Robust Dissimilar Metal Friction Welded Spool for Enhanced Capability for Steam Power Components

FY23 FECM Spring R&D Project Review Meeting

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Robust Dissimilar Metal Friction Welded spool for enhanced capability for steam power components

DOE DMW

Team

GE Research, GE Gas Power & GE Steam Power

Program impact

3 year, $6.25MM DOE program to improve dissimilar metal weld (DMW) durability to reduce maintenance costs and provide enhanced cycling capability

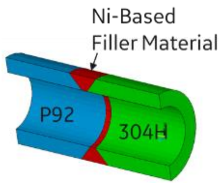
Key Innovations

- Demonstrate **friction welded** dissimilar metal spool w/superior properties
- Mature GE developed **nanostructure ferritic alloy (NFA)** tech for steam cycle applications
- Enhanced durability through **oxidation protective coatings** on DMW joint
- GE **lifing methodology** to predict joint life & durability

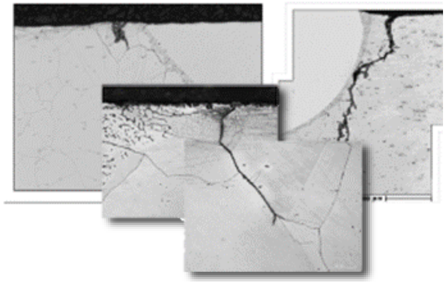
Anticipated Benefits

- 5x increase in cold starts & cycling behavior of steam turbine fleet
- Reduced DMW repair frequency
- Improved DMW creep & fatigue behavior
- Advance NFAs from TRL4 to TRL6

Traditional DMWs

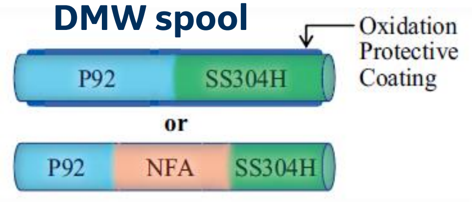


Oxide notching and cracking near fusion line and HAZ

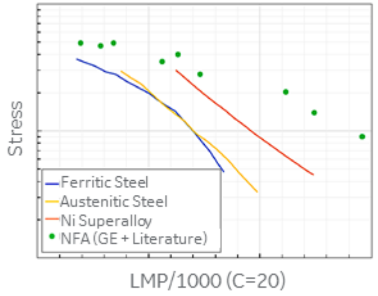


Proposed Solution

Friction Welded DMW spool

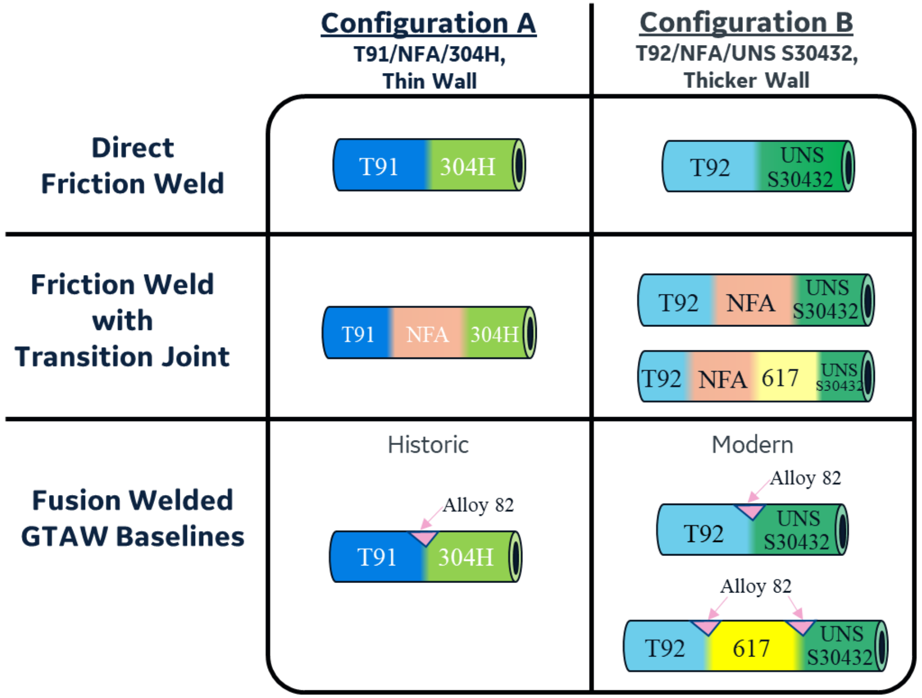


NFA superior creep resistance



Deliverable Update

Task	Deliverable Title	Due Date	Current Status
1.1	Project Management Plan (PMP)	11/30/2020	Completed
1.3	Technology Maturation Plan (TMP)	5/31/2021	Version 1 completed
4.1	Initial NFA material for friction welding trials	5/31/2021	Completed
3.1	Optimal coating down-selection	6/30/2021	Completed
1.2	Workforce Readiness Plan (WRP)	8/31/2021	Completed
2.1	Crack free friction-welded tubes of *T91/304H - Config A*	10/15/2021	Completed
2.1	Crack free Rotary friction-welded tubes of T91/NFA/304H - Config A	3/31/2022	Completed
3.2	Coating process optimization	3/31/2022	Completed
4.2	Report on NFA tube demonstration - Config A (thin wall)	4/30/2022	Completed
2.1	Crack free friction-welded tubes of *T92/UNS S30432 - Config B*	4/29/2022	Completed
1.3	Technology Maturation Plan (TMP)	5/15/2022	Completed
3.3	Coating property assessment	6/30/2022	Completed
5.2	Parameters for accelerated durability testing	7/29/2022	Completed
2.1	Crack free friction-welded tubes of T92/NFA/UNS S30432 - Config B	7/31/2022	Completed
2.1	Crack free friction-welded tubes T92/NFA/617/UNS S30432 - Config B	06/30/2023	Optimization in progress
2.2	Weld property assessment data	03/31/2024	Testing in progress



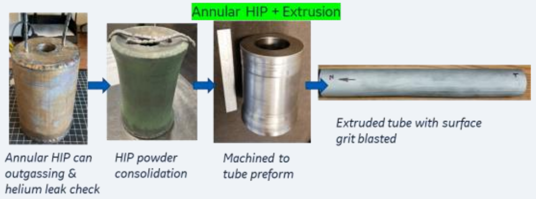
- Dissimilar Metal Weld (DMW)
- Nanostructured Ferritic Alloy (NFA)
- 2 Configurations:
  - Config A: thin wall
  - Config B: thick wall
- Friction welds
  - Rotary friction weld (RFW)
  - Low force friction weld (LFFW)

Major Technical Achievement To-date

Capability

NFA Tube Demonstration

- **(4.1)** Completed mechanical alloying and **produced 1000 lbs** of NFA materials
- Successfully produced **defect-free**, pilot-scale thin wall NFA tubes (Config A) via 2 processing routes
- Produced **thin wall (Config A) NFA tubes** for friction weld development
- Successfully produced **defect-free thick wall tubes** (Config B)

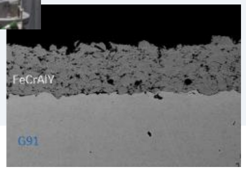


Rotary Friction Weld

- **(2.1)** Successfully produced **crack free** rotary friction weld of thin wall and thick wall (Config A & B) **T91/304H tubes, T91/NFA, NFA/IN617, IN617/SS304232**
- **Tensile, LCF, and creep** assessment of thick wall (Config B)was **T92/UNS30432 completed.** Characterization of remaining welds underway
- **Low Force Friction Welding** trials for T92/SS30432 underway

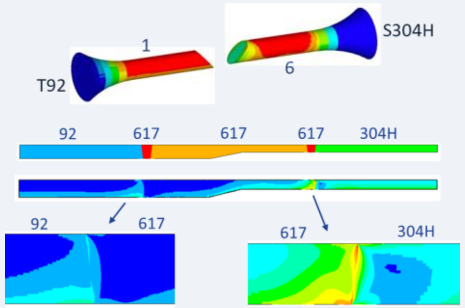
Coating Materials and Process

- **(3.1)** Identified **oxidation resistance coating chemistry** capable of forming protective oxide on the surface at temperature **up to 715°C**
- Produced coating **meeting thickness requirements** using **industry standard** thermal spray process
- Demonstrated the coating process for the Config B tube and GTAW tube using optimized coating parameters



Lifing Methodology

- **Implemented DMW lifing methodology** for fatigue and creep –tubes and solid bars/test coupons
- **Completed life prediction** of several baseline and **NFA DMW** tubes for industrial application (Boiler and HRSG)
- Defined **DMW coupon design and test conditions** for LCF and creep tests – coupon manufacturing underway



Field design example: DMW Spool
(Effective strain range contour plots for Hot Start)

NFA Tube Demonstration

Deliverable 4.1

- Completed mechanical alloying and **produced 1000 lbs** of NFA materials

Technical Progress

- Thin wall (Config A) tube manufacturing (4.2)
  - Successfully produced **defect-free**, pilot-scale NFA tubes via 2 processing routes
  - Produced **over 30" of thin wall (Config A)NFA tubes** for friction weld development
- Thick wall (Config B) tube manufacturing
  - Successfully produced pilot-scale **defect-free thick wall tubes** of via 2 processing routes
  - Produced **over 60" of thick wall(Config B) NFA tubes** for friction weld development

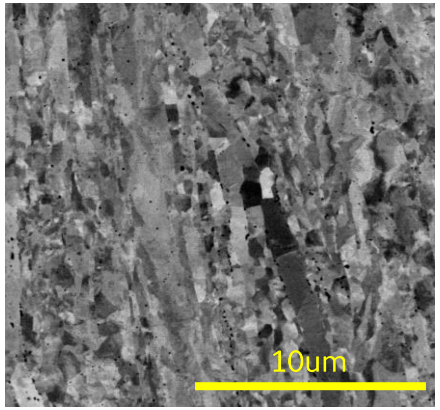
Nanostructured Ferritic Alloy Tube Pilot-Scale Fabrication & Properties

Annular HIP + Extrusion

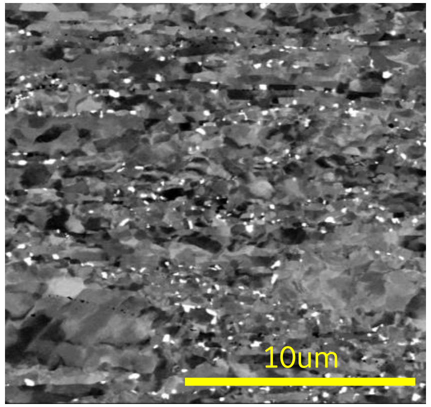
Mechanical Testing Matrix

Material Condition	Tensile	Creep	Low cycle fatigue (LCF)
NFA, as-extruded	Testing conditions: - Room Temp - 635°C	Testing conditions: - 635°C 400MPa - 635°C 500MPa	Testing conditions: - 635°C, 0.4% total strain - 635°C, 0.7% total strain
NFA, PWHT (Laves phase present)	Testing conditions: - Room Temp - 635°C	Testing conditions: - 635°C 400MPa - 635°C 500MPa	Testing conditions: - 635°C, 0.4% total strain 635°C, 0.7% total strain

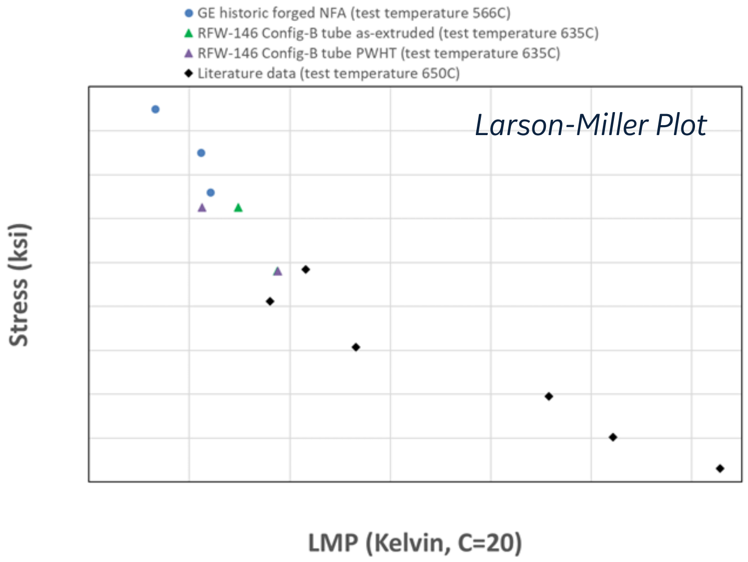
As Extruded



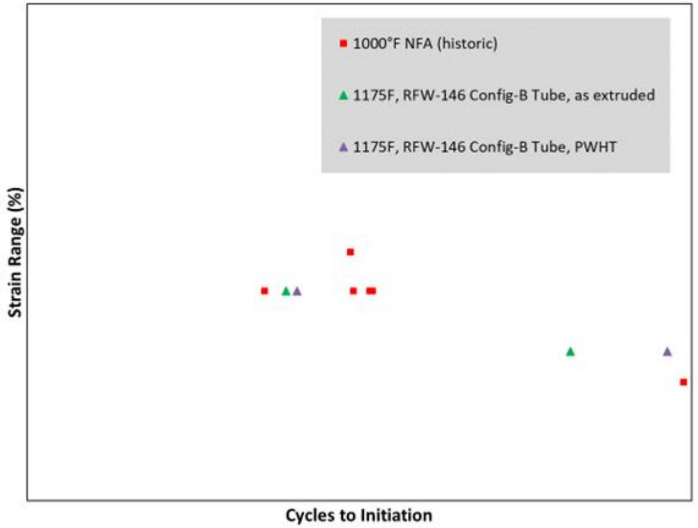
PWHT



Creep Property (short-term)



Low Cycle Fatigue



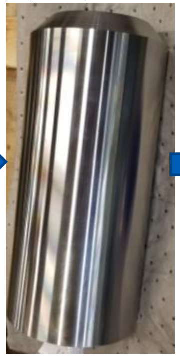
- Downselected **HIP + Extrusion route** and showed good **reproducibility** in **pilot-scale thick wall (Config B)** tubes for weld development
- **Tensile, creep, fatigue properties** of HIP and extruded tube material comparable to historic HIP and forged material.
  - **Superior to base metal of P92 and SS304H.** Laves phase formed during PWHT showed marginal effect.

Nanostructured Ferritic Alloy Tube Full-Scale Manufacturing Trial

HIP + Extrusion Trial

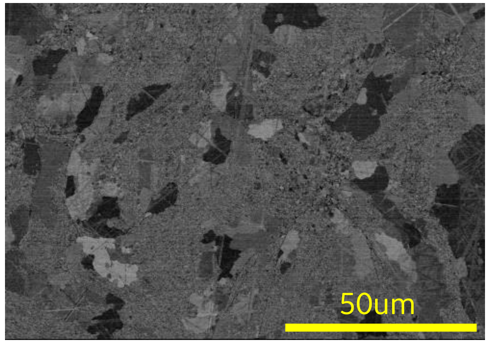
After HIP

Machined to tube pre-form

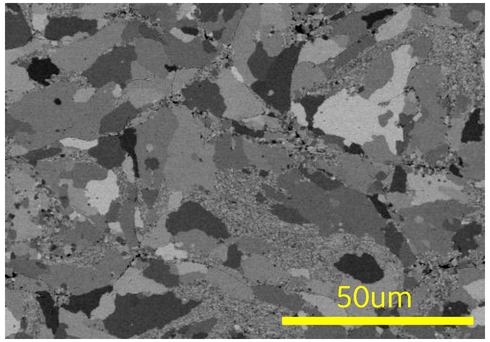


Cracking after pre-heat

As-HIP Microstructure



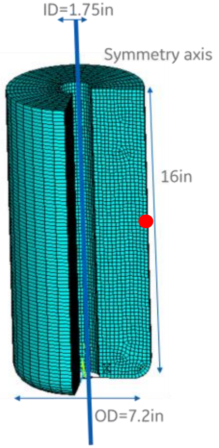
Pre-Heated Microstructure

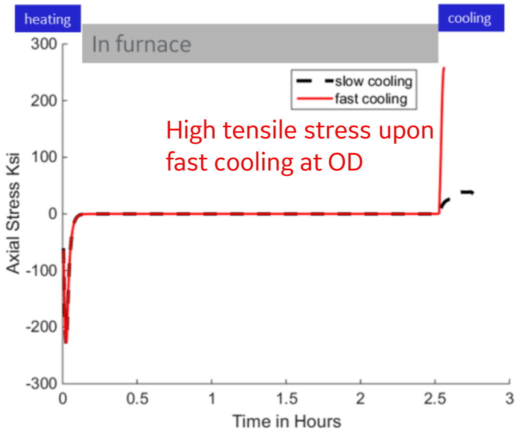


Changes Made in the New Trial

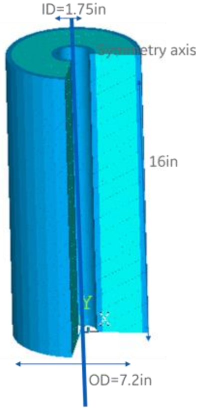
1. *Improve outgassing condition*
2. *Improve packing density and tighter particle size distribution*
3. *Keep SS304 can to tube extrusion*
4. *Modified HIP condition*
5. *Add upsetting after HIP*
6. *Slow heating and cooling and wrap by insulation to reduce thermal stress*
7. *Replace EDM wiring by hole drilling for tube pre-form*

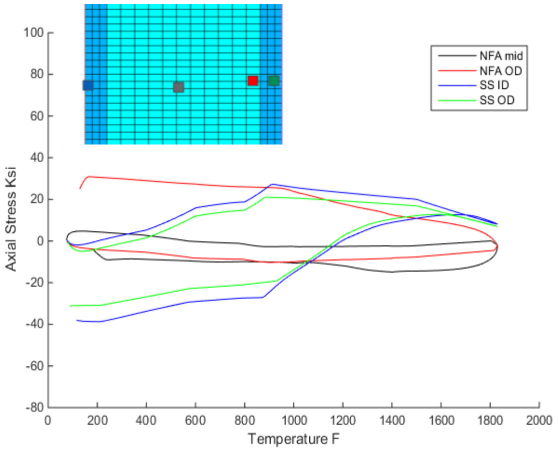
FEM Analysis of Thermal Stress





VS.





- Billet cracking during pre-heat right before tube extrusion. Never encountered this issue in pilot scale material.
  - Possible causations: **material brittleness in as-HIP state, thermal stress in thick wall billet**
- FEM analysis suggested that **SS304 material at ID and OD effectively reduced the max stress** for NFA to remain below the tensile fracture strength of as-HIP NFA.

Rotary Friction Weld

<u>Deliverable 2.1</u>

- (2.1) Successfully produced crack free rotary friction weld of thin wall and thick wall (Config A & B) T91/304H tubes, T91/NFA, NFA/IN617, IN617/SS304232

<u>Deliverable 2.2</u>

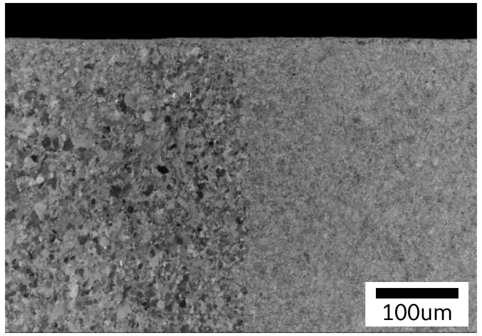
- Tensile, LCF, and creep assessment of thick wall (Config B) for both RFW and GTAW was T92/UNS30432 completed.

<u>Technical Progress</u>

- Currently optimizing the process parameters to tackle cracking in thermally and mechanically affected zone of NFA
- Low Force Friction Welding trials for T92/SS30432 underway

Friction Welding Evaluation Progress

Config B T92/S30432 Friction weld



Config B T92/S30432 GTAW

Inertia welding significantly reduces weld affected zone width and dilution

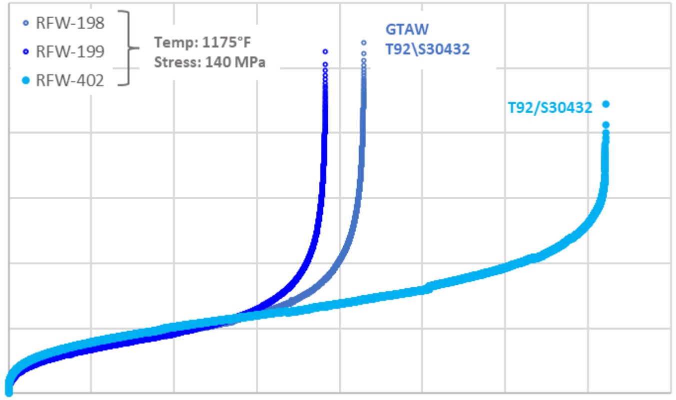
- Inertial welding process parameter studies were used to produce crack-free configuration B inertia welds for T92/S30432, T92/NFA, S30432/IN617, and IN617/NFA joints
- Cross-weld tensile, LCF, and creep bars have been made from the inertial weld material and the tests are being compared samples taken from GTAW welds

LCF and Creep testing completed for GTAW and RFW T92/S30432

- Strain range = 0% - 0.4%

Weld configuration	Temperature	Cycles to failure	Failure location
GTAW T92/IN82/S30432	1100F	2216, 5716, 6472	IN82
RFW T92/S30432	1100F	3436, 14104, 19518	T92
GTAW T92/IN82/S30432	1175F	5350, 5664, 8144	T92
RFW T92/S30432	1175F	3752, 4430, 6450	T92

- At 1100F, IN82 filler material is weak link so RFW has more cycles to failure
- At 1175F, T92 becomes weak link and RFW is comparable to GTAW

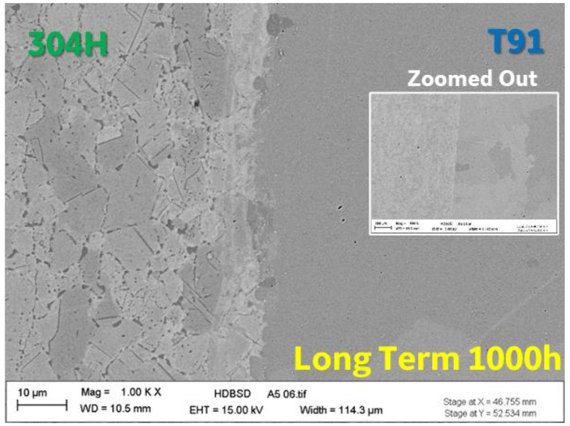


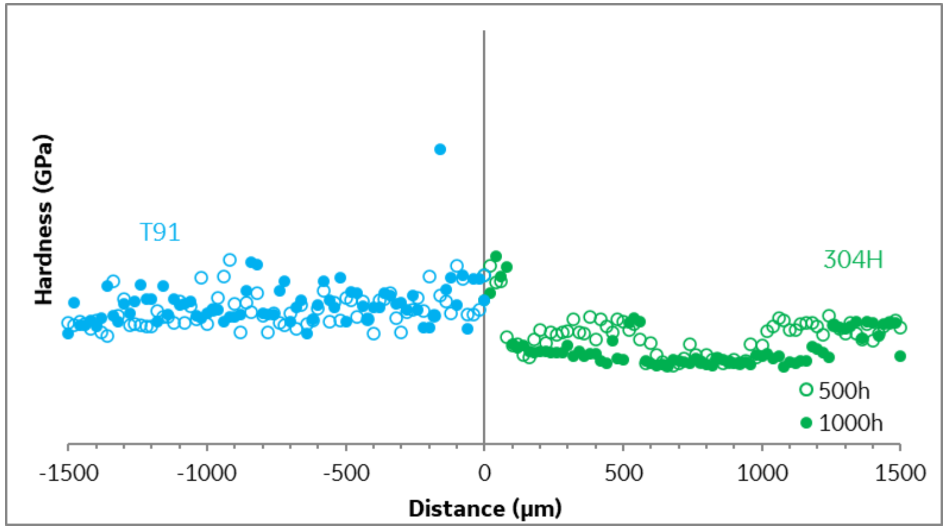
- RFW samples are more resistant than GTAW welds to creep

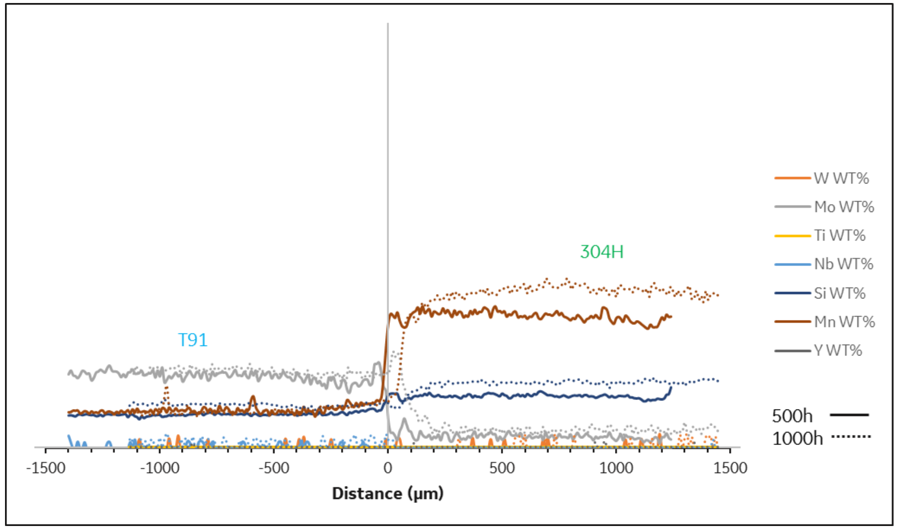
Preliminary Long-Term Exposure Diffusion Analysis Friction Welded Join

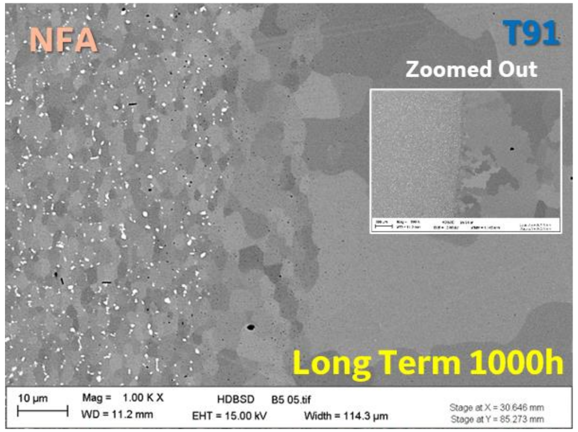
Nano-hardness

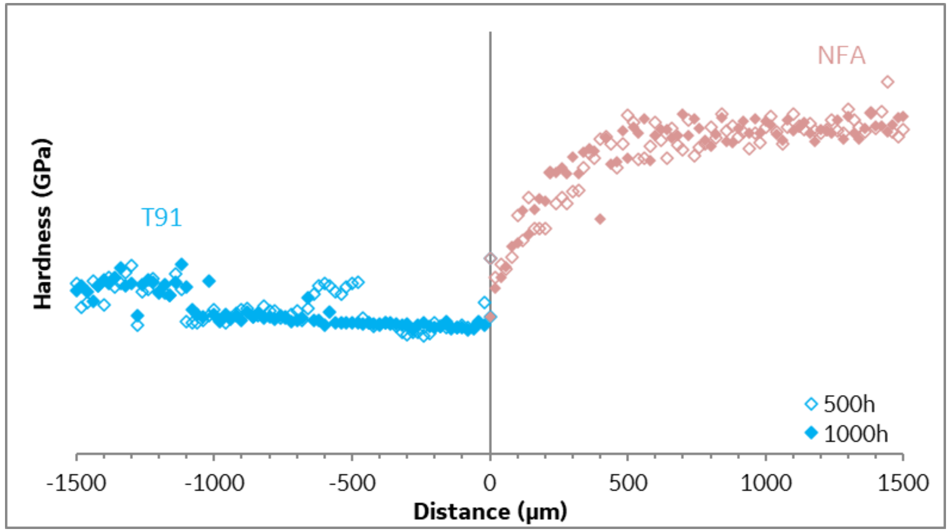
Minor Elemental Diffusion

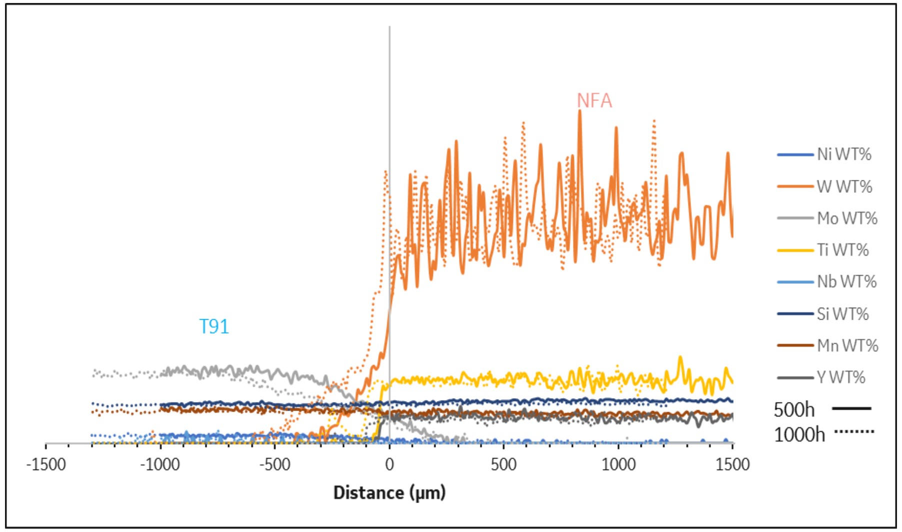












- Stark contrast in nano-hardness was noticed on each side of the weld zone though there was not significant change with exposure time
- *Most* diffusional elements were independent of exposure time, excluding W, which tended to diffuse towards the T91 bulk material

Coating Materials and Process

Deliverable 3.1

- Identified **oxidation resistance coating chemistry** capable of forming protective oxide on the surface at temperature **up to 715°C (1320F)**
- Produced coating **meeting thickness requirements** using **industry standard** thermal spray process
- Demonstrated the coating process for the Config B tube and GTAW tube using optimized coating parameters

Technical Progress

- Assessment of **phase stability** due to long term exposure for friction welded joins
- Continuation of **coating performance assessment** and exploring modifications

Oxidation Protective Coating Development

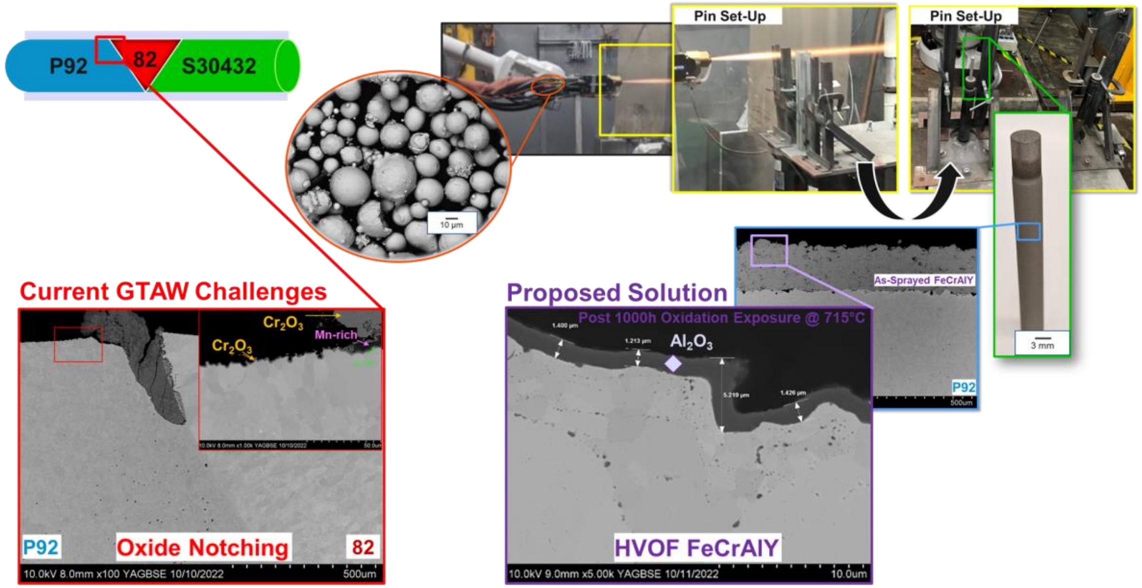
Coating Process Optimization

Coating Requirements:
- Oxidation resistance in temperature range
- Thermal expansion compatibility
- Commercially available & compatible process
- Phase stability (coating & coating/substrate)

Delivered:
- Optimal coating parameters to-date on GTAW & Friction Welded Tubes

In-Progress:
- <u>Thermal Mechanical Fatigue Testing-</u> Evaluation of lifing under service conditions:
    - GTAW & Friction Welded Tubes (@ 1250 cycle)

Method: Industry-standard Thermal Spray

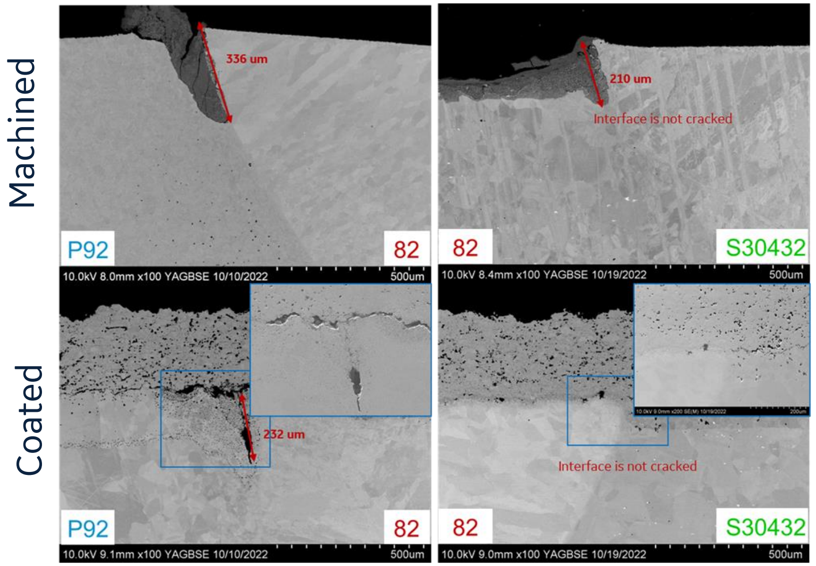


Coating Performance

Conventional GTAW Coating Performance
- The protective coating decreased the length of the oxide notch for both interface regions
- Inherent thermal stress of 92/82 join, further convinces our efforts to transition to the friction weld joining

In-Progress:
- Diffusion barrier (Pt) between coating and bulk material
- Post-process shot peening to reduce first few mils of porosity formation that evolves during service temperature exposure
- Alternate coating process methods

1000h



Exposure @ 715°C, Cycle Time (50min hot, 10min cold)

Lifing

Technical Progress

- **Implemented DMW lifing methodology** for fatigue and creep –tubes and solid bars/test coupons
- **Completed life prediction** of several baseline and **NFA DMW** tubes for industrial applications (Boiler and HRSG)

Modeling & Lifing: ***Flowchart for LCF of RFW Configuration***

Inputs

- Operating Temperature
- Thermal and midlife cyclic stress-strain properties of base metals
- Target max. and min. strain values of RFW

RUN

- ANSYS APDL model of RFW

Outputs

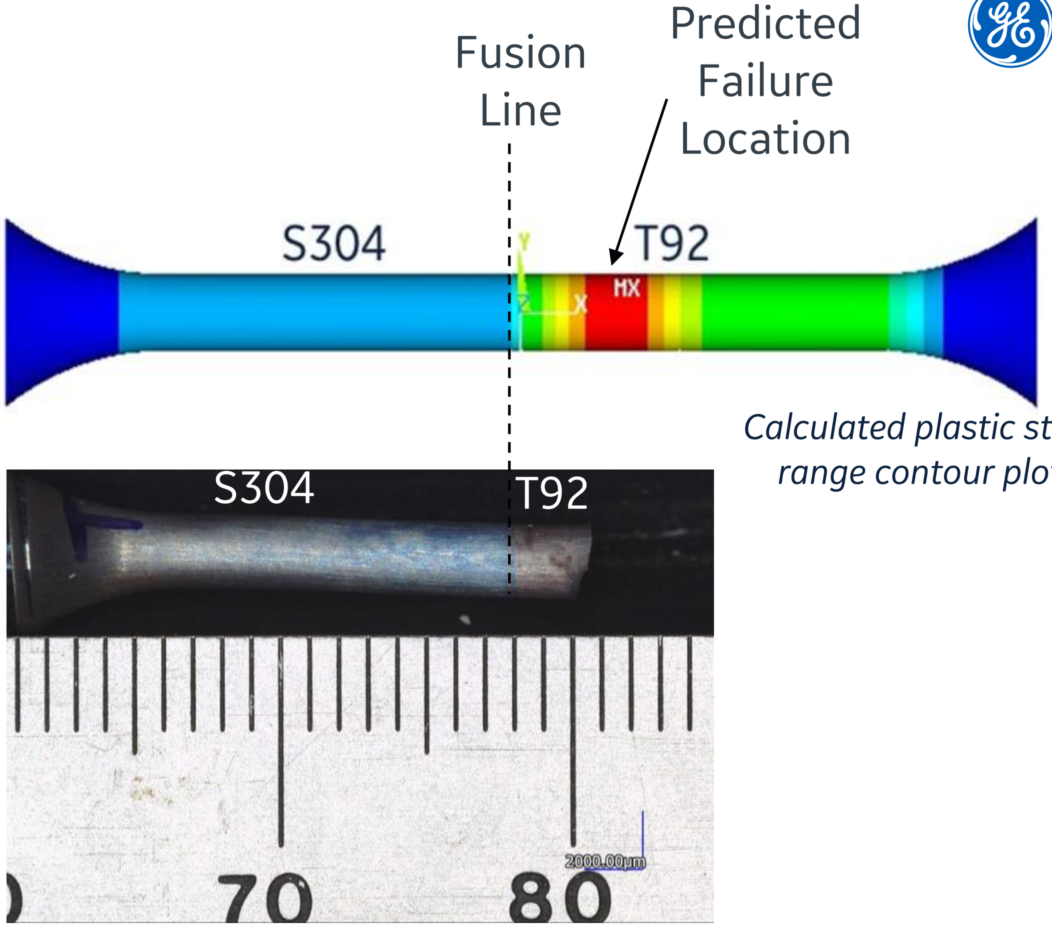
- Hysteresis loop
- Plastic strain range
- Total strain range
- Effective strain range

LCF Prediction

- Failure location
- Number of cycles to failure

Modeling & Lifing: ***Results***

FW Configuration	T=593C		
	$R_p = \frac{\Delta\varepsilon_{p,Model}}{\Delta\varepsilon_{p,Test}}$	$R_p = \frac{N_{f,Model}}{N_{f,Test}}$	**Failure location from Model**
T92-NFA	**1**	**From 1.46 to 2.06**	**T92 (Test: T92)**
T92-S304H	**1.05**	**From 0.92 to 1.27**	**T92 (Test: T92)**



Calculated plastic strain range contour plots

GE proprietary lifing methodology can

- predict the failure location of a RFW test coupon that matches with the test observation
- predict the life with sufficient accuracy compared to test data
- help building the mechanistic understanding of LCF behavior of different DMW configurations

Going Forward Plan

Q2-2023

- (2.1) Crack free friction-welded tubes T92/NFA/617/UNS S30432 - Config B
- (2.2) Weld property assessment data

2023 Planned Tasks

Friction Welding – with Transition Pieces

- **(2.1) Friction weld** development for **thick wall** T92, NFA, IN617 & UNS30432 (Config B) tubes with and without **NFA transition pieces**
- **Low Force Friction welding trials**
- Evaluation of **weld quality** in tensile, LCF, and creep under **industrial-relevant testing conditions**

NFA Tube Manufacturing – Scale up

- **Full-scale NFA thick-wall (config B) tube production**

Coating Process – Optimization & Phase Stability Assessment

- **Evaluate thermal mechanical fatigue behavior of coated tube** with thick wall (Config B) dimension
- Determine **risk of phase stability due to long term exposure** of coating on welds
- Continue to explore **improvement of coating characteristics** by post-surface prep or alternate spray methods.

Lifing – Validation & Fiction Weld Geometry

- **(5.2) Identify parameters** for accelerated thermal fatigue test for **durability evaluation**
- **Validate model prediction** with LCF and creep test data for solid bar/test coupon geometry
- Evaluate **configuration geometry and the effect of an NFA transition piece** on the strains produced during thermal cycling

ACKNOWLEDGMENT

This Technical Review Summary is based upon work supported by the Department of Energy under Award Number DE-FE0031907.

DISCLAIMER

Thank you!

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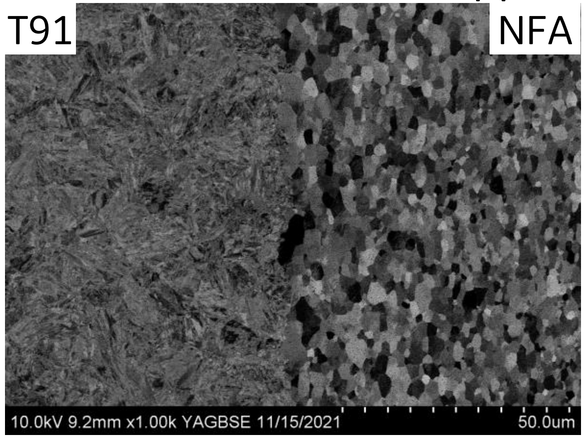
Microstructure of Rotary Friction Weld of NFA tubes

As-welded: No W-rich ppts



PWHT: W-rich ppts