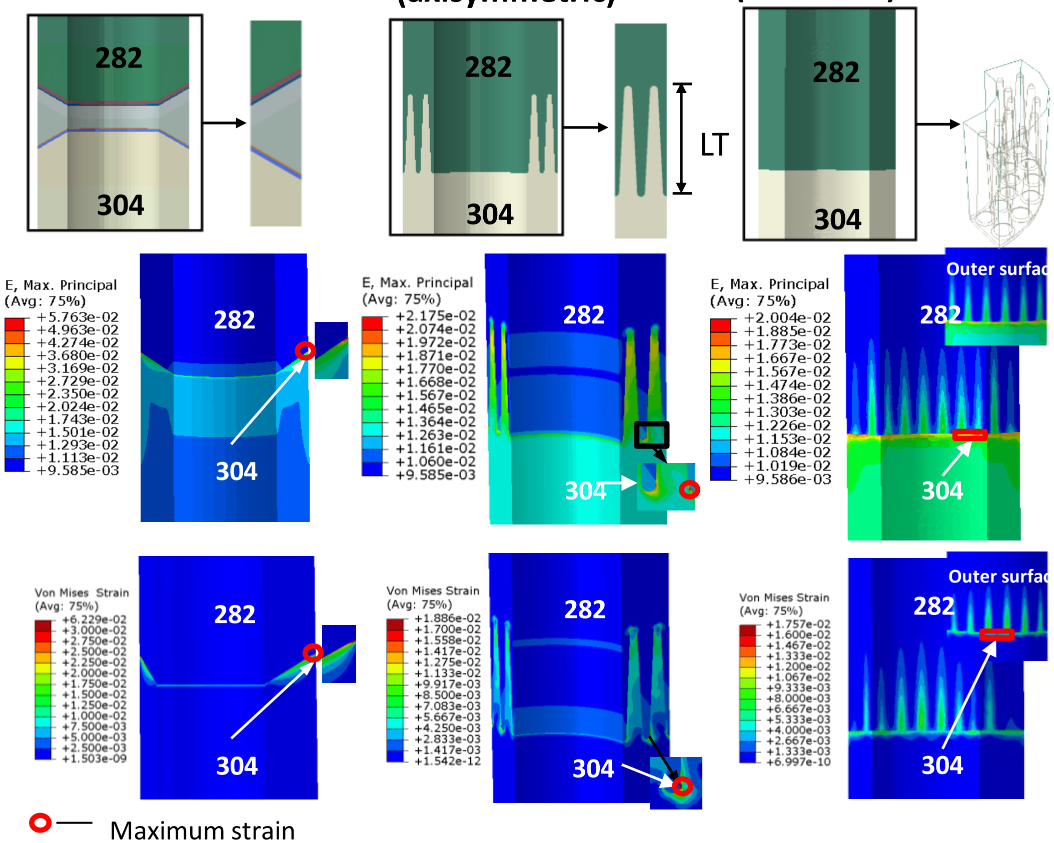


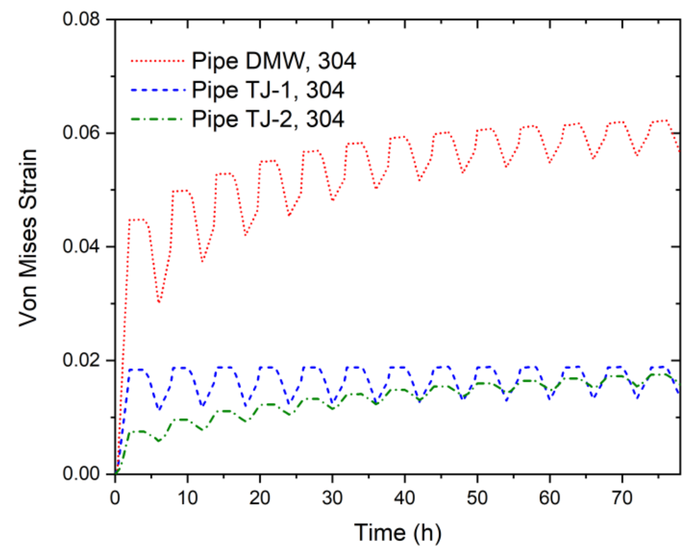
- With the transition design, the net strain accumulation per cycle and the accumulated strain was effectively reduced
- Critical location of DMW is located at the joining interface of 304, while that of AM-GCTJ is located at 304 region surrounding the tips of 282 alloy

Prediction of Prediction of Thermal Fatigue Deformation of 304-282 Plate Joints

ICWE Model Guided Design - Thermal Fatigue

- DMW
- AM-GCTJ-1 (axisymmetric)
- AM-GCTJ-1 (columnar)

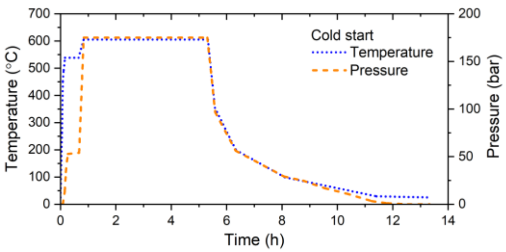




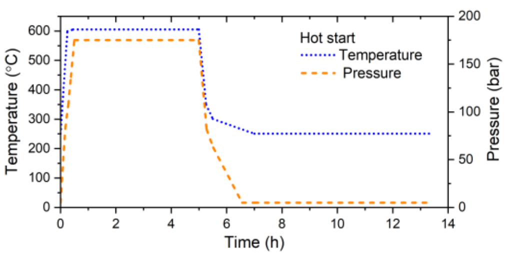
Prediction of 304-282 Pipe Joints under Thermal Fatigue Test

ICWE Model Guided Design - Transients

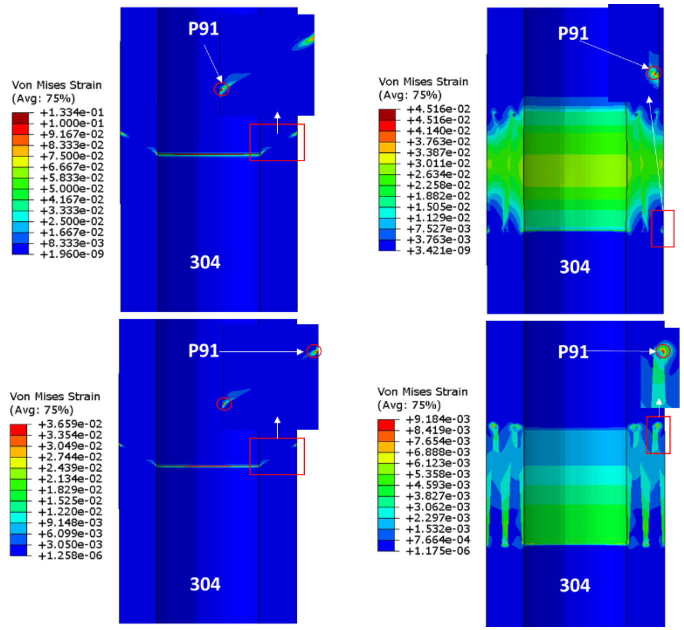
- Cold start

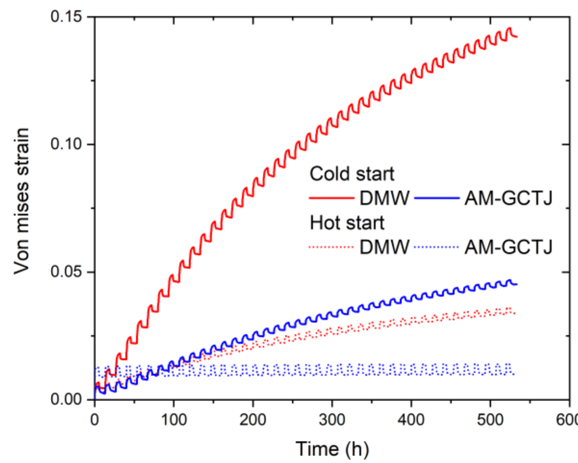


- Hot start



- DMW
- AM-GCTJ





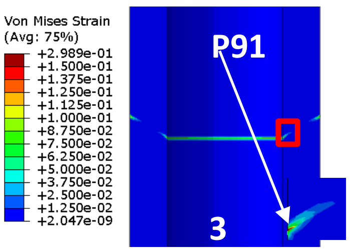
Strain at the end of 40 cycles

- DMW: strain mainly accumulates at the joining interface on ID of P91 under cold start transient, while in hot start condition, the accumulated strain decreases as the thermal stress is reduced due to the small range of temperature variation
- AM-GCTJ: the accumulated strain is effectively reduced since the thermal stress is suppressed by the composite design of material distribution induced the continuous variation of thermal expansion and strong constraint on the softer material in the transition region

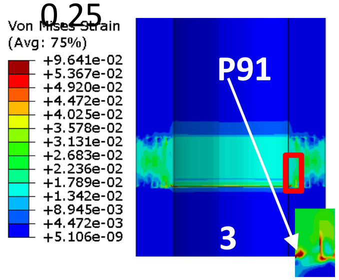
Creep Fatigue Deformation of P91-304 Joints under Cold and Hot Start Transients

ICWE Model Guided Design - Transition Length

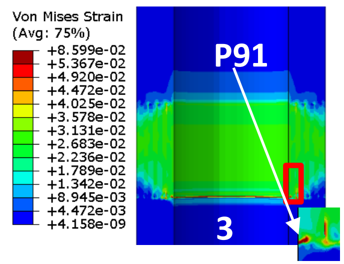
- DMW



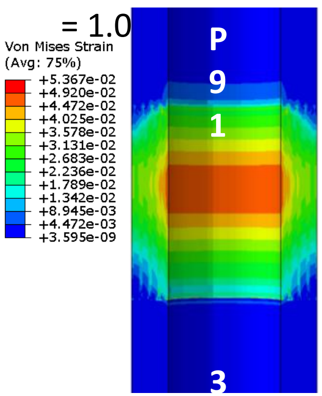
- AM-GCTJ, LT/OD = 0.25



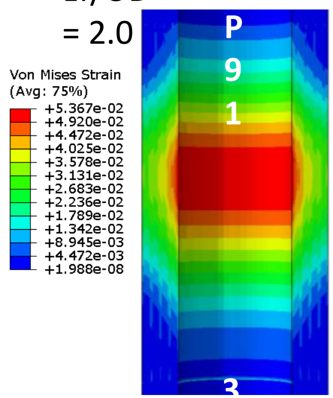
- LT/OD = 0.5



- LT/OD = 1.0

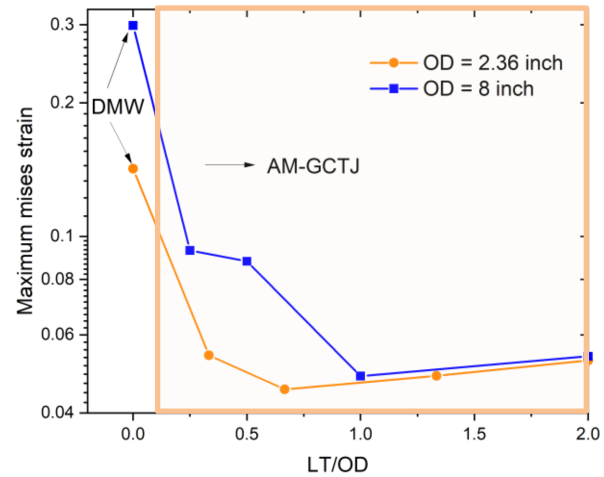


- LT/OD = 2.0



Dimensions: OD = 8inch, T = 40mm
Load: 40 cold start transients

- The accumulated strain generally decreases with the increasing ratio between transition length and OD, while it increases when LT/OD becomes greater than 1.0
- There may exist an optimized design of transition length for the pipe of a given diameters
- The accumulated strain in both small and large OD joint pipes was significantly reduced by the design of transition joints



Effects of Transition Length by ICWE Simulations & Evaluation of the Dimensional Scalability of AM-GCTJs

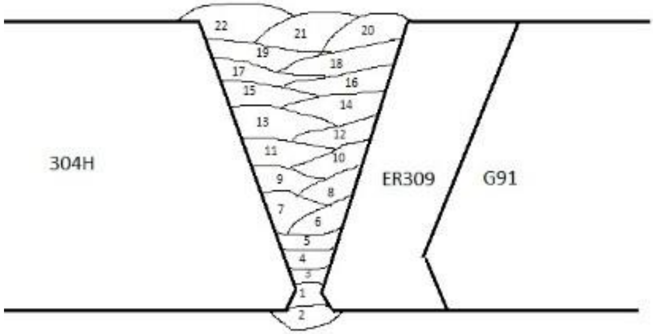
ICWE Model Guided Design - Summary

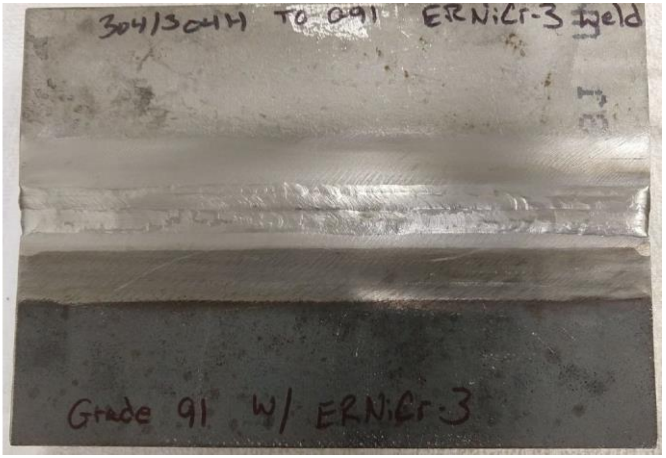
- ICWE simulations demonstrate that AM-GCTJs possess better deformation resistance than the conventional DMWs under high temperature creep, thermal fatigue, as well as operational hot/cold start transient conditions
- The root cause for the localized deformation and premature failure of dissimilar metal joints has been identified as the high thermal stress induced by the thermal expansion mismatch
- The composite design of material distribution leads to the effective reduction of thermal stress as the materials in the transition area result in the smooth variation of thermal expansion between the two materials and strong mechanical constraint on the ‘softer’ material enforced by the ‘stronger’ material
- The dimensional scalability and potential of AM-GCTJs’ application for large pipe components have been demonstrated by the ICWE simulations
- The transition joint design will be continuously refined and improved to diminish the accumulated deformation and enhance the service life

DMW and AM-GCTJ

AM-GCTJ

Conventional DM Weld



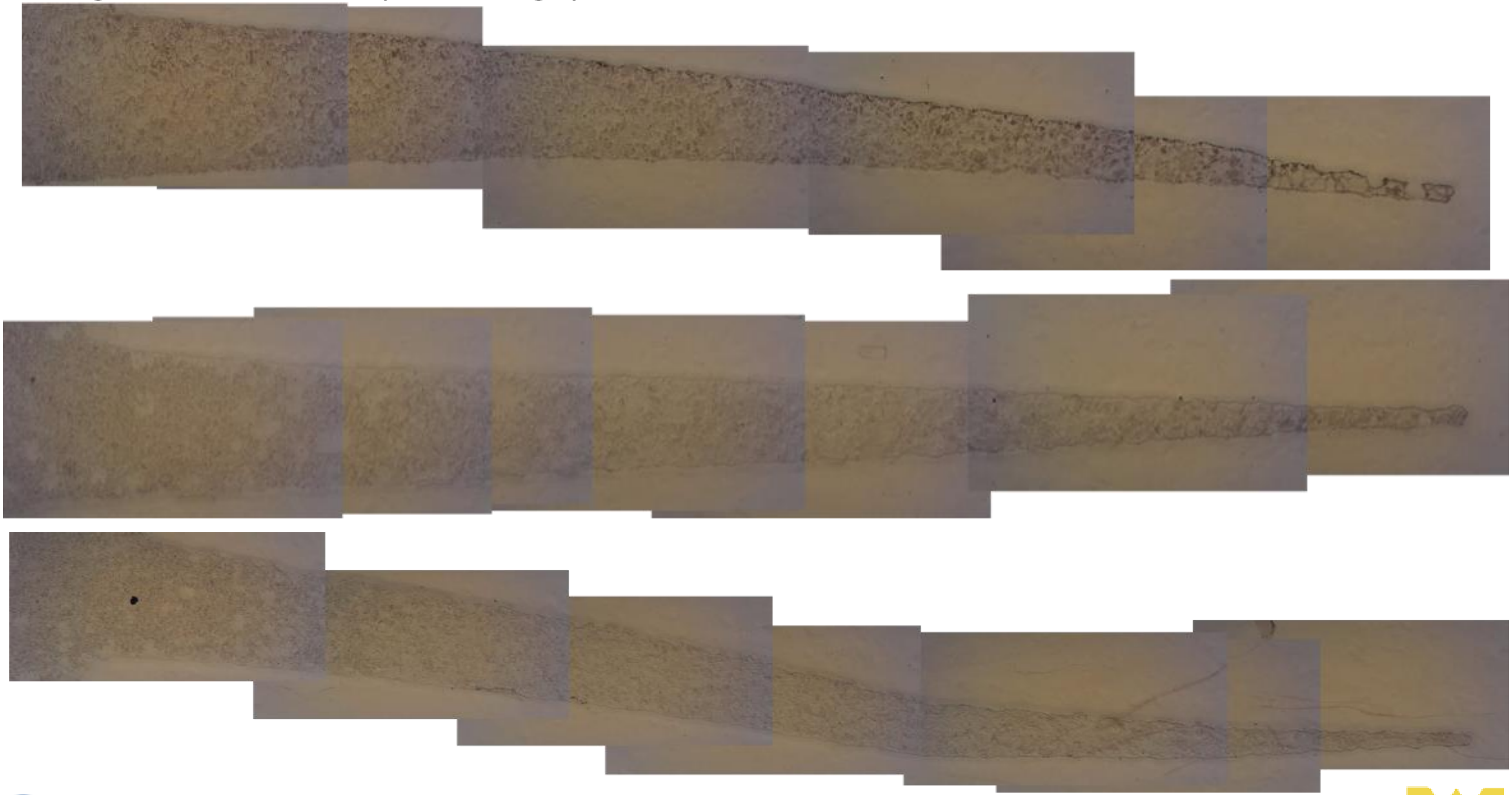


Fabricated 2 types of welds using either SS309 or A182 weld wire

Oak Ridge National Laboratory

AM-GCTJ

- Both 304 and P91 are totally dense, and the adhesion between 304 and P91 is good without any visible gaps



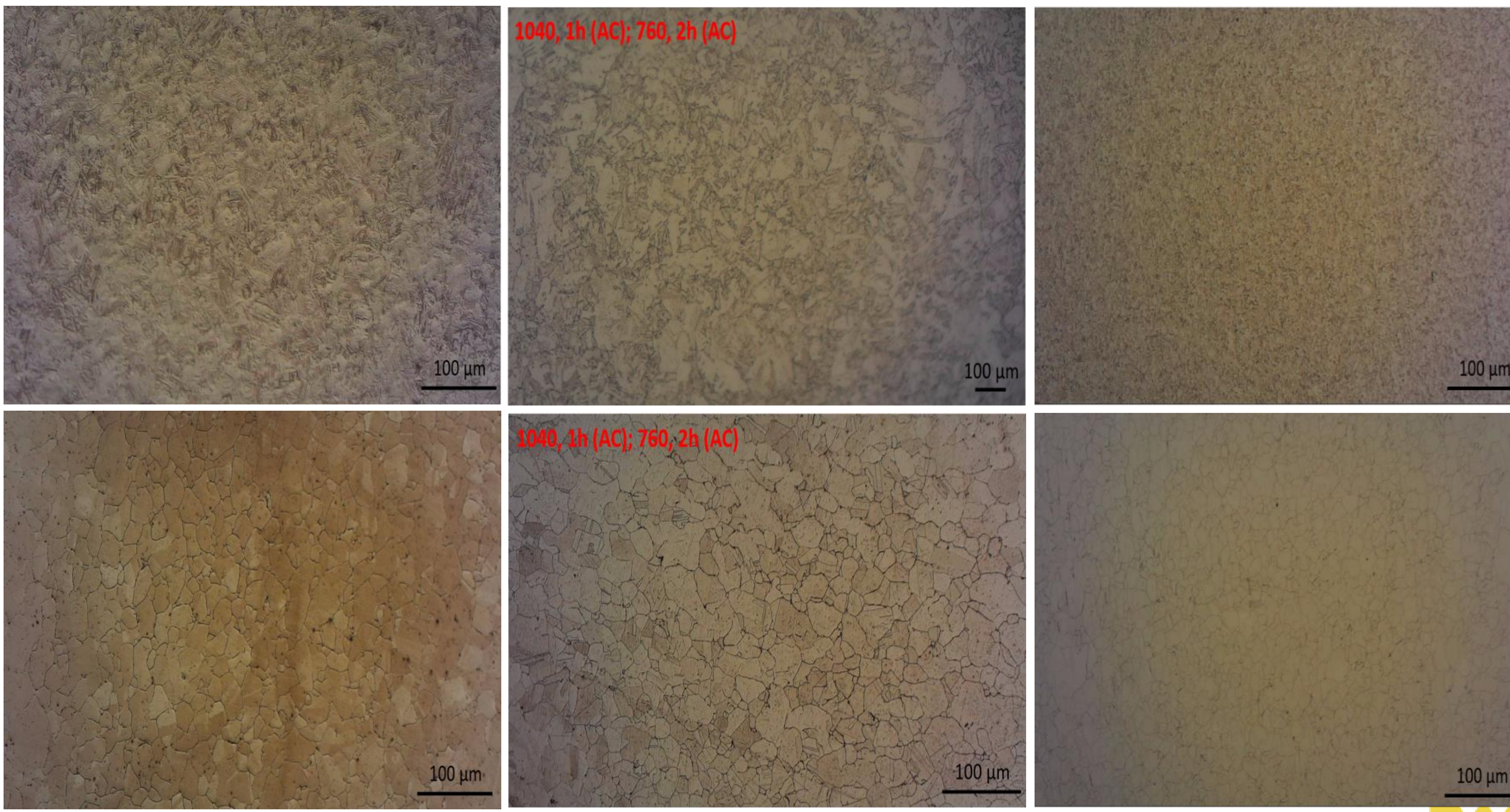
AM-GCTJ

- 1040 °C 1h (AC), 760 °C 2h (AC) was adopted as the heat treatment for P91&304 to minimize the growth of grain size

As-received | After heat treatment | DMW

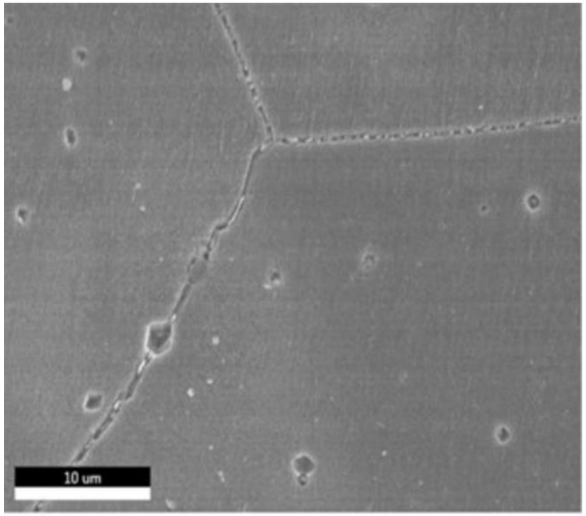
P91

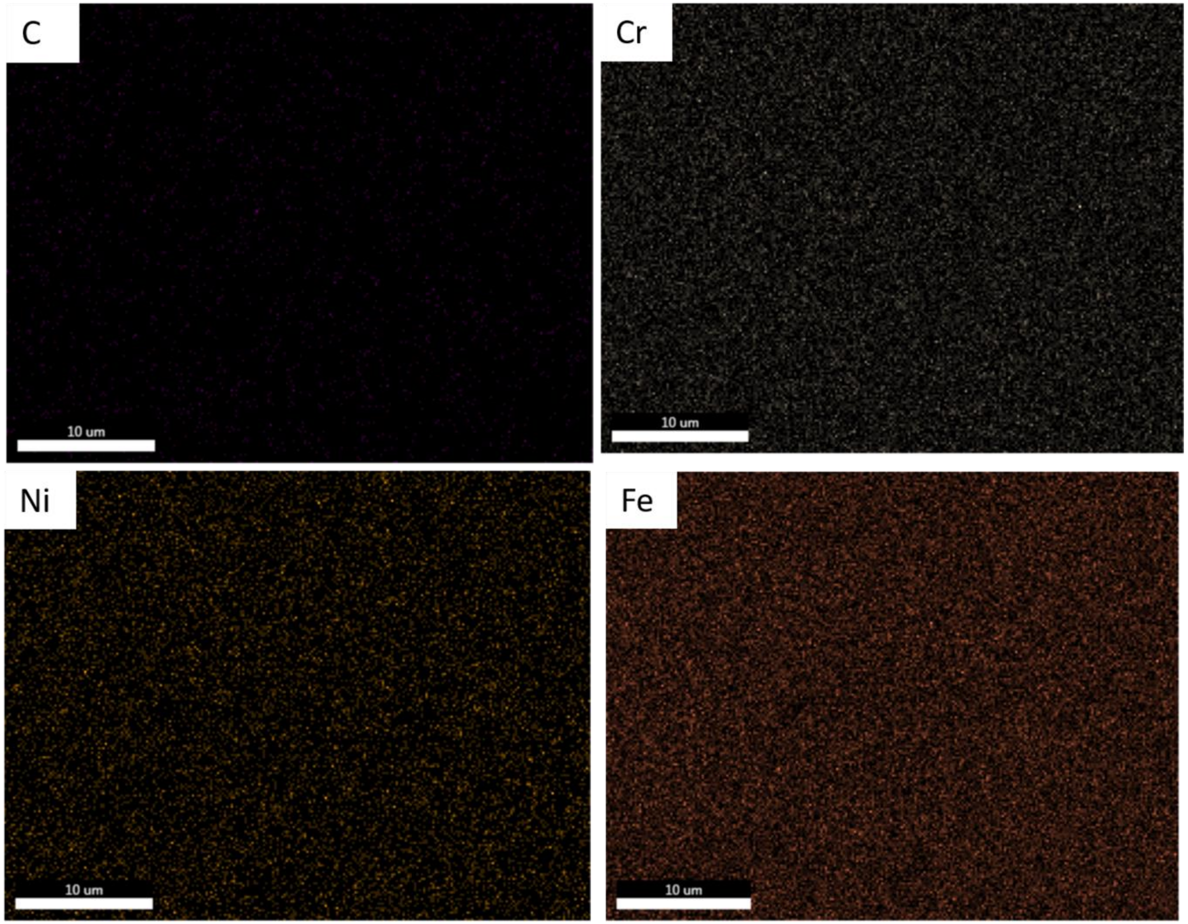
304



AM-GCTJ

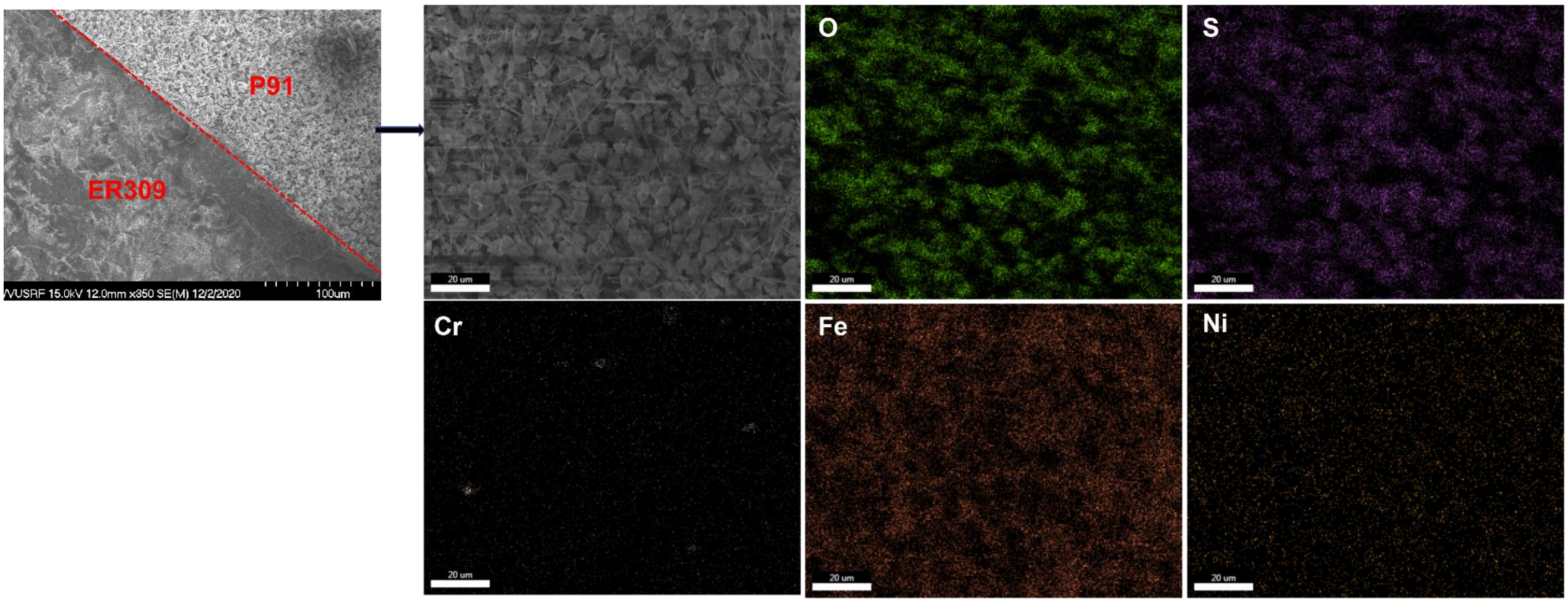
- No Cr depletion along the grain boundary of 304 was observed after heat treatment





Hot Corrosion in Coal Ash - DMW

- The corrosion product of P91 in DMW is mainly composed of iron oxides and iron sulfides.



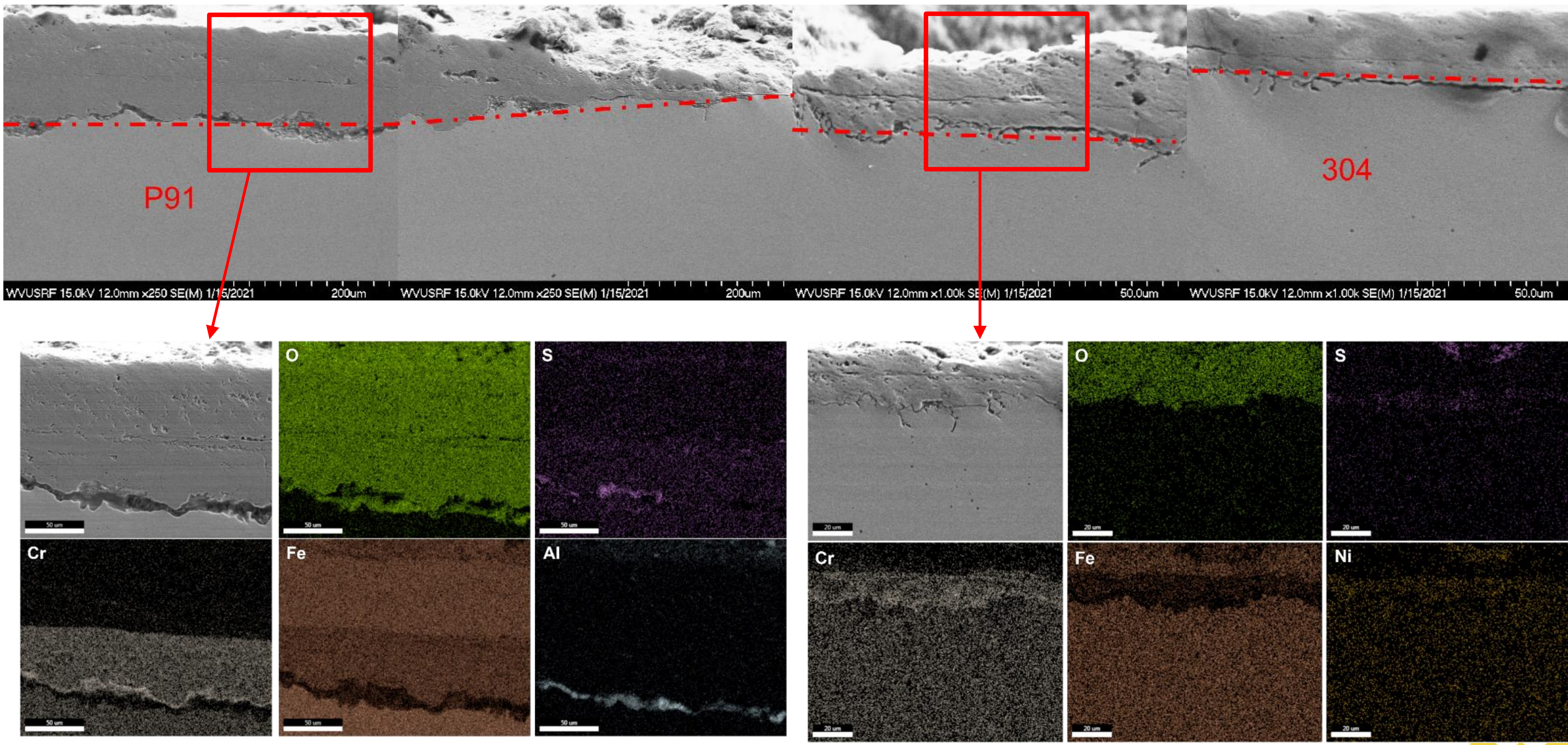
Temperature - 650 °C Time – 30 days

Coal Ash - 10% Na_2SO_4, 10% K_2SO_4, 10% Fe_2O_3, 35% Al_2O_3 and 35% SiO_2

Gas - 1 vol. % SO_2, 4 vol. % O_2, 15 vol. % CO_2 & 80 vol.% N_2

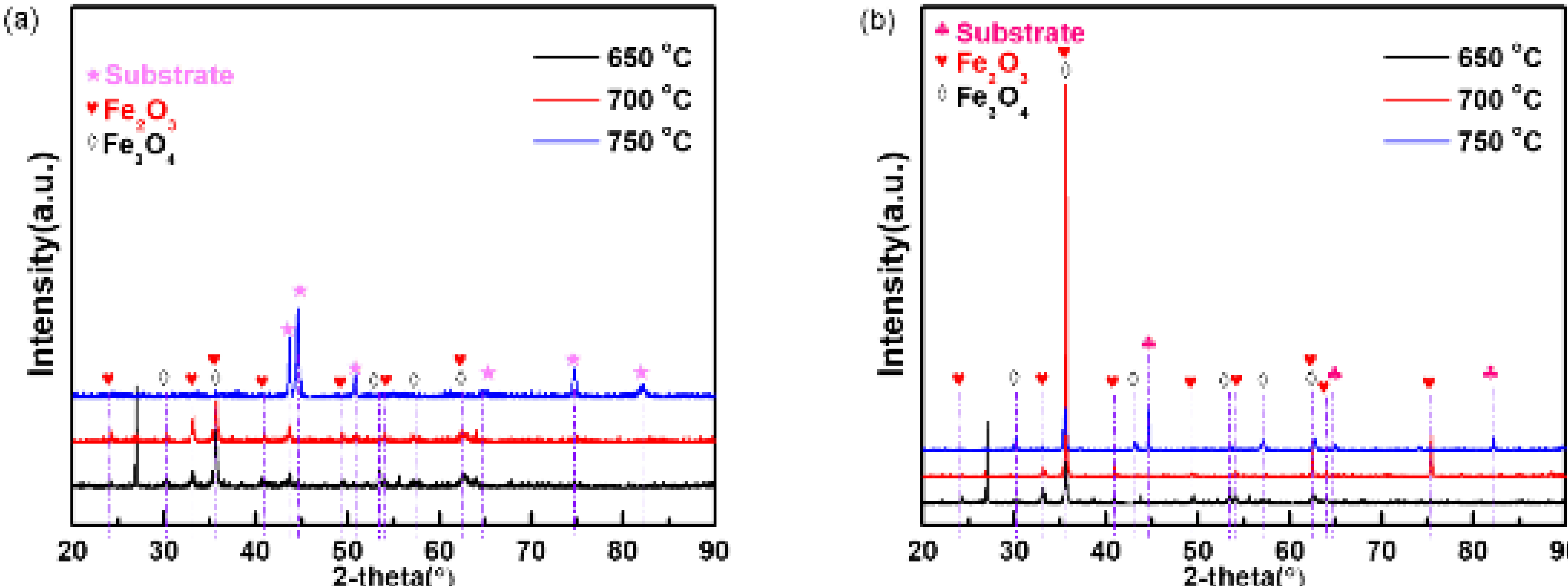
Hot Corrosion in Coal Ash – AM-GCTJ

- The thickness of the corrosion products on P91 is about 150 um which is about three times larger than that on 304, i.e., 40 um.
- The corrosion product is divided by two layers: outer layer composed of iron oxides; inner layer consisted of chromium oxides dispersed with some chromium sulfides.



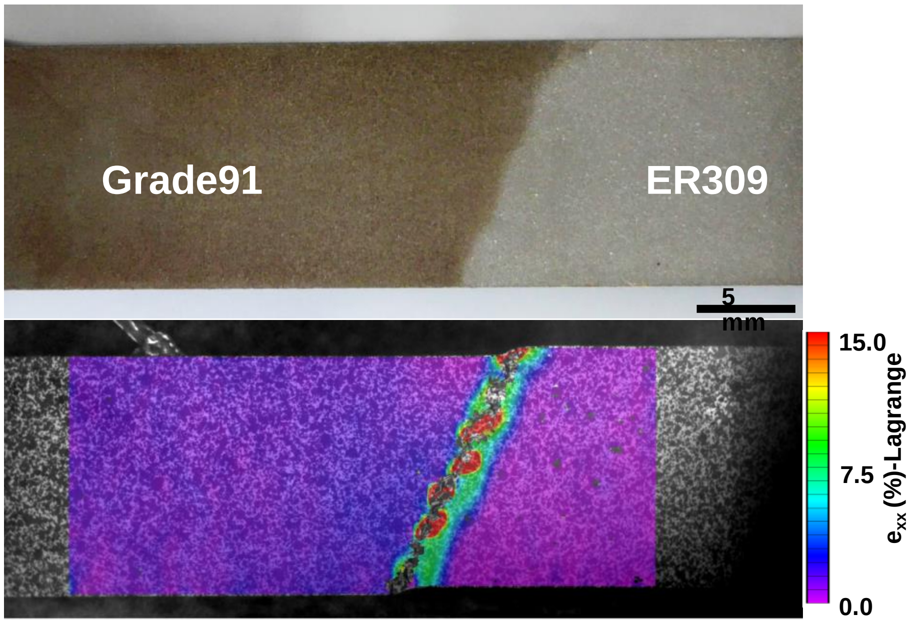
Hot Corrosion in Coal Ash – AM-GCTJ

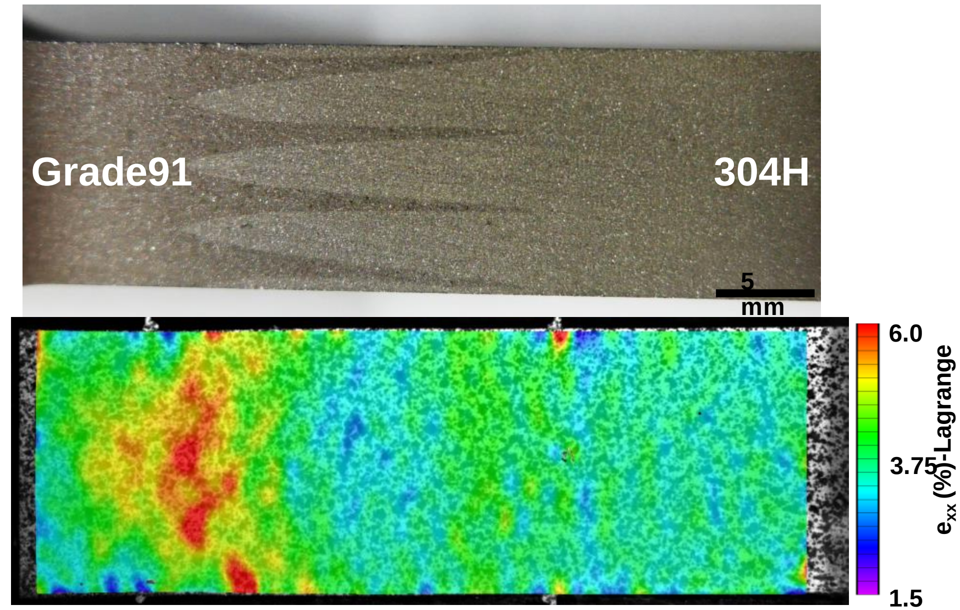
- the corrosion product is composed of Fe_2O_3, Fe_3O_4. The absence of Cr_2O_3 is ascribed the shielding effect of iron oxides in the outer layer.



XRD pattern of (a) 304H and (b) P91 after hot corrosion

Creep of DMW & AM-GTCJ – Model vs. Experiments



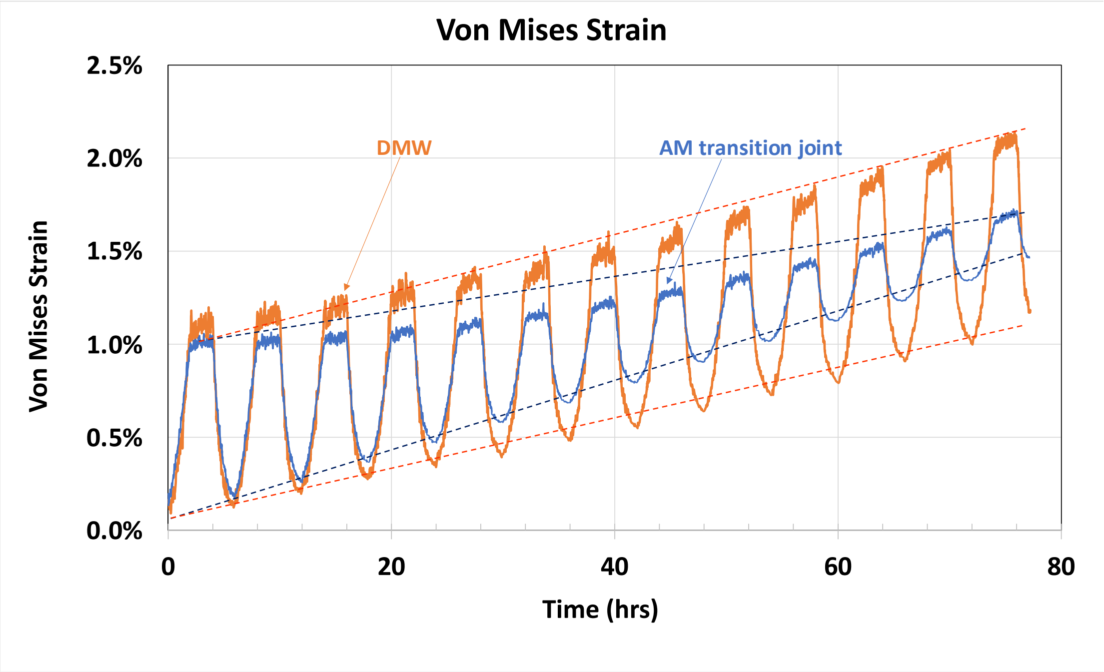


650C, 90MPa	Conventional DM	AM-GCTJ
Model Prediction	230 hrs, at G91 interface	1815 hrs, in G91 base metal (near interface)
Actual Test	214 hrs, at G91 interface	1259 hrs, near G91/Transition Joint interface

OAK RIDGE National Laboratory

Experimental Measurement of Strain Evolution during Thermal Cyclic Test

- Initial observations from in-situ DIC measurement:
  - Considerable reduction of thermal cyclic strain range with AM-GCTJ

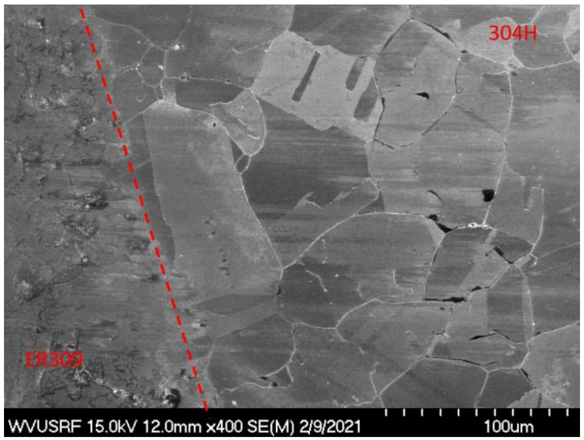


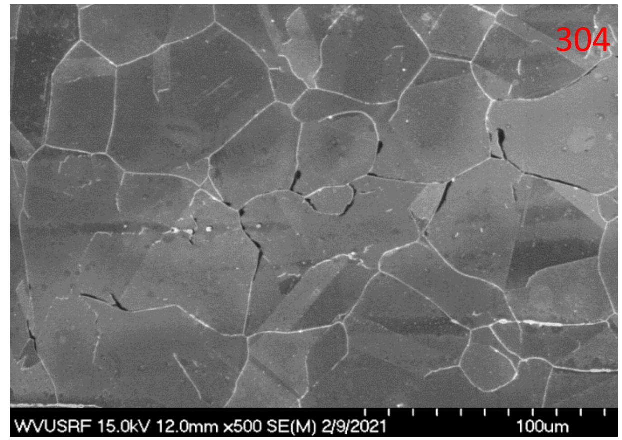
AM-GCTJ: averaged over the transition region
Conventional DMW: averaged over P91/SS304 interface region

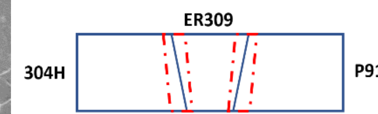
Thermal Fatigue Test of AM-GCTJ and DMW

- Some microcracks have been found along the 304H&ER309 interfaces after thermal fatigue test

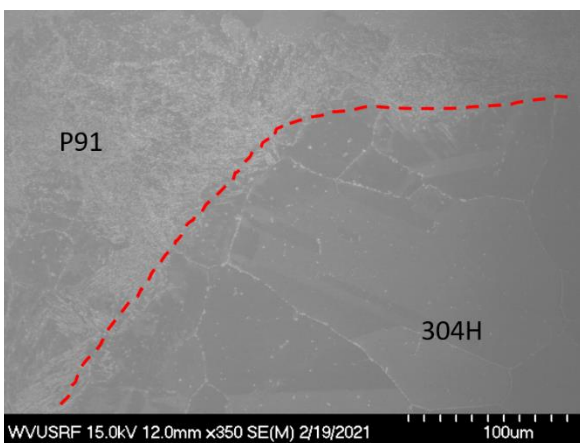
DMW

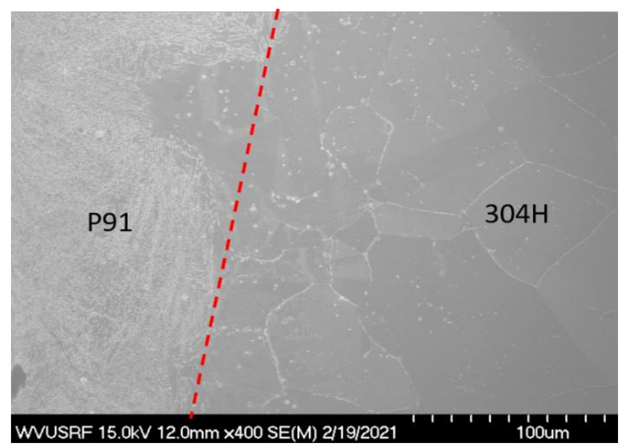


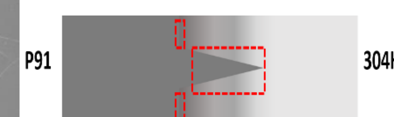




AM-GCTJ







Preliminary TEA – Case of HRSG

Economic Data Inputs

		Sensitivity Analysis Ranges	
Economic Data Inputs	Base	Low Value	High Value
Year $	2021		
Discount Rate	8%	6	10
Escalation Rate	0%	0	3
HRSG Lifetime	25	20	30
Labor Rate $/hr	100	50	150

Preliminary TEA – Design & Cost Parameters

Sensitivity Analysis Ranges

Conventional DMW Cost for New HRSG (based on Hsinta)	Base	Low Value	High Value
Total Number of DMW spools (per HRSG)	462		
Average Cost per DMW spool - material & labor ($)	1,716	cost varies with labor rate	
Time Period between replacements (Years)	5	5	10
% of DMW spools to replace	50%	50%	100%

AM-GCTJ Cost for New HRSG (Same Diameter)	Base	Low Value	High Value
Total Number of AM-GCTJ spools (per HRSG)	462		
Average Cost per AM-GCTJ spool - material & labor ($)	1,984	cost varies with labor rate	
Time Period between replacements (Years)	25	10	25
% of AM-GCTJ spools to replace	25%	0%	25%

AM-GCTJ Cost for New HRSG (Larger Diameter)	Base	Low Value	High Value
Total Number of AM-GCTJ spools (per HRSG)	150		
Average Cost per AM-GCTJ spool - material & labor ($)	3,417	cost varies with labor rate	
Time Period between replacements (Years)	25	10	25
% of AM-GCTJ spools to replace	25%	0%	25%

Preliminary TEA

Net Present Value Costs for DMW Spools Installation and Replacements

DMW Case (for 1 HRSG)	NPV ($)
HRSG DMW Cost	792,612
Spool Repair Cost - 50% replacement	663,245
Spool Repair Cost - 100% replacement	1,326,489
NPV Costs per HRSG	
50% DMW Replacement per Outage	1,455,857
100% DMW Replacement per Outage	2,119,102

Preliminary TEA

Net Present Value Costs of AM-GCTJ Spool Installation and Replacements

AM-GCTJ Case (for 1 HRSG)	NPV ($)
Small Spool Sizing	
HRSG AM-GCTJ Cost (small spool sizing)	916,682
Spool Repair Costs - 25% every 10 years	310,637
Larger Spool Sizing	
HRSG AM-GCTJ Cost (large spool sizing)	512,494
Spool Repair Costs - 25% after 10 years	173,669
NPV Costs per HRSG	**Small Tube**
25 year life	916,682
10 year life - 25% replacement	1,227,319
	Large Tube
25 year life	512,494
10 year life - 25% replacement	686,164

Preliminary TEA - Sensitivity Analysis

Discount Rate	6%	8%	10%
ΔNPV (DMW vs. AM-GCTJ)	682,303	539,175	428,579
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)	1,086,491	943,363	832,767
Escalation Rate	**0%**	**2%**	**4%**
ΔNPV (DMW vs. AM-GCTJ)	539,175	552,440	565,705
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)	943,363	956,627	969,892
Plant Life	**20 Yr**	**25 Yr**	**30 Yr**
ΔNPV (DMW vs. AM-GCTJ)	454,148	539,175	597,043
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)	858,336	943,363	1,001,230
Labor Rate ($/hr)	**50**	**100**	**150**
ΔNPV (DMW vs. AM-GCTJ)	271,948	539,175	806,402
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)	551,500	943,363	1,335,225
Time Period Between DMW Replacements (Years)		**5 Yr**	**10 Yr**
ΔNPV (DMW vs. AM-GCTJ)		539,175	173,357
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)		943,363	577,545
% of DMW spools to Replace Each Outage		**50%**	**100%**
ΔNPV (DMW vs. AM-GCTJ)		539,175	1,202,420
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)		943,363	1,606,607
Time Period Between AM-GCTJ Replacements (Years)		**10 Yr**	**25 Yr**
ΔNPV (DMW vs. AM-GCTJ)		228,538	539,175
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)		721,202	943,363
% of AM-GCTJ spools to Replace Each 10 Yr Outage	**0%**	**25%**	**50%**
ΔNPV (DMW vs. AM-GCTJ)	539,175	383,856	228,538
ΔNPV (DMW vs. AM-GCTJ, Larger Diameter)	943,363	739,553	632,726

Summary

- We designed and fabricated a new class of AM-GCTJ
  - Avoid unknown & often undesired complex composition in the conventional AM-GTJ
  - Shows similar corrosion performance in coal ash as conventional DMW
  - Reduce the maximum strain & strain range, and (can) improve thermal mechanical fatigue life of DMW during cyclic operation of thermal-electric power plants
  - Significantly improve creep properties, as compared with convention DMW
- AM-GCTJ has broad applications in various energy systems, AUSC, Gas, CSP, NE, etc.

Phase II Plan

- Investigate the interfacial diffusion between P91 and 304, 282 and 304
- Optimize the heat treatment process of AM-GCTJ for 304&282
- Continue the characterization of thermal-fatigue and creep test of the AM-GCTJ and optimize the design of AM-GCTJ
- To manufacture and test the components with AM-GCTJ, to advance the technology readiness level to TRL-7, and manufacturing readiness level to MRL 6-7
- Work on detailed TEA and start code case

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