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

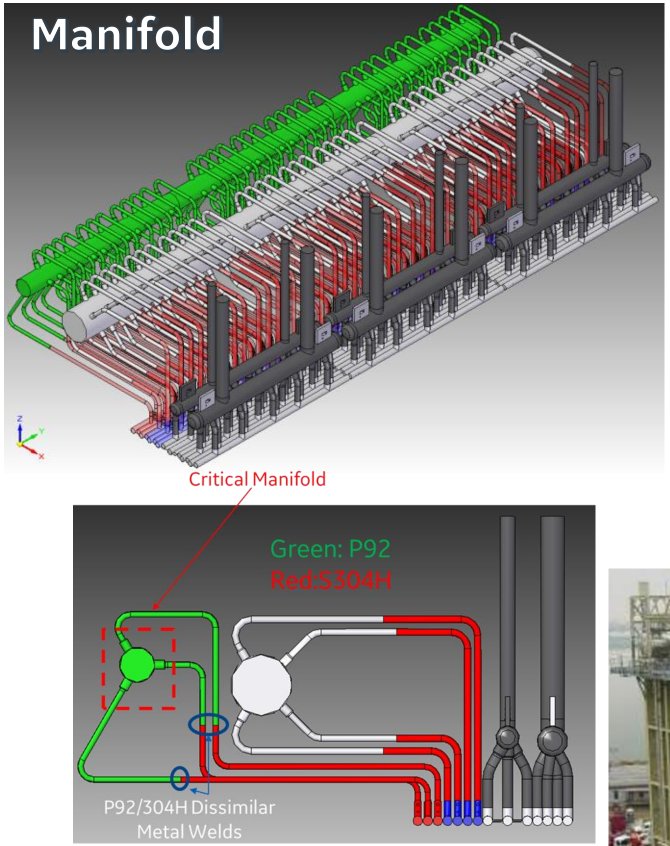
US Dept. of Energy/NETL Annual Review

Dr. Erica Sampson, GE Research

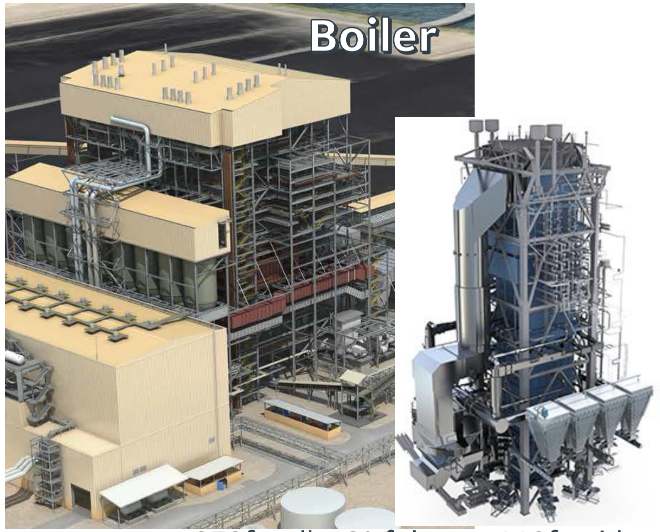
DE-FE0031907

June 10th, 2021

Why are Dissimilar Metal Welds (DMWs) needed?



Different colors represent different sections and/or materials



~278ft tall x 60 ft long x 118ft wide

~80ft tall x 100ft long x 30ft wide

- Increased steam temperature >580°C in HRSG and boilers drives need for transition to austenitic steels from the creep strength enhanced ferritic steels (CSEF)
- In each HRSG and boiler there are thousands of high temperature DMWs throughout the complex tubing system joining the CSEF steels to austenitic stainless steels
- Unpredictable nature of current DMWs represents a risk of unplanned downtime
  - Taking 1000MW off the grid impacts 1 million houses
- These DMWs frequently require being repaired or replaced due to in-field failures and the location of these DMWs can make this difficult increasing the outage time
- Targeted life of HRSG/boiler is 25-30 years with expectations for minimal/routine maintenance
  - Does not account for multiple outages to repair/replace 1000s of DMWs
- Due to the increase use of renewable energy, combined cycle plants will be required to come on and offline more often. This means that:
  - There will be an increase number of cold starts
  - Cycling behavior of the steam fleet will increase
- Therefore, there is a need to improve the creep and fatigue behavior and durability of high temperature DMWs to improve joint life

Improved DMW joint durability needed for increased temperature and cyclic nature of steam fleet

Current High Temperature DMW challenges

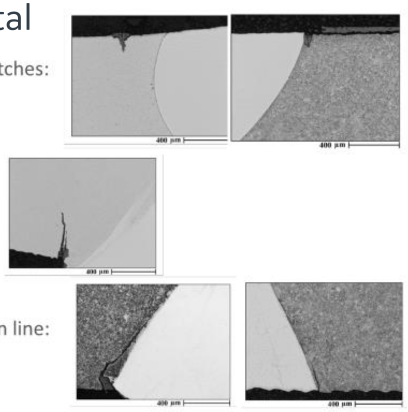
Oxide notching near the fusion line

Crack mechanism:
CSEF/Weld Metal

Oxide notches:

Cracking extending from notches into HAZ:

Cracking following fusion line:

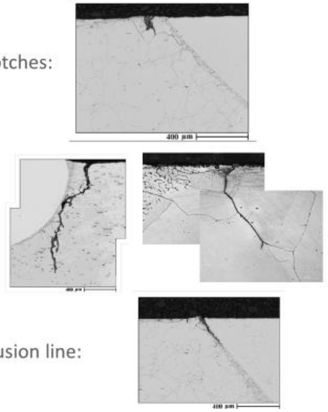


Crack mechanism:
Austenitic/Weld Metal

Oxide notches:

Cracking extending into HAZ:

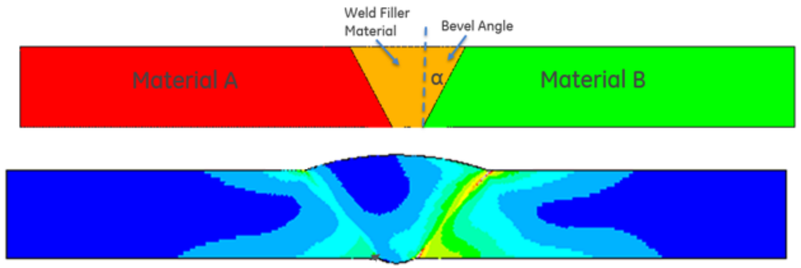
Cracking following fusion line:



CTE mismatch stresses

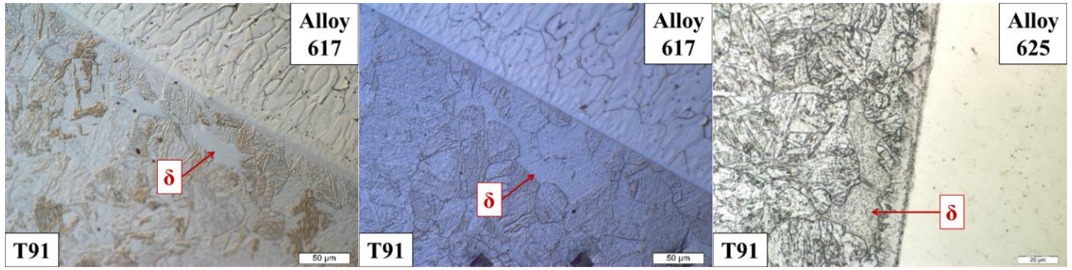
ID and OD corners are strained significantly just because of CTE mismatch stresses

Effective Total Strain Range Plot



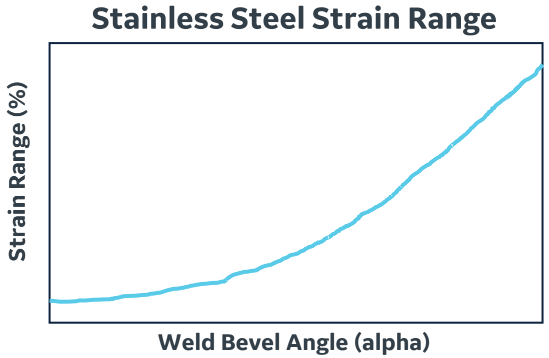
Elemental diffusion and deleterious phase changes

δ-ferrite and untempered martensite formation due to C depletion and Ni diffusion between the filler and ferritic steel driven by fusion welding high-temperature dwell times



M. Kuper. PhD Thesis, the Ohio State University, 2018. Figure 2.1: δ ferrite grains appearing in a DMW as welded (left,) after PWHT (middle), and after 10 years of service inside of a power plant (right).

Weld/Fusion line geometry – bevel angle



Relationship between strain range and the bevel angle – reducing bevel angle reduces strain range of joint

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

DOE DMW

Team

GE Research, GE Gas Power & GE Steam Power

Edison Welding Institute

Mfg. Tech., Inc.

Program impact

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

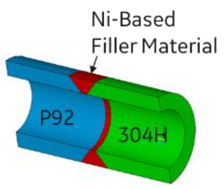
Key Innovations

- 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

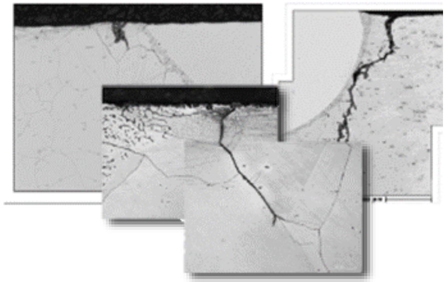
Anticipated Benefits

- 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

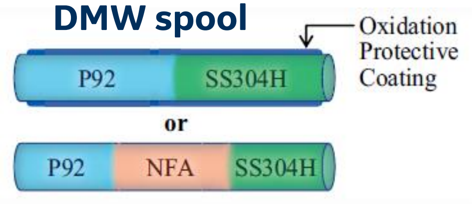


Oxide notching and cracking near fusion line and HAZ

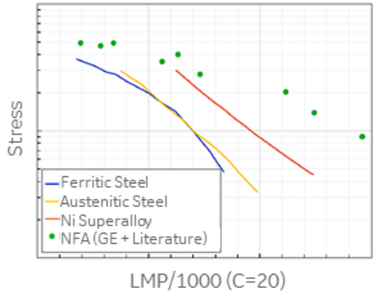


Proposed Solution

Friction Welded DMW spool



NFA superior creep resistance



Project Team

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HRSG

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HRSG System Architecture & Design

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HRSG Mechanical Integrity

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Principal Engineer – *Materials & Welding*

GE Research

DMW Materials Development, Testing, Lifing

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Lifing

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Lifing

Mr. Genghis Khan
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Edison Welding Institute

Tube Friction Welding Development, Production

Mr. Tim Stotler
Advanced Welding Techniques

Manufacturing Technology, Inc

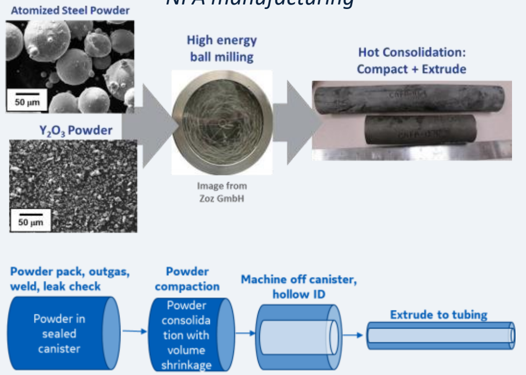
Collaborator Production Friction Welding

Program Technical Task Summaries

NFA Optimization

- Produce NFA material for tubing extrusion trials
- Hollow tube extrusion trials to produce NFA for friction welding trials
  - Subscale – GE Research
  - Full Scale – H.C. Starck

NFA manufacturing

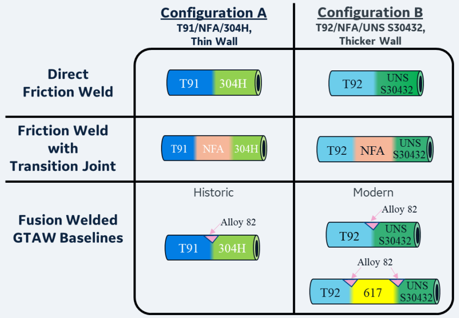


Planned manufacturing route of powder compaction and extrusion process to fabricate NFA thin-wall tubing

Friction Welding

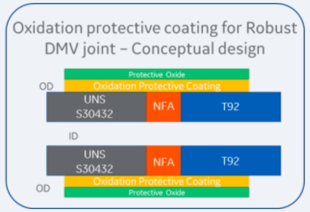
- Evaluation of friction welding methods: rotary friction welding and low force friction welding
- Friction welding parameter down-selection
- Microstructural and mechanical assessment of welded spools

Planned spool configurations for evaluation

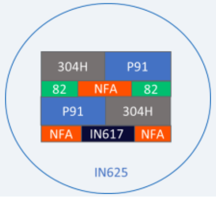


Coating and Diffusion

- Identify a coating chemistry and process to prevent differential oxidation and oxide notching across the join
- Evaluate the long-term stability of the spool microstructures through modeling and diffusion multiples



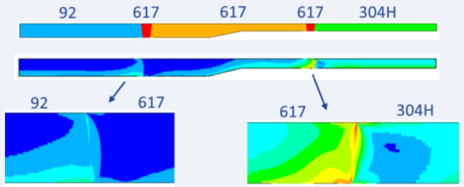
Schematic showing proposed conceptual design for protective coating



Example of diffusion multiple for long term stability study

Lifing

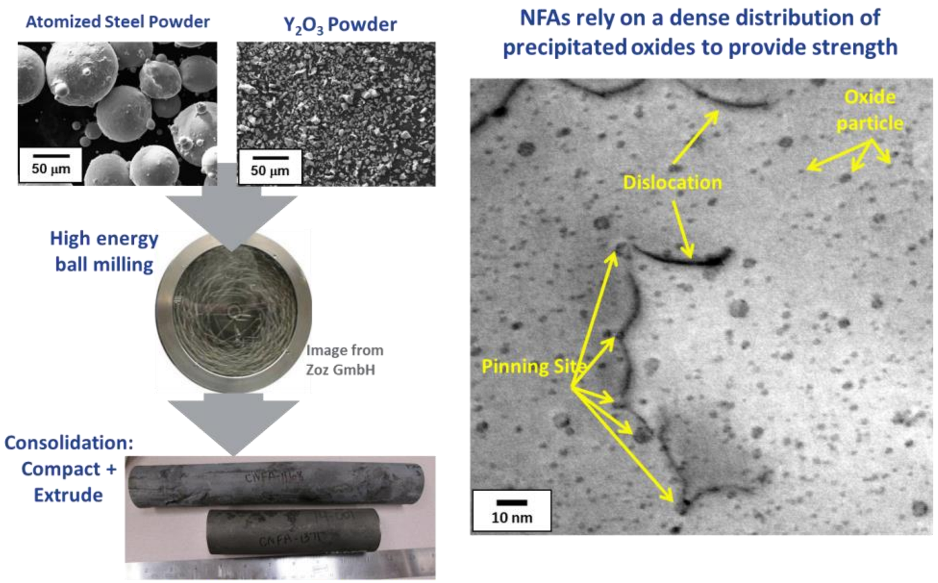
- Establish representative accelerated durability testing parameters
- Evaluate durability of proposed designed against baseline configurations utilizing GE developed lifing methodology



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

Nanostructured Ferritic Alloy Progress

NFA Production

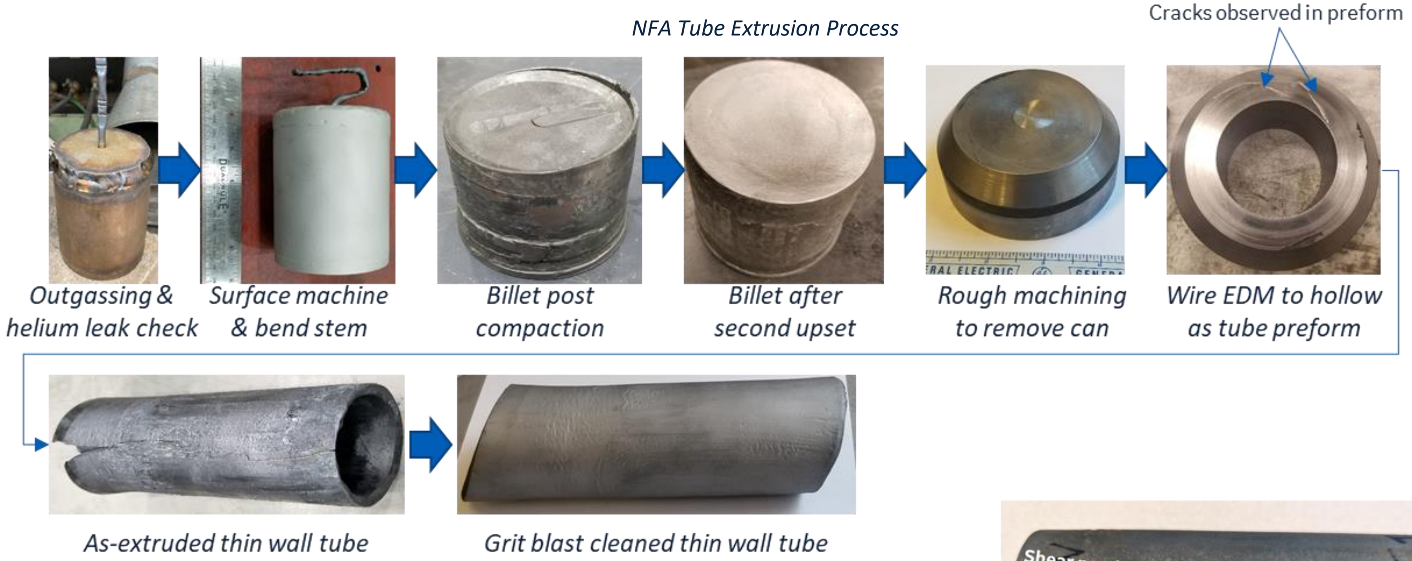


Composition and attrition process controls oxide dispersion.

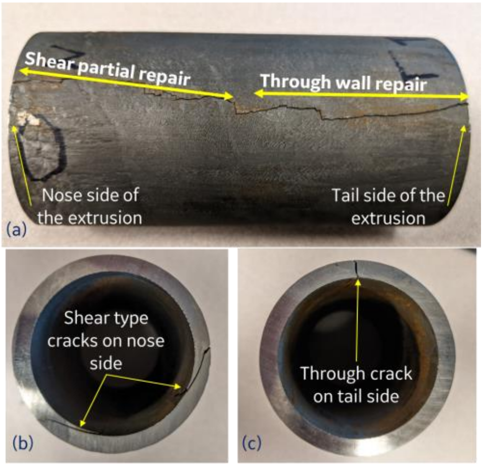
- Mechanical alloying of 1,000 lbs. NFA powder by Zoz GmbH using CM100 attritor mills in ~33 lb. batches
- Composition: Fe-12Cr-3W-0.8Ti + 0.5 wt.% Y_2O_3
- 258 lbs. received in March – remainder expected end of May

NFA Tube Manufacturing Process Development

- First subscale NFA thin wall tubing trial completed



- First thin-walled tube cracked prior to extrusion
  - Parameters adjusted for extrusion trial 2 being completed in May
  - Optimal parameters will be used for full scale thicker-wall extrusion trials (~180lbs. powder)
- Also assessing alternative processing route of hollow HIP can + Extrusion to preserve NFA powder



E-beam weld repair plan for 1st extrusion tube

Friction Welding Progress

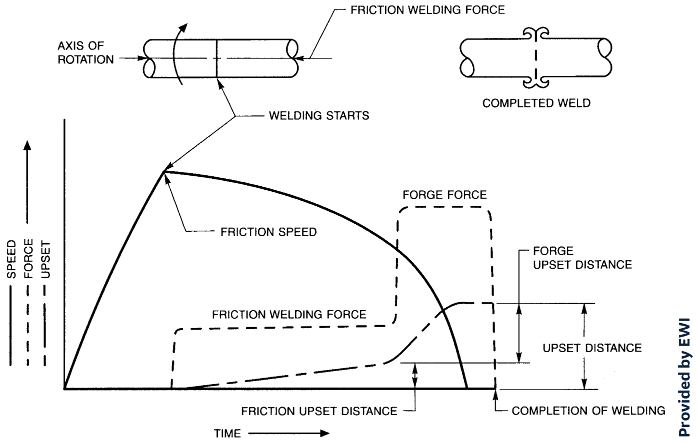
Two solid-state processes being evaluated:

Rotary Friction Welding

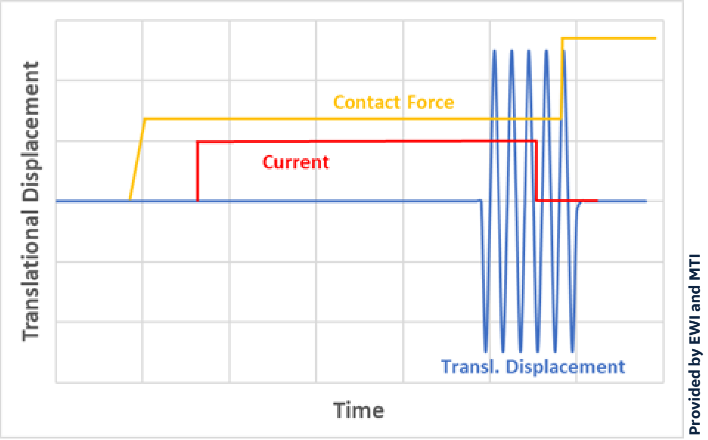
One part is rotated at high speed and is pressed against another part that is held stationary. The resulting friction heats the parts, causing them to forge together.

Low Force Friction Welding

Uses an external energy to raise the interface temperature of the two parts reducing the forces required to make a solid-state weld compared to traditional friction welding.

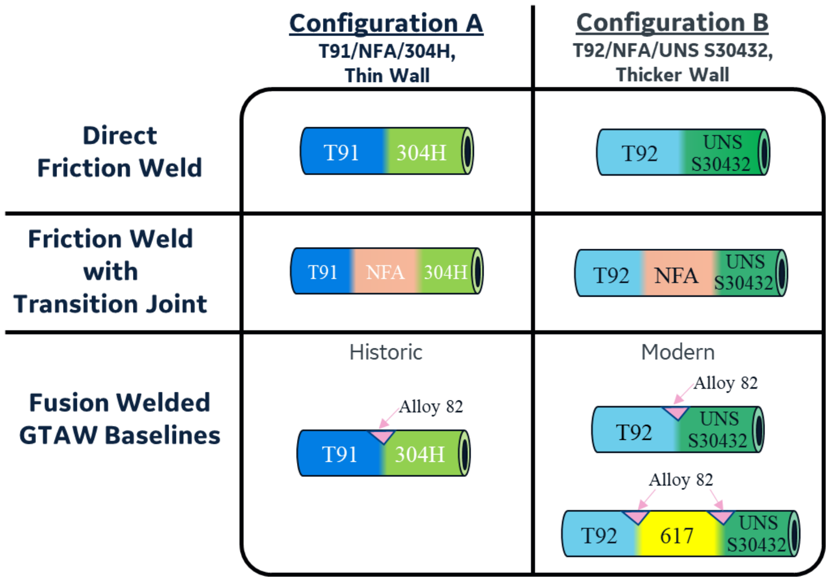


Generalized inertia welding process diagram (AWS Handbook). A forge force may not always be used.



Generalized process curve example using resistance heating

Planned spool configurations for evaluation



First EWI rotary friction welded T91/304H spool. Small coupon passed a hammer bend test before a small fracture started. Welding procedure to be further modified adding upset.

Evaluation Plan

- Configuration A:
  - Thermal fatigue capability of welded spools
  - Microstructural and oxidation
- Configuration B
  - Thermal fatigue capability of welded spools
  - Microstructural and oxidation
  - Extract cross-weld specimens for mechanical testing (creep, LCF, tensile)

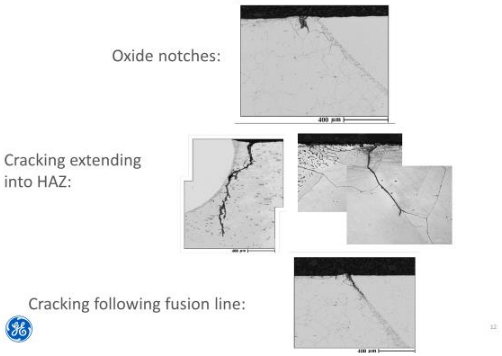
Current Status

- T91/304H received, T92/Super 304H (UNS S30432) ordered with ~6mo lead time, NFA tubing trials in process
- Tooling designed and built for thinner walled tubing configurations
- Starting optimizing process parameter evaluation for T91/304H

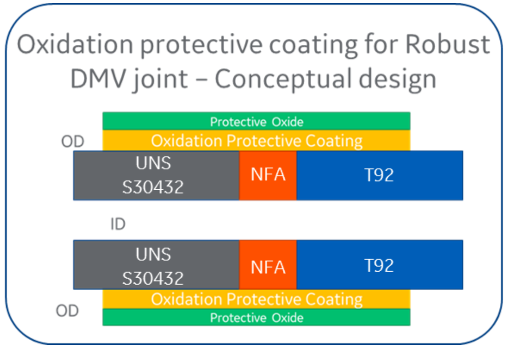
Oxidation Protective Coating and Microstructural Stability

Oxidation Protective Coating Development

Oxide notching mechanism



Coating concept

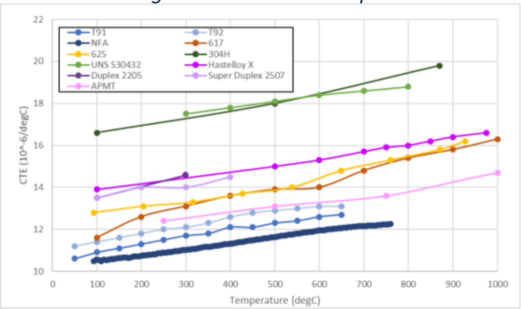


- Initial coating requirements:
  - Oxidation resistance in the temperature range
  - Thermal expansion compatibility
  - Phase stability (of coating as well as coating/substrate interdiffusion)
- Other considerations:
  - Commercially available coating process and compatible with current practice
  - Commercially available material systems (steel, Ni/Co alloys)

Initial coating candidates

Candidate coatings	Alloy family	Rational	Notes
IN625	Ni alloy	Chromia former & CTE between ferritic/austenitic alloys	Ni alloy: may cause unwanted phase(s) in steel
Hastelloy X	Ni alloy	Chromia former & CTE between ferritic/austenitic alloys	Ni alloy: may cause unwanted phase(s) in steel
APMT	Ferritic steel	Chromia & alumina former (depending on temperature range) – maybe beneficial in moisture-containing application	CTE compatibility?
Duplex steel	Duplex steel	Chromia former & CTE between ferritic/austenitic alloys	Duplex 2205 and/or Super duplex 2507

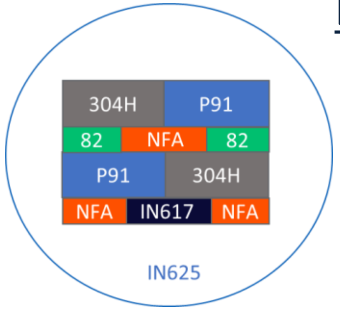
Coating candidate CTE comparison



Joint and Coating Long-Term Stability

- Assessing deleterious phase formation due to elemental diffusion

Diffusion Multiples

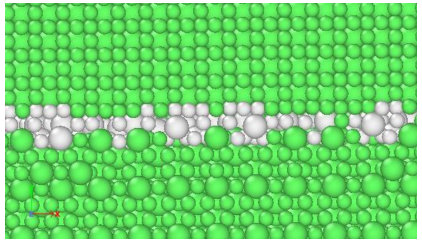


Configuration A diffusion multiple for long-term stability

- Evaluates chemical and microstructure changes due to long-term exposure at elevated temperatures of multiple diffusion couple in 1 experiment
- Assembly of configuration A diffusion multiple is in progress

Modeling: Atomistic Molecular Dynamics Simulations

- Numerical, step-by-step, solution of the equations of motion to predict material properties and evolution
- Identified interatomic potentials for interactions in materials system and tested for simplified material systems
- Developed scripts to be used with Sandia National Lab Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) code



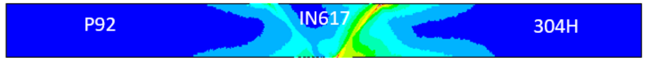
Atomic configuration of an L12 bicrystal structure. The large spheres are corner atoms while smaller ones are the face atoms. The white spheres show the atoms residing at the grain boundary.

Modeling and Lifing

Joint Durability Assessment

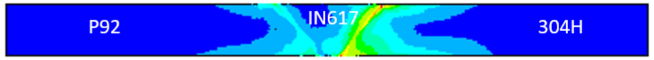
- Joint durability compared to baseline using a GE developed finite element based methodology
  - Utilizes LCF analysis by calculating strain range arising from CTE mismatch for targeted missions and field conditions
  - Residual stress and its impact on time-dependent durability (creep rupture) will be analytically computed & compared to baseline
- Will also be used to define accelerated durability testing conditions

Legacy results



Effective strain range contour plots from thermal cyclic testing obtained by updated macros versus legacy results

Current results



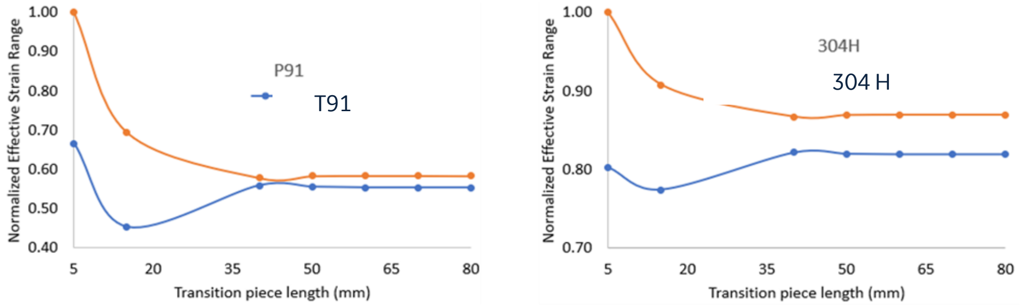
Current Status

- Updated macros with more robust parametric capabilities
- Developed ANSYS-based material input files for NFA material properties (Young's modulus, Poisson ratio, CTE, and LCF)
- Modeling results will be compared to the thermal-mechanical fatigue results from the friction welded spools

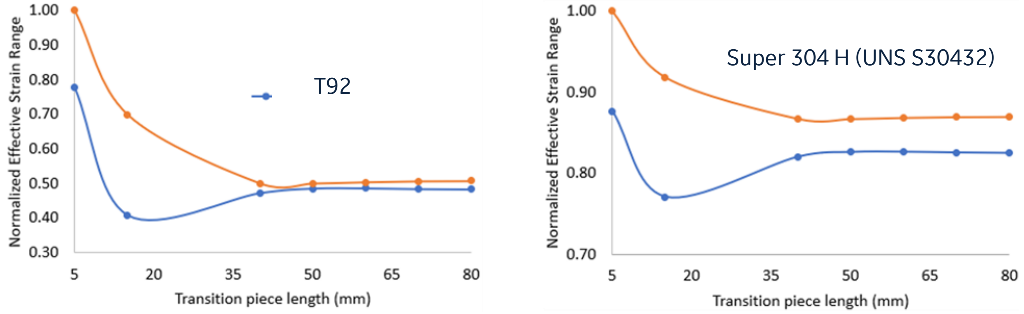
Effect of Transition Piece Length

- Parametric study on effect of transition piece length via nonlinear elastic-plastic analysis
  - Determined minimum length of 50mm for transition piece for lowest effective strain range in T91/T92 & 304H/Super 304H

Configuration A



Configuration B



Effect of transition piece length on the maximum effective strain range at either side of Configuration A (top) and Configuration B (bottom), for a thermal cyclic testing specimen. Thermal cycling was done between 640°C (hot steady state) and 39°C (cold steady state).

2021 Quarter 2 Planned Tasks

NFA Optimization

- **Complete mechanical alloying** of NFA material
- Demonstrate successful **in-house tubing extrusion trials for thin walled NFA tubing** for EWI's Configuration A friction welding trials
- Begin **full-scale NFA thicker-wall tube extrusion trial preparation -** Pack large can with ~200lbs NFA powder, compaction at H.C. Starck, machine to remove canister material and hollow center by EDM wiring at GE. Targeted extrusion ~July.

Friction Welding

- Friction welding **parameter assessment of T91 to 304H** by rotary friction welding
- Build **low force friction welding tooling** for Configuration A
- Develop rotary and low force friction welding **tooling for Configuration B**
- Finalize **testing matrix** for welded spools

Coating and Diffusion

- Identify coating requirements, a **testing protocol** to simulate actual application, and **beginning to evaluate coating process** for DMW joints
- Complete machining and assembly of Configuration A diffusion multiple and **begin long-term exposure**

Lifing

- Evaluate **configuration geometry and the effect of an NFA transition piece** on the strains produced during thermal cycling

ACKNOWLEDGMENT

This Quarterly Progress Report is based upon work supported by the Department of Energy under Award Number DE-FE0031907.