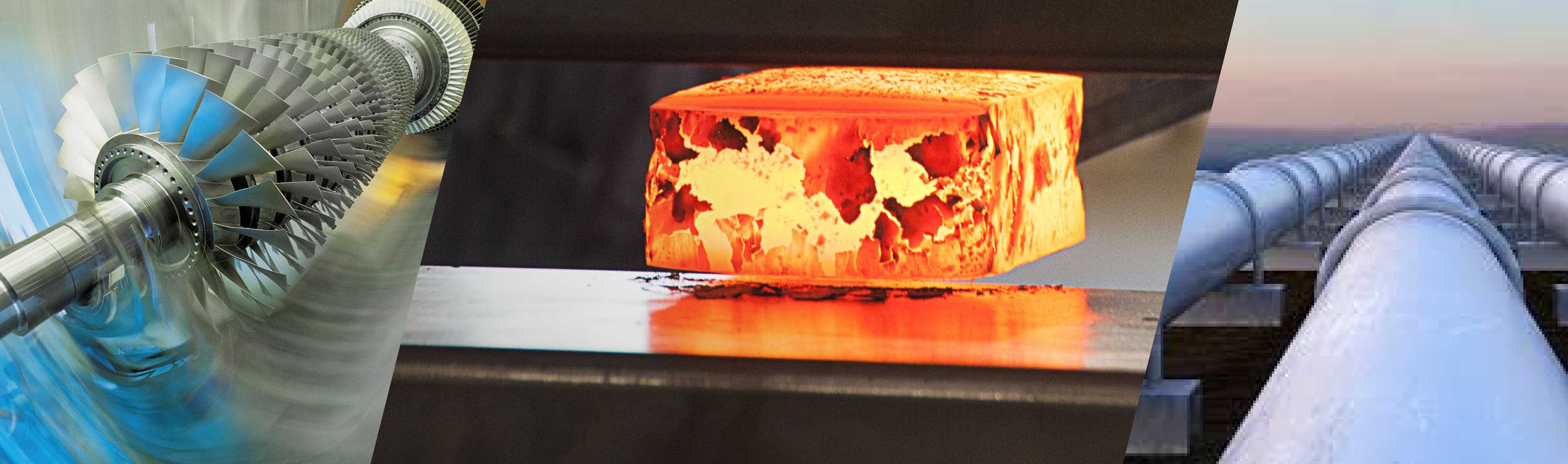
Advanced Alloy Development FWP

Ömer Doğan
omer.dogan@netl.doe.gov

FY22 FECM Spring R&D Project Review Meeting
Crosscutting (High Performance Materials) Session
May 9, 2022



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Contributors

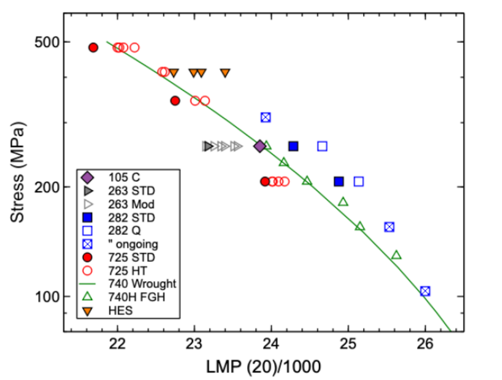
- David Alman
- Stoichko Antonov
- Marisa Arnold
- Dennis Burkey
- Casey Carney
- Tianle Cheng
- Richard Chinn
- Keith Collins
- Laurel Cooper
- Martin Detrois
- Ömer Doğan
- Matthew Fortner
- Michael Gao
- Trevor Godell
- Richard Gregory
- Sydney Hughes
- Paul Jablonski
- Kaimiao Liu
- Christopher McKaig
- Joe Mendenhall
- Richard Oleksak
- Christopher Powell
- Kyle Rozman
- Travis Shultz
- Erik Shuster
- Chantal Sudbrack
- Kristin Tippey
- Youhai Wen
- Michael Verti
- Fei Xue

Advanced Alloy Development (AAD) FWP

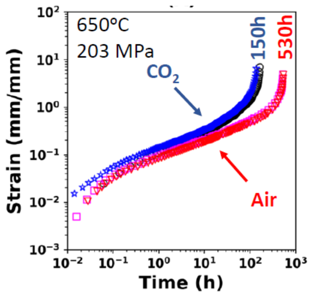
Execution Year: April 1, 2021, to March 31, 2022.

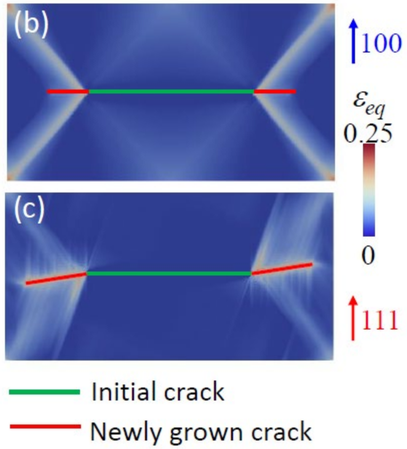
- Task 2 – SSAE—Guide Advanced Materials R&D
- Task 5 – Simulate and Manufacture Large-Scale Ingots - Completed
- Task 6 – 650°C Martensitic-Ferritic Steel Development - Completed
- Task 12 – Effect of sCO2 Cycle Environment on Mechanical Behavior - Completed
- Task 14 – Materials Issues in Manufacturing Compact Heat Exch. - Completed
- Task 16 – Design Tool for Creep-Resistant Materials and LCF Modeling
- Task 19 – Gap Analysis of Alloy Feedstock Development for Large Area Wire-Arc Additive Manufacturing (LA-WAAM) - Completed

Creep of NETL Superalloys compared to wrought 740H

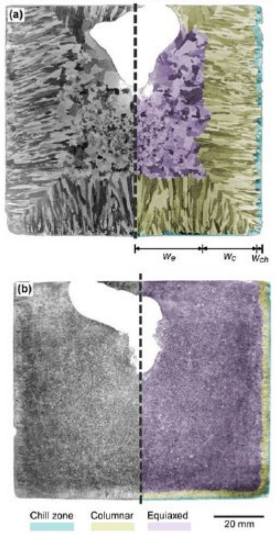


MARBN Ferritic-Martensitic 9Cr steel





Conventional casting
Non-Uniform Microstructure



NETL-modified casting
Uniform Microstructure

Task 2 – System Analysis and Engineering Guide for Advanced Materials R&D

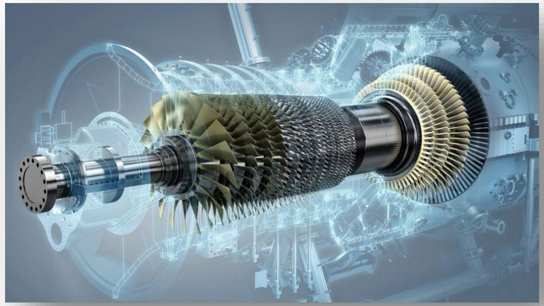
NATIONAL ENERGY TECHNOLOGY LABORATORY

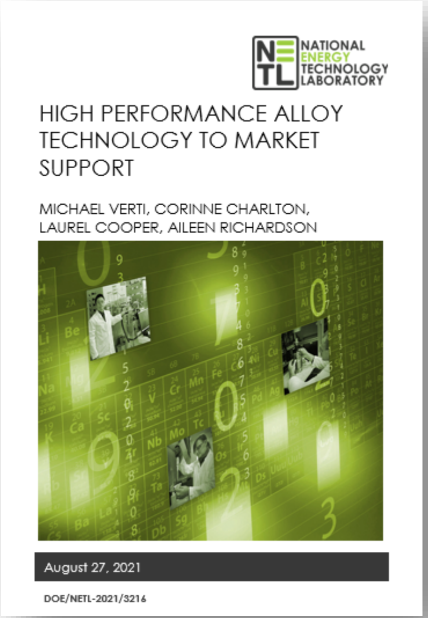
POC: Travis Shultz/Erik Shuster

Objective(s): The objective of this task is to provide research and program guidance for advanced materials R&D, set meaningful targets, assess their potential to contribute to the achievement of program and FECM goals, broadly inform program stakeholders, and project the impact of successful development on the Nation's energy markets and environment into the future

Expected Outcomes:

- Develop a study regarding advanced material needs in natural gas combined cycle (NGCC) plants and in hydrogen (H_2) production systems
- Identify non-technical support needs of research teams that could accelerate a path toward commercialization of NETL R&D technologies




NATIONAL ENERGY TECHNOLOGY LABORATORY

HIGH PERFORMANCE ALLOY TECHNOLOGY TO MARKET SUPPORT

MICHAEL VERTI, CORINNE CHARLTON, LAUREL COOPER, AILEEN RICHARDSON

August 27, 2021

DOE/NETL-2021/3216

Market-Level Analysis

Tech to Market Report

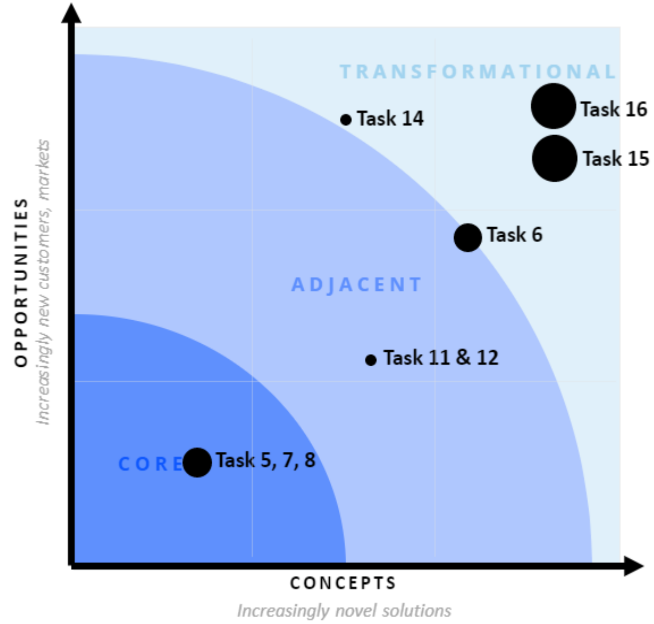
The goal of the Technology to Market Assessment for Advanced Alloys is to identify non-technical support needs of research teams that could accelerate a path toward commercialization of NETL R&D technologies

Final report complete

- Analysis utilized three different frameworks
- The frameworks provide best course of action for each project
- One-page communication documents

Projects were given a score of 1–5 for each question.

Individual research projects as a function of potential market and novelty of the solution



Market-Level Analysis

Modeling Economics Of Advanced Alloy Development

This report evaluated pathways to reduce cost and build resiliency in the domestic superalloy supply chain with a focus on alternatives to extrusion for large-diameter steam piping and near-net shaped (NNS)-based processes as an alternative to casting.

The report also assessed opportunities to use large area additive manufacturing (LAAM) for power plant operations.

Seam Welding

Investigating **technology needs related to seam welding valuable,** but unlikely to lead to commercialization in the FE power plant sector.

Welding Challenges
Advance bending and welding alloys of greater than 1.5" wall thickness

Technical Demonstrations
Seek opportunities to demonstrate large and small diameter seam-welded superalloy tube and pipe in attractive adjacent applications like Gen 3 CSP and high temperature thermal storage

HIP

Feasibility demonstrated for small fittings, opportunity for additional R&D to **improve technical properties** and **manufacture larger components.**

Technical Feasibility Challenges
Studies on powder cleanliness, powder size distribution, and HIP cycle optimization, creep, fatigue, hold-time fatigue, long term microstructure stability, etc.

Welding Challenges
Studies on wrought/PM weld on thick wall component, cross-weld mechanical property evaluation, and NNS HIP and PM/wrought weld demonstration on full-scale component

Machinability & ASME Code Case
Machinability in solution annealed or solution and aged conditions, and ASME code cases for PM HIP IN740H and PM/wrought IN740H welds

AM/PBF

Opportunity for further **demonstrations of feasibility and viability of PBF** for FE and NGCC power plants applications to **improve supply chain resiliency.**

Manufacturing Demonstrations
Conduct feasibility and viability demonstrations for high impact components to improve commercialization outcomes

Industry Research Gaps
Investigate ongoing development efforts in industry for high impact components and identify research gaps NETL could address

Understanding Domestic Fabrication Supply Chain
Identify potential supply chain risks, specifically related to domestic fabrication and areas where NETL could mitigate those challenges

LAAM

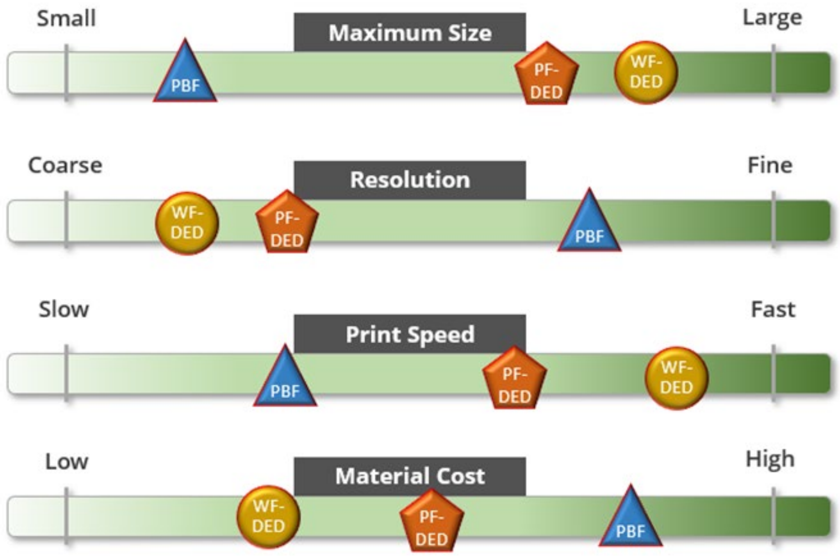
There is a large opportunity space to **assist commercialization of LAAM technologies.** NETL should focus efforts on **specific LAAM subject areas.**

Reduce Manufacturing Cost
Advancing Alloy Mixing/FGM technologies for Large, Ni-superalloys and LAAM novel designs in the HRSG and Turbine components in NGCC

Advancing Materials Science R&D
Further Wire Feedstock Development as there are few alloys available in wire form today

Considering Safety Requirements
NDE Ensuring critical products maintain safety level is key to enabling commercialization.

Printing Unique Parts for FE
Investigate LAAM production/repair of unique parts (seals, diaphragms, pumps), outside of the boiler.



Task 5 - Simulate and Manufacture Large-Scale Ingots

Objectives:

Design, development, and manufacture HPMs for advanced energy systems. To achieve this goal, task objectives fall into the following categories:

- Optimize the industrial melting processes used for advanced alloys in existing and emerging energy systems.
- To maximize properties of Ni-base superalloys through alloy design and thermomechanical processing (TMP) control, thereby providing alloy solutions that will enable and improve advanced energy cycles.

Effect of Key Elements and Aging in IN725 Variants

Influence of η Phase in Alloy 263

C Content in Nimonic 105

Influence of Trace Elements

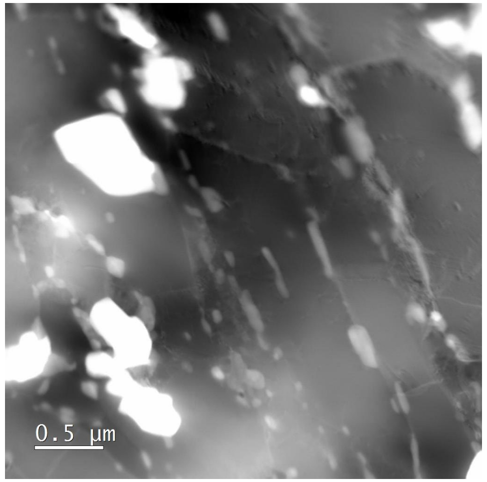
Ni-Base Superalloy Castings

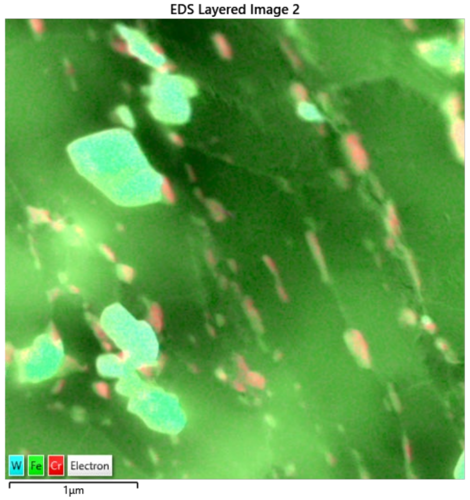
May 9th, 2022
3 PM EDT

Task 6 - 650°C Martensitic-Ferritic Steel Development

POC: Martin Detrois

Objectives:
Improve the temperature capability and performance life of the relatively low-cost 9–12% Cr ferritic-martensitic steel; thereby, reducing the costs and improving the performance of advanced power cycles. Current advanced 9–12% Cr ferritic-martensitic steels are used to about 600°C in high pressure (HP) steam turbines. NETL research has indicated that a W-containing steel (NETL JMP) may allow ~650°C operations.





IP/Licensing:

- J.A. Hawk, P.D. Jablonski, C.J. Cowen, Creep Resistant High Temperature Martensitic Steel, US 9,181,597 B1, 2015.
- J.A. Hawk, P.D. Jablonski, C.J. Cowen, Creep Resistant High Temperature Martensitic Steel, US 9,556,503 B1, 2017.
- *P.D. Jablonski, M. Detrois, J.A. Hawk, Ferritic-Martensitic Fe-Cr-W-Co Steel and Method of Manufacture, Recommended to DOE for the Filing of a Patent Application.*

Publications

- Rozman, K.A., Oleksak, R.P., Doğan, Ö.N., Detrois, M., Jablonski, P.D., Hawk, J.A., Mater. Sci. Eng. A 826 (2021) 141996. https://doi.org/10.1016/j.msea.2021.141996
- Detrois, M., Jablonski, P.D., Hawk, J.A., Joint EPRI-123HiMAT International Conference on Advances in High Temperature Materials. ASM International, Nagasaki, Japan, pp. 104–115 (2019).
- Detrois, M., Jablonski, P.D., Hawk, J.A., Metall. Mater. Trans. B 50 (2019) 1686–1695. https://doi.org/10.1007/s11663-019-01614-z

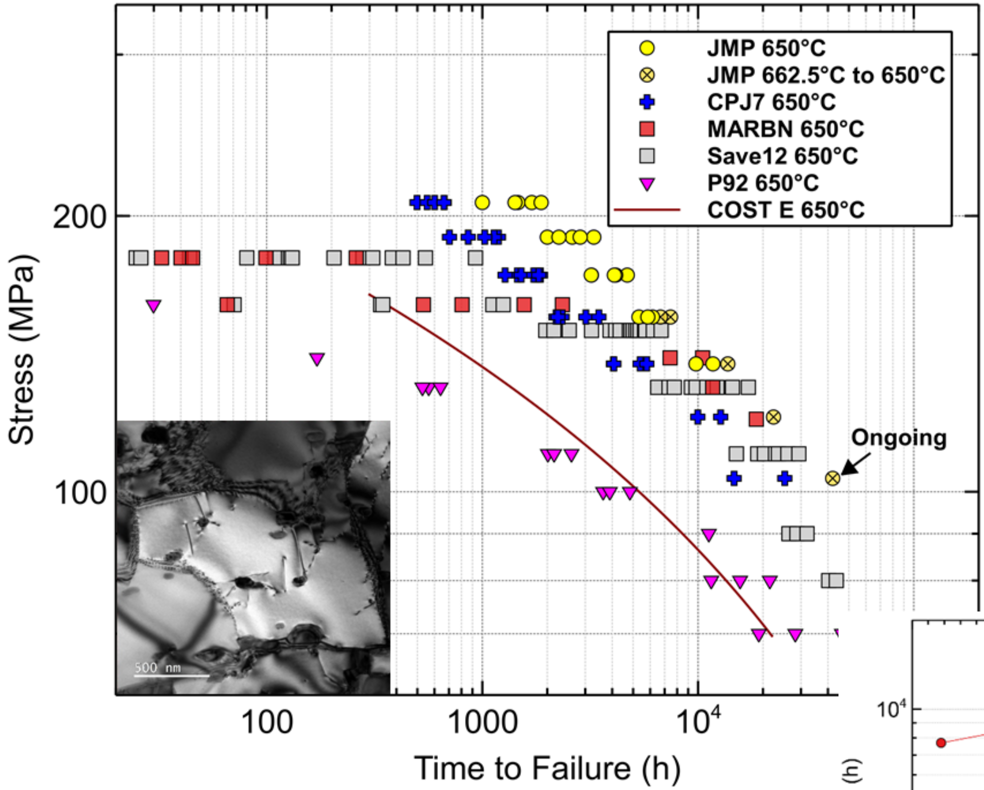
Task 6 - 650°C Martensitic-Ferritic Steel Development

CPJ-7 Steel

- Creep resistant martensitic steel, CPJ-7, was developed with an operating temperature approaching 650°C.
- The design originated from computational modeling for phase stability and precipitate strengthening.
- A computationally optimized heat treatment schedule was developed to homogenize the ingots prior to hot forging and rolling.
- The prolonged creep life was attributed to slowing down the process of the destabilization of the MX and $M_{23}C_6$ precipitates at 650°C.

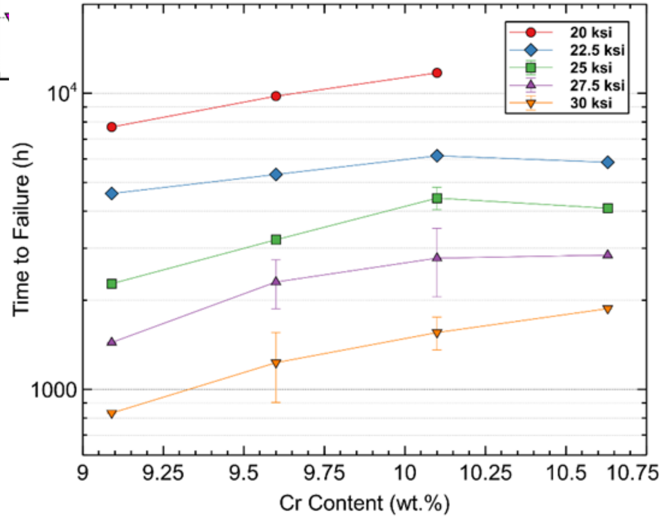
JMP Steels

- Following the work on CPJ-7, the JMP steels were designed with higher Co for increased solid solution strengthening, Si for oxidation resistance and increased W (with low Mo content) for matrix strength and stability as well as solid solution strengthening.
- The JMP steels showed increases in creep life compared to CPJ-7 between 118 to 150% at 650°C for testing at various stresses. On a Larson-Miller plot, the performance of the JMP steels surpasses that of state-of-the-art MARBN steel.

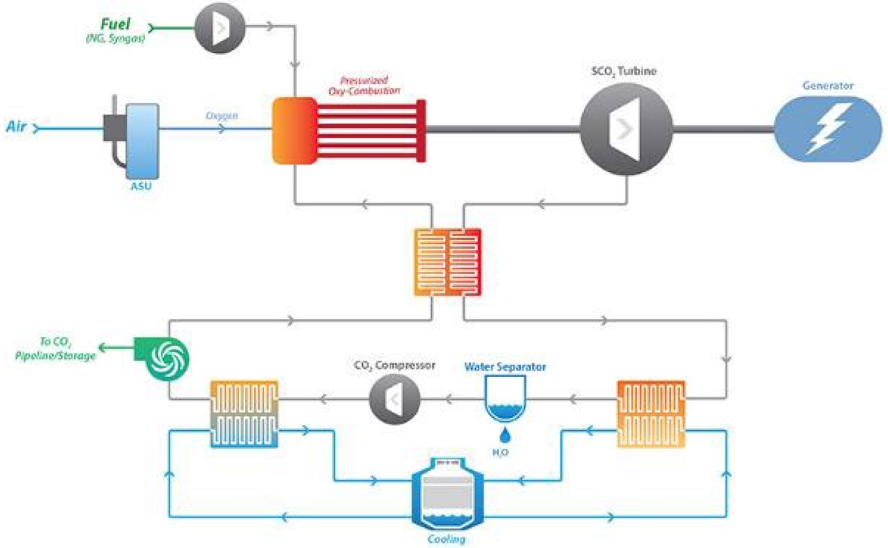


Comprehensive Report on NETL Martensitic-Ferritic Steel Development to be Published.

- ★ Cast and wrought forms
- ★ Multiple 70 kg (150 lb) ingots produced
- ★ VIM and ESR
  - ESR slag formulated
- ★ Tensile
- ★ Creep
- ★ Fatigue
- ★ Oxidation
- ★ Welding trials/studies
  - Conventional NETL
  - Friction Stir Welding PNNL



Task 12 - Effect of sCO_2 Cycle Environment on Mechanical Behavior



POCs: Richard Oleksak, Ömer Doğan

Partnerships: 8 Rivers, OSU, PNNL

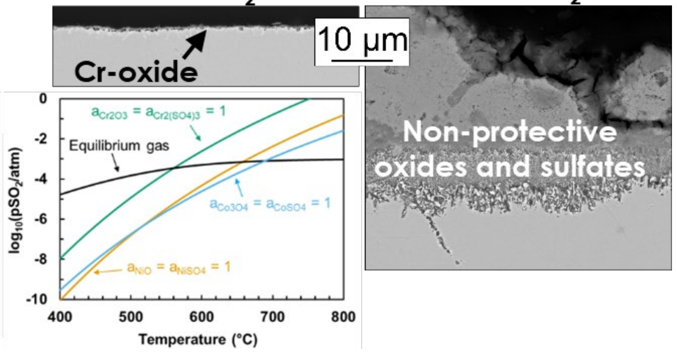
Objective(s): Evaluate commercial alloys under direct-fired sCO_2 cycle conditions to identify cost-effective materials suitable for constructing these power plants. This task will also generate data for the U.S./UK supercritical materials performance task. Current focus involves two complementary thrusts: (1) Identifying cost-effective steels for intermediate-to-low temperature portions of the cycle to enable significant cost savings and (2) Understanding combined effects of environment and stress to enable accurate lifetime predictions for critical components.

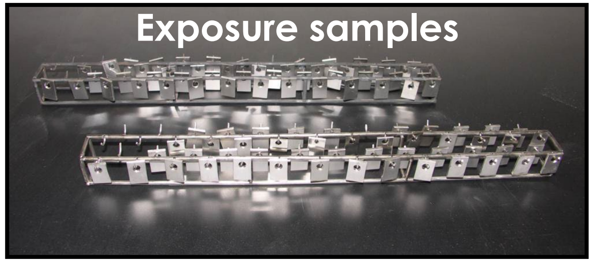
Outcomes: Generating materials performance data and identifying cost-effective materials which can be used in the direct-fired sCO_2 power cycles will reduce the risk for commercialization of this technology.

Identifying Cost-effective Steels

An Opportunity for Significant Cost Reduction in Building sCO_2 Plants

Revealing the impact of impurities in the CO_2





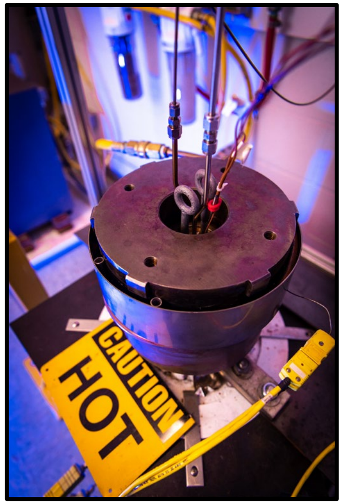
400 °C → 800 °C

Ni content ($$$)
Creep strength
Environmental resistance

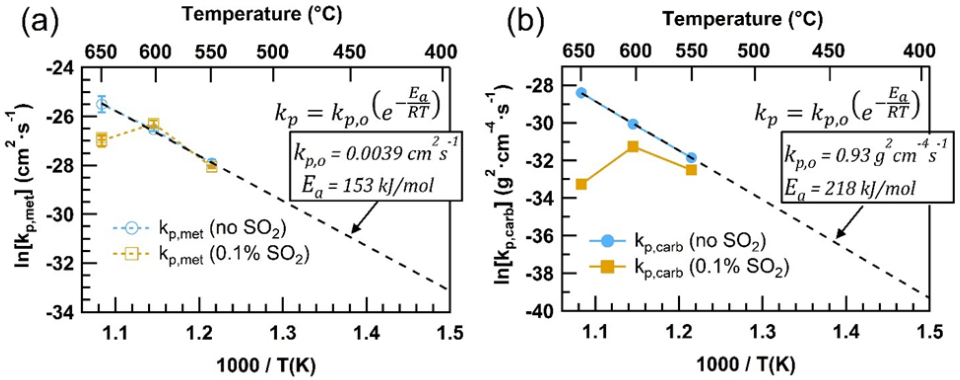
$2/kg — $70/kg

Ferritic/martensitic steels	Austenitic steels	Ni-based superalloys
(0-12 wt% Cr)	(16-25 wt% Cr)	(16-25 wt% Cr)

Determining effects of supercritical pressures on steel degradation



Establishing temperature-dependence of important degradation processes

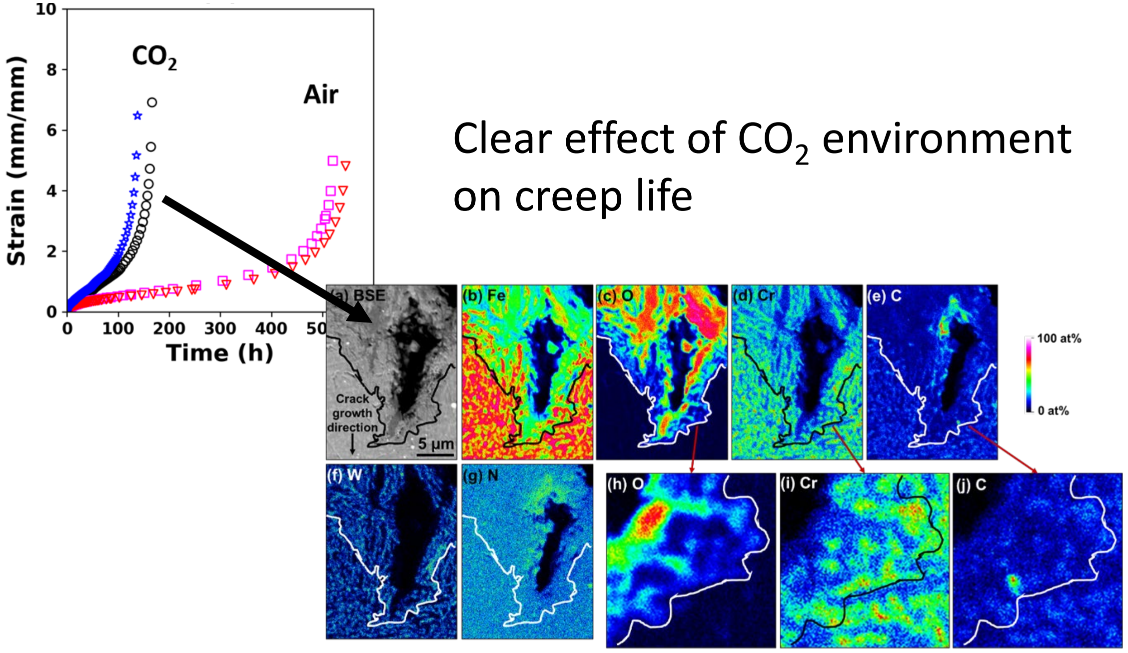


Recent Publications

- R.P. Oleksak, J.H. Tylczak, Ö.N. Doğan, "Temperature-dependence of oxidation and carburization of Grade 91 steel in CO_2 containing impurities," *Corros. Sci.* **198** (2022).
- R.P. Oleksak, J.H. Tylczak, Ö.N. Doğan, "High-Temperature Oxidation of Steels in Direct-Fired CO_2 Power Cycle Environments," *JOM* **73** (2021).

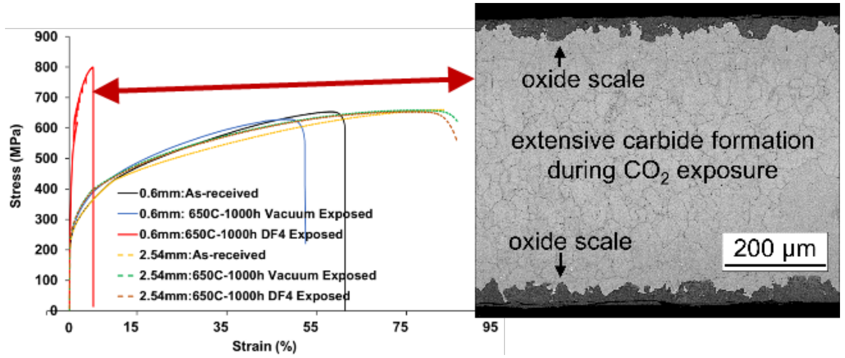
Effect of Environment on Mechanical Degradation

Understanding the Interplay between Oxidation, Carburization, and Mechanical Performance to Enable Informed Selection of Cost-effective Materials



Clear effect of CO_2 environment on creep life

Embrittlement strongly dependent on steel thickness



Recent Publications

- K.A. Rozman, R.P. Oleksak, Ö.N. Doğan, M. Detrois, P.D. Jablonski, J.A. Hawk, “Creep of MARBN-type 9Cr martensitic steel in gaseous CO_2 environment,” *Mater. Sci. Eng. A* **826** (2021).
- S.R. Akanda, R.P. Oleksak, R. Repukaiti, K.A. Rozman, Ö.N. Doğan, “Effect of thickness on degradation of austenitic 347H steel by direct-fired supercritical CO_2 power cycle environment,” *Corros. Sci.* **192** (2021).
- S.R. Akanda, R.P. Oleksak, R. Repukaiti, K.A. Rozman, Ö.N. Doğan, “Effect of Specimen Thickness on the Degradation of Mechanical Properties of Ferritic-Martensitic P91 Steel by Direct-fired Supercritical CO_2 Power Cycle Environment,” *Metall. Mater. Trans. A* **52** (2021).

Task 14 - Materials Issues in Manufacturing Compact Heat Exchangers (CHX)

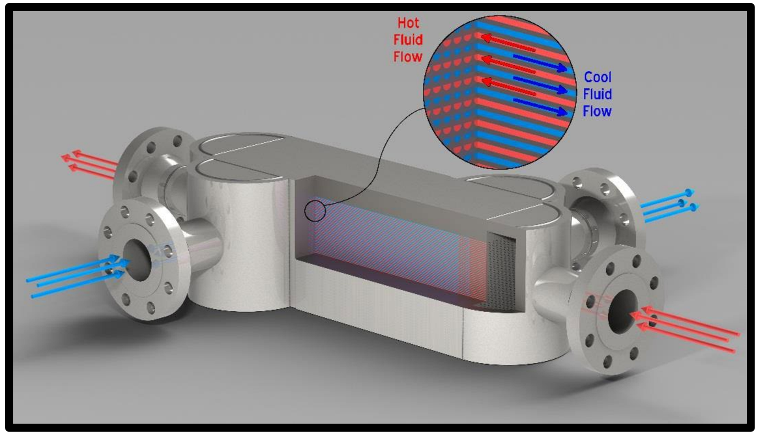
Diffusion Bonding of IN740H

POC: Ömer Doğan

Partnerships: Vacuum Process Engineering, Special Metals

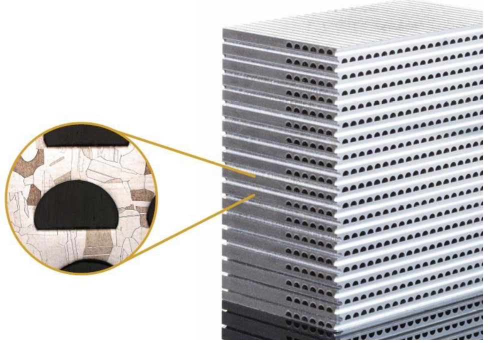
Research Objective

- sCO_2 power cycle conditions necessitate the use of higher temperature materials (in many cases Ni based alloys) in manufacturing CHX. This task will focus on enabling the manufacturing of CHX for sCO_2 cycles by developing surface preparation and bonding techniques for IN740H alloy.



Outcome

- Demonstrated a fully developed diffusion bonded stack of IN740H with a yield strength and elongation better than 75% of the bulk material yield strength and elongation.
- Improved performance of CHX by advancing manufacturing techniques and increasing temperature capability



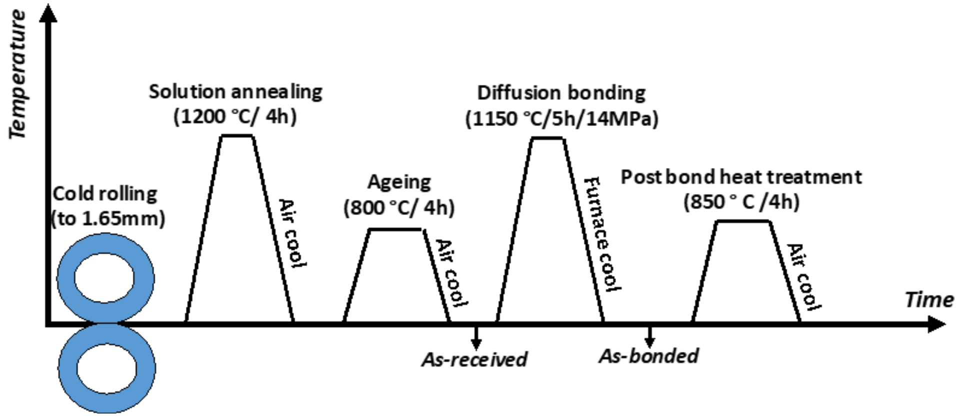
SPECIAL METALS

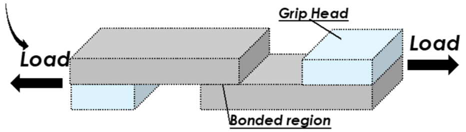
VPE Vacuum Process Engineering

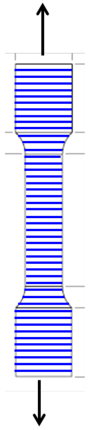
Demonstrated diffusion bonding of 740H

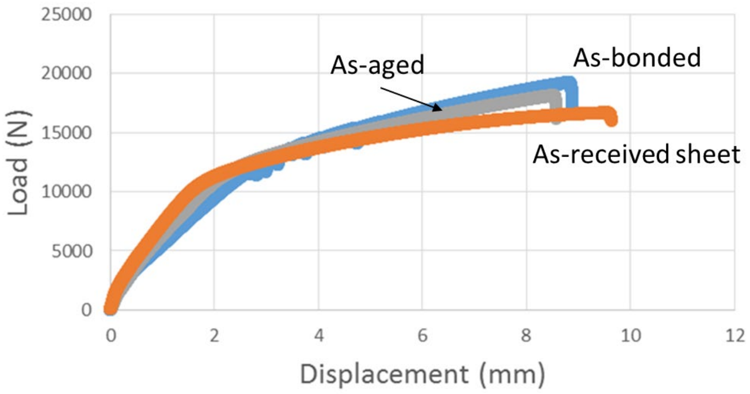
IN740H

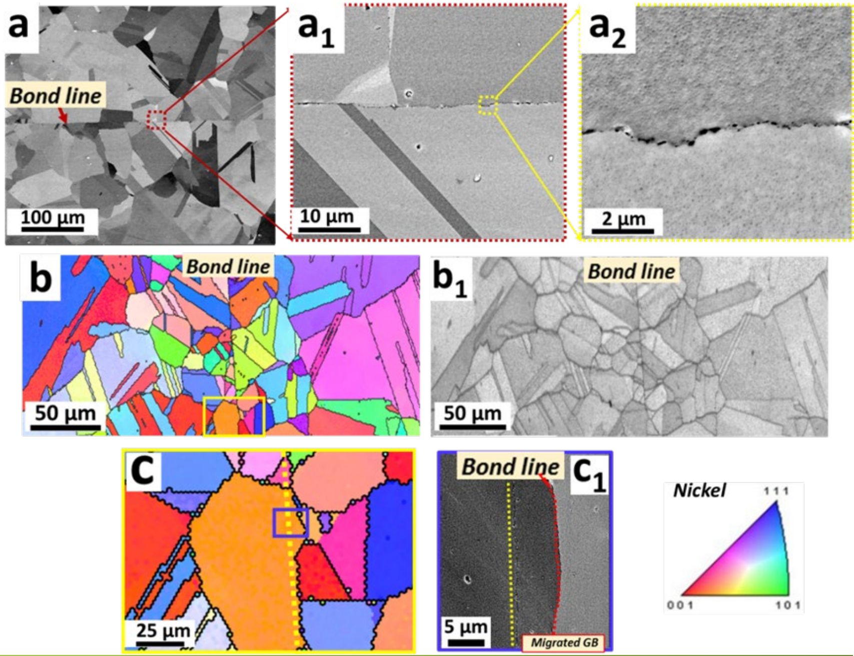
Ni	Cr	Co	Al	Ti	Nb	Mo	Mn	Fe	C
Bal.	24.6	20.0	1.4	1.5	1.5	0.5	0.3	0.2	0.03











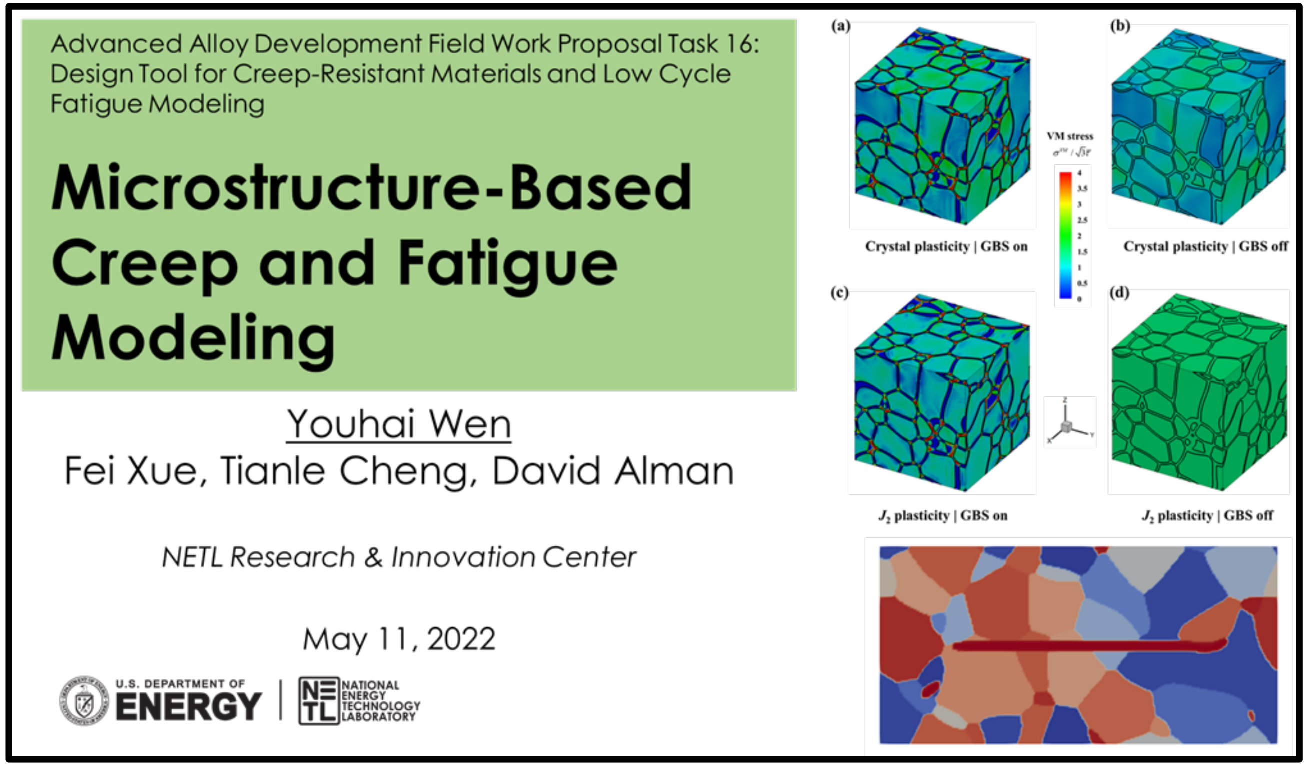
- Demonstrated a diffusion bonding process in accordance with Appendix 42, ASME Section VIII,DIV 1.
  - Produce diffusion bonded stacks of 50 coupons
  - Machine and test tensile bars for yield, UTS, and elongation data
- Demonstrated a fully developed diffusion bonding process for IN740H by producing a diffusion bonded stack of IN740H with a yield stress and elongation better than 75% of the bulk material yield stress and elongation.

Task 16 - Design Tool for Creep-Resistant Materials and Low Cycle Fatigue Modeling

NATIONAL ENERGY TECHNOLOGY LABORATORY

Objective: Develop a ***microstructure-based life prediction tool*** that **couples** creep, fatigue, and environmental effects.

- Enhances the predictive capability for the performance of materials undergoing cycling conditions at elevated temperatures
- Enables power system flexibility through improved materials performance predictive capability.



WEDNESDAY, MAY 11th
11:30 AM EDT

Accomplishments:

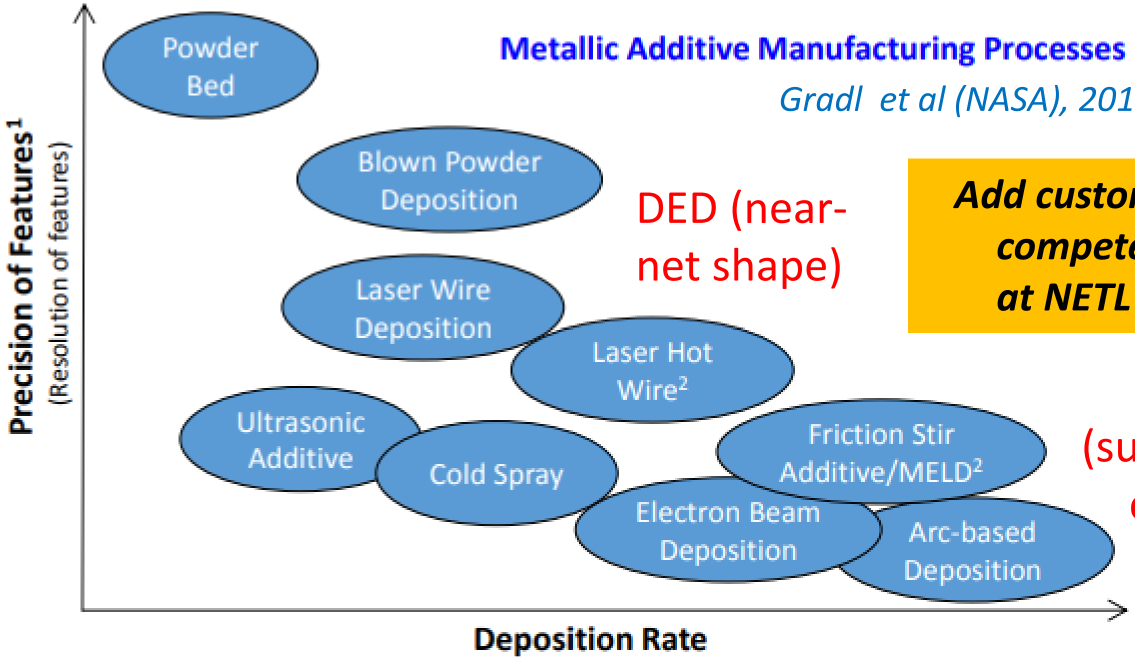
Developed a modeling framework to simulate the simultaneous evolution of complex crack patterns and plastic strain in ductile materials, which is a key progress towards our goal of microstructure-based life prediction

Developed a phase-field model for the oxidation processes within a multi-phase multi-component framework. The model can be applied to investigate high-temperature oxidation mechanisms and predict the resulting morphologies of protective oxides.

Task 19 - Gap Analysis of Alloy Feedstock Development for Large Area Wire-Arc Additive Manufacturing (LA-WAAM)

POC: Chantal Sudbrack
Gap Analysis Partnership: Deloitte team - *Modeling Economics of Advanced Alloy Development*

Deposition Trials Partnerships: Haynes International, Oregon State University Advanced Technology and Manufacturing Institute (ATAMI), Meltio, Oregon Manufacturing Innovation Center (OMIC)



Add custom wire competency at NETL ALB

WAAM (subtractive clean-up)

Motivation – *Schedule & cost savings*: High deposition rate, less scrap, shorter production cycles, wire feedstock

Target: Medium and low complexity parts with low batch production for WAAM

Outcomes: Develop research execution plans that facilitate cost-effective manufacturing options and help advance feedstock development opportunities in LA- WAAM and other wire-based DED processes

Task 19. Gap Analysis of Alloy Feedstock Development for Large Area Wire-Arc Additive Manufacturing (LA-WAAM)

NATIONAL ENERGY TECHNOLOGY LABORATORY

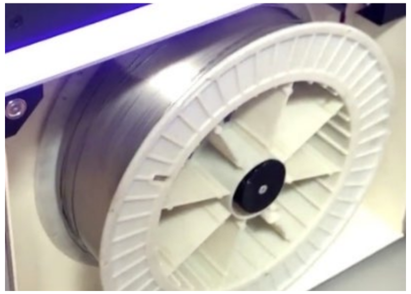
Outcome: Research execution plans that facilitate cost-effective manufacturing options and help advance feedstock development opportunities in LA- WAAM and other wire-based AM processes

Objective(s):

- Identify LA-WAAM research challenges and opportunities to support gap analysis & FWP development
- Identify external partners to join a technical committee to review gap analysis & research execution plans
- Identify possible manufacturing collaborators and assess capabilities with limited set of processing trials

HAYNES International

Benchmark to Haynes 282



0.035" diameter (July 2021)

0.045" diameter (March 2022)

- Wire spool exchanged after marginal results with DED trials

Oregon State University | ATAMI

DED processing trials

5.9" x 7.9" x 17.7"

MELTIO

M450

1200 W
6-laser

Wire/Powder

- 0.035" diameter results
- 0.045" diameter preliminary results

OMIC R&D
Collaborate. Innovate. Elevate.

WAAM processing trials

31.5" x 35.4" x 39.4"

5-axis

GEFERTEC arc605

- Supports Task 22 process development in EY22

Task 19. Gap Analysis of Alloy Feedstock Development for Large Area Wire-Arc Additive Manufacturing (LA-WAAM)

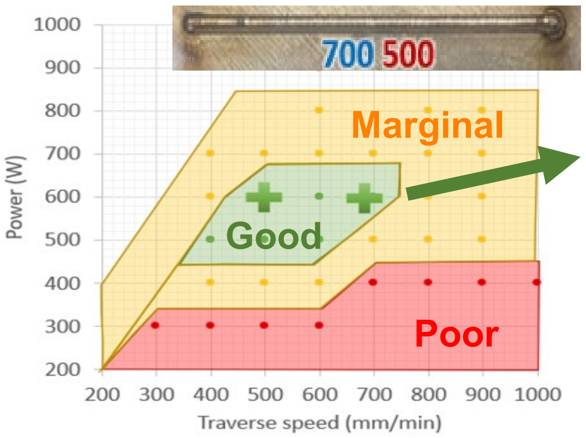
NATIONAL ENERGY TECHNOLOGY LABORATORY

Haynes 282 Processing Trials: Laser Wire DED on Meltio 450 at OSU ATAMI

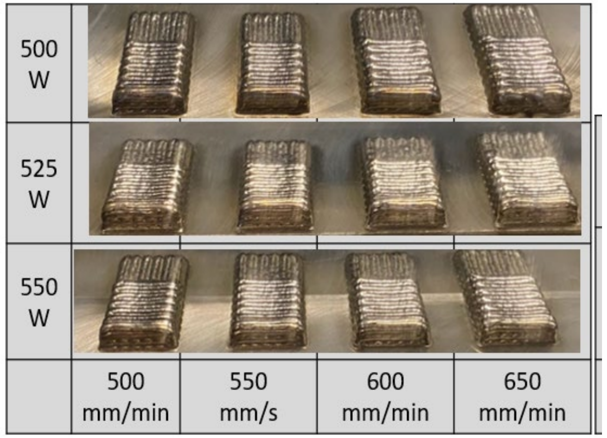
GOAL: Optimize processing parameters and compare optimized builds to conventional 282

0.035” diameter results

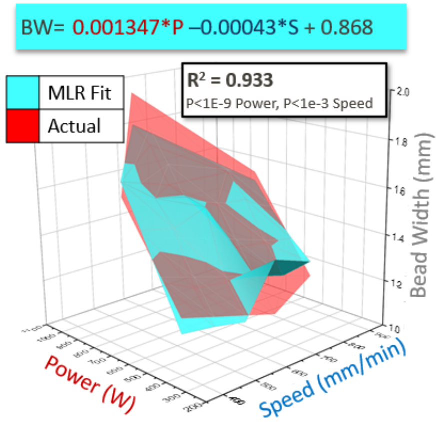
Quality Map – Single-bead tracks



Short Stacks

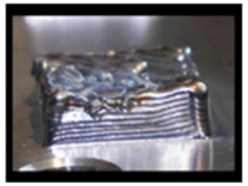


Analyze Bead Geometry

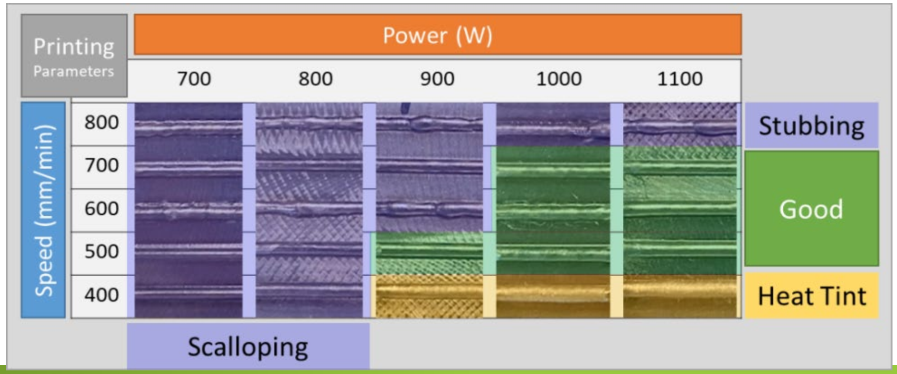


Irregularities with taller cubes

- Defects like balling, melt track issues, and kinked wire were observed
- 4 of 7 cubes failed prematurely, likely linked to feed issues of fine wire



Recent 0.045” diameter results



Robust and consistent printing with larger wire

- 5 of 14 successful cubes: Varying the offset and extrusion ratio

Transition to Hydrogen

AAD to AMD

Advanced Alloy Development FWP was focused on alloys to enable A-USC, sCO_2 and other efficient power systems

IN EY 22: **NETL's Advanced Materials Development FWP** focuses on

- Structural materials to enable transition to hydrogen.
- Hydrogen production from carbonaceous sources with carbon capture
- Power generation from hydrogen gas turbines.

Task 20 - Design and Evaluation of Environmental Barrier Coatings

NATIONAL ENERGY TECHNOLOGY LABORATORY

A Key Technology for Enabling Hydrogen Gas Turbines for Power Generation

- Develop environmental barrier coatings (EBCs) to protect ceramic matrix composites (CMCs) in hot sections of hydrogen gas turbines
- Focused on multiscale computational modeling to design new EBCs optimized for hydrogen combustion environments
- EY22 focus establishing capabilities for EBC evaluation.

Task 21 - High-Temperature Hydrogen Attack on Steels and Weldments Used in Hydrogen Production

U.S. Chemical Safety and Hazard Investigation Board

INVESTIGATION REPORT

Catastrophic Rupture of Heat Exchanger (Seven Fatalities)

Tesoro Anacortes Refinery

Anacortes, Washington

April 2, 2010

Task motivation

- API RP 941 "*Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*" (a.k.a. The Nelson Curves).
- The estimated operating regions for the stainless steel clad portion of the B and E heat exchangers extended above the carbon steel Nelson curve.
- At the rupture location, the estimated operating conditions are just below the carbon steel Nelson curve.

Task objective

- Fundamental understanding of HTHA mechanism of various steels
- Developing integrated testing and modeling tools for optimizing the current HTHA guideline (API RP 941 Nelson curves)
- Designing next-generation HTHA-resistant alloys.
- The ultimate goal of this project is to improve the infrastructural integrity and efficiency of pressure vessels and steam components, and promote hydrogen as a versatile, sustainable, clean fuel.

Planned Collaboration with ORNL

Task 22 - Obtaining Hydrogen-Resistant Superalloys with Large-Area Wire-Arc Additive Manufacturing (WAAM)

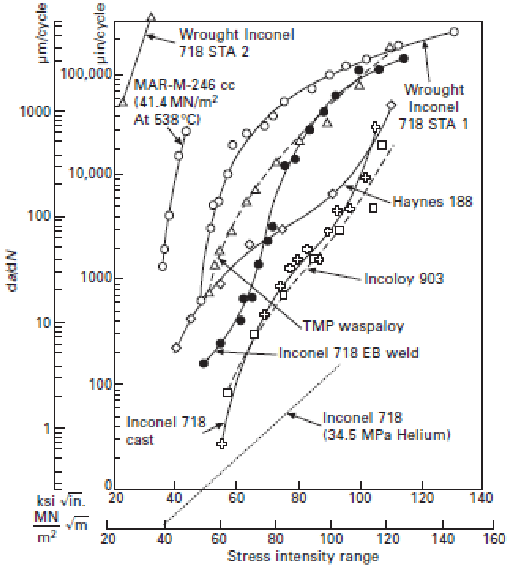
NATIONAL ENERGY TECHNOLOGY LABORATORY

Task Motivation

- **Cost-effective manufacturing and performance optimization of thick wall components** for combined cycle power plants and higher efficiency advanced energy systems
  - Haynes 282 has target use for 760°C operation or higher and thick wall components
  - Potential to reduce production times & material scrap; Increase shape complexity
- WAAM likely produces less than optimal structure for hydrogen resistance

Impact of Product Form

HE cyclic crack growth rate



Gaseous HE of materials in energy technologies, Chapter 17, Lee (2012)

Task Objectives

- Investigate improving hydrogen resistance of WAAM superalloy candidate(s) through in-situ processing, alloy feedstock modification, and/or heat treatment optimization

Task Goals

- Establish baseline manufacturing, microstructure, & properties of WAAM H282
- Screen hydrogen embrittlement (HE) mitigation strategies & select high impact strategies for full larger scale characterization and testing (Compare to cast and wrought counterparts)
- Utilize NETL's expanding wire drawing capabilities towards custom wire feedstock production

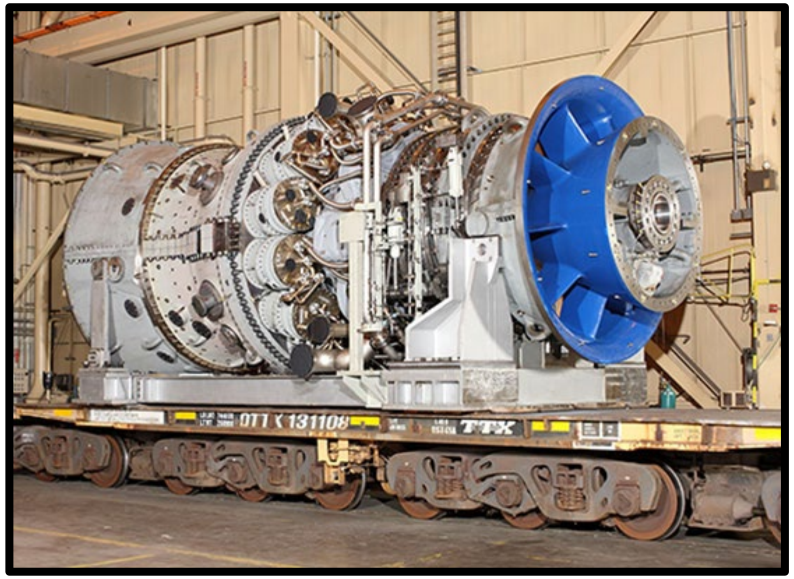
Planned Collaboration with ORNL

Task 23 - Transformational Alloys for Hydrogen Service

NATIONAL ENERGY TECHNOLOGY LABORATORY

Focus/Objective: >850 superalloys & beyond superalloys

- Next generation turbines for power generation will be fired by hydrogen or hydrogen plus methane.
- Hot-gas path will be increased along the entire turbine system
- Alloys needed to transition to CMC sections, alloys with properties compatible to CMC



Focus/Objective: alloys that are resistant to hydrogen

- Designed using an ICME approach

Advanced Materials Development for Hydrogen Production and Energy Systems

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CONTACT:
Ömer Doğan, Technical Portfolio Lead
omer.dogan@netl.doe.gov