AMM
Advanced Methods for Manufacturing

DEC 2 – 3, 2020

Irradiation studies on electron beam welded PM-HIP pressure vessel steel

Award Number: *DE-NE0008907*

Award Dates: *10/01/2019 to 09/30/2026*

PI: *Janelle P. Wharry (Purdue University)*

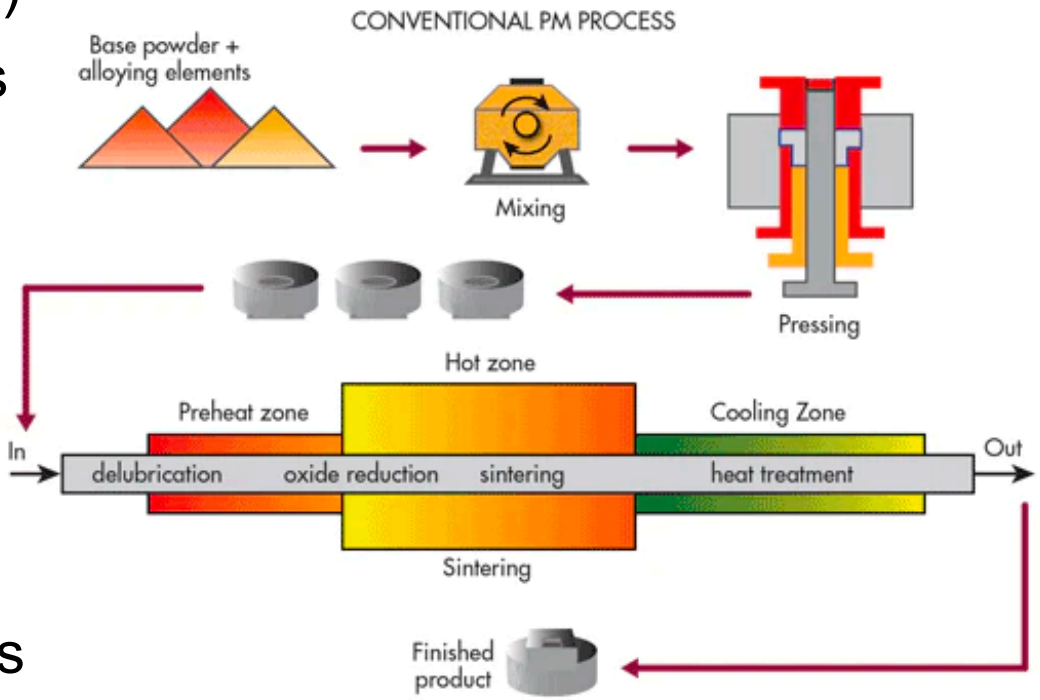
Team Members: *David W. Gandy (EPRI), Will Kyffin (Nuclear AMRC), Thomas Dutieleull (Nuclear AMRC)*

Project Objectives

- Assess the structural and mechanical integrity of electron beam weldments on pressure vessel steel under service-relevant irradiation conditions

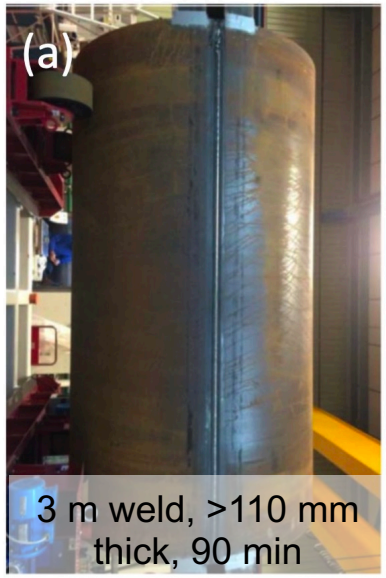
Powder Metallurgy with Hot Isostatic Pressing (PM-HIP)

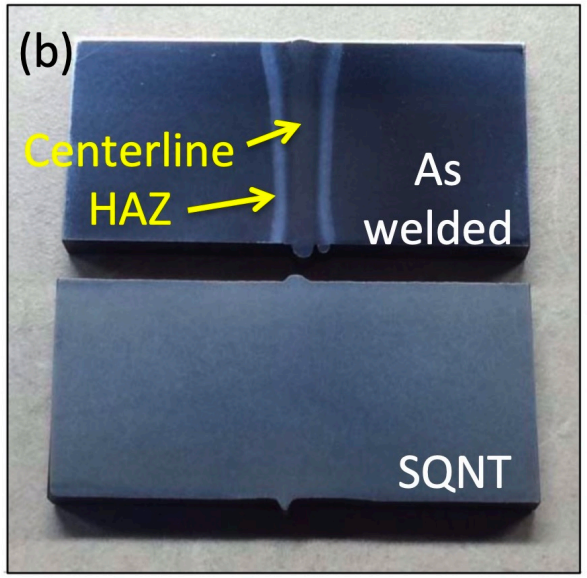
- Powder consolidation ~1000-1200°C (i.e. <T_M)
- Slow cooling eliminates local thermal stresses typical of casting or forging
- Homogeneous microstructures
- Near-net shape production
- Enhanced weldability and inspectability
- Alternative supply routes – domestic manufacturing
- Can reduce or eliminate dissimilar metal welds

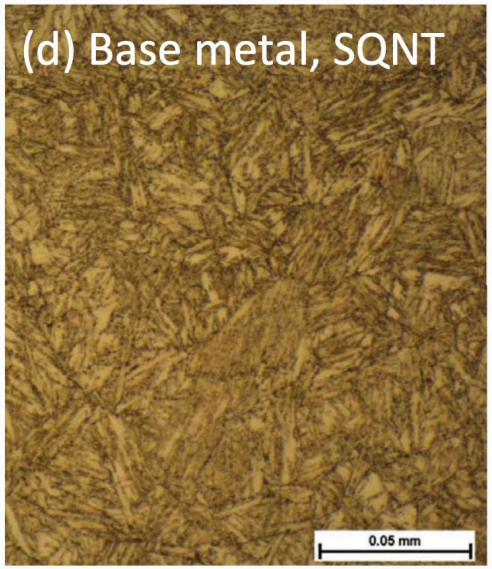


Electron Beam Welding

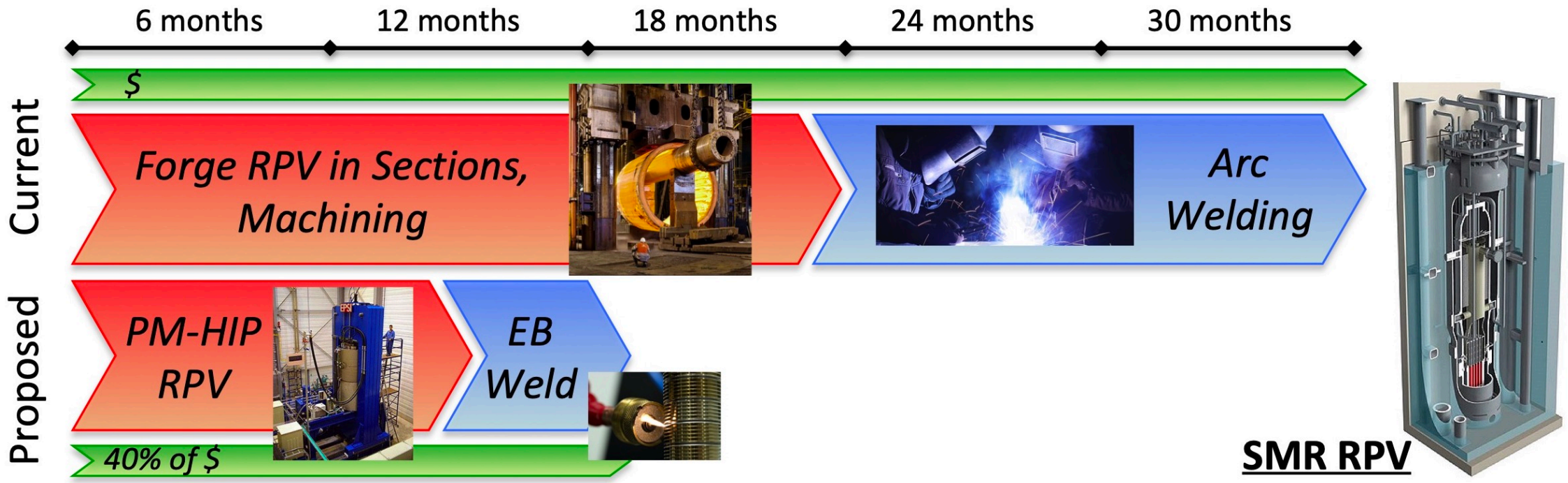
- Fusion welding using high-energy e^- beam
- Typically performed under vacuum
  - Minimize tramp element pickup
- Narrow, high intensity electron beams
  - Rapid heating and cooling
  - Localized welds, narrow HAZ
  - Weld centerline microstructures consistent with base metal
- High speed, low cost
  - Only one weld pass
  - Autogenous
  - Field deployable



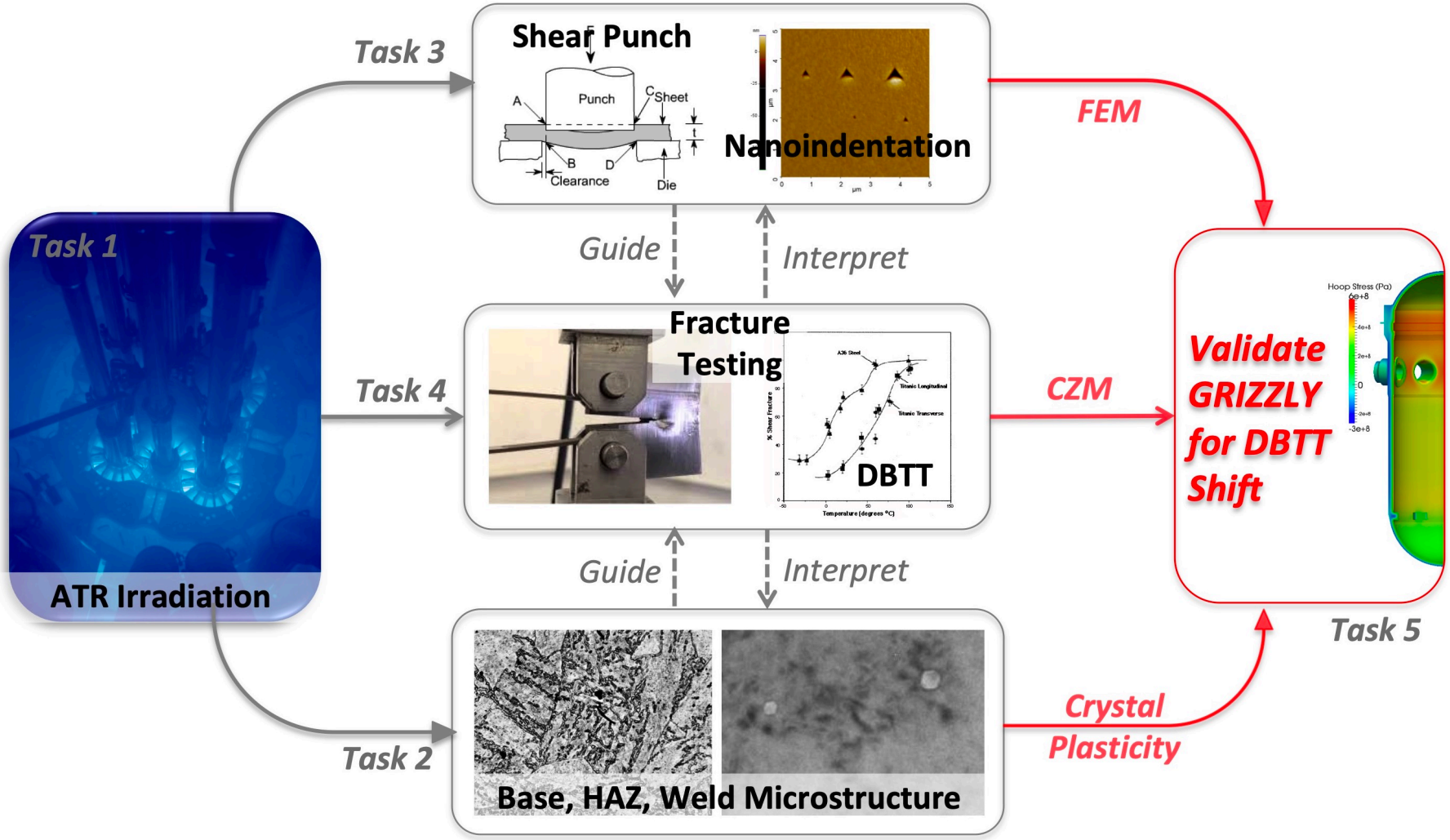




Why Combine PM-HIP with EB Welding?



Project Tasks



Experiment Matrix

Processing	Region	Heat treatment	No. of mini CTs	No. of TEM discs
PM-HIP	Base	none (as-consolidated)	10	6
PM-HIP	Base	PWHT	10*	6*
PM-HIP	Centerline	PWHT	10	6
PM-HIP	HAZ	PWHT	10	6
PM-HIP	Base	SQNT	10*	6*
PM-HIP	Centerline	SQNT	10	6
PM-HIP	HAZ	SQNT	10	6
Forging	Base	PWHT	10	6*
Forging	Centerline	PWHT	10	6
Forging	HAZ	PWHT	10	6
Total	-	-	100	60

Project Tasks

- 1 – Materials Preparation and Irradiation
  - Fabricate a set of electron beam (EB) welded pressure vessel steels with post-weld heat treatment (PWHT) or solution anneal, quench, normalization, tempering (SQNT) treatment
  - Irradiate in Advanced Test Reactor (ATR) to service-relevant conditions (~0.25 dpa, ~300°C)
- 2– Microstructural Characterization
  - Establish a multiscale understanding of irradiation effects on microstructure across the weldment [base metal + heat affected zone (HAZ) + weld centerline]
  - Determine whether the irradiated microstructure evolution is comparable across the weldment, and between the PM-HIP and forging [SEM, TEM, APT]
- 3 – Mechanical Testing
  - Carry out quantitative mechanical testing to rapidly evaluate irradiation effects on elastic properties and hardness [nanoindentation, shear punch testing]
  - Establish whether fundamental mechanical properties are comparable across the weldment, and between the PM-HIP and forging
- 4 – Fracture Testing & DBTT Curves
  - Carry out fracture toughness testing of irradiated miniature CT specimens to determine quantitative fracture toughness, qualitative fracture mode, and irradiation-induced ductile-to-brittle transition temperature (DBTT) shift
  - Results will contribute to ASME BPVC code case development
- 5 – Multiscale Validation of GRIZZLY DBTT Predictive Model
  - Validate the GRIZZLY multiscale, mechanistic models of embrittlement of pressure vessel steels and their weldments, using experimental results
  - Shed light on microstructural underpinnings of fracture toughness, while validating an industry-relevant predictive tool for DBTT shifts over reactor lifetimes

Technical Progress/Accomplishments – FY20

- 1 – Materials Preparation and Irradiation
  - Fabricate a set of electron beam (EB) w… solution anneal, quench, normalization, te…
  - Irradiate in Advanced Test Reactor (ATR) to s…
- 2– Microstructural Characterization
  - Establish a multiscale understanding of irradiation e… heat affected zone (HAZ) + weld centerline]
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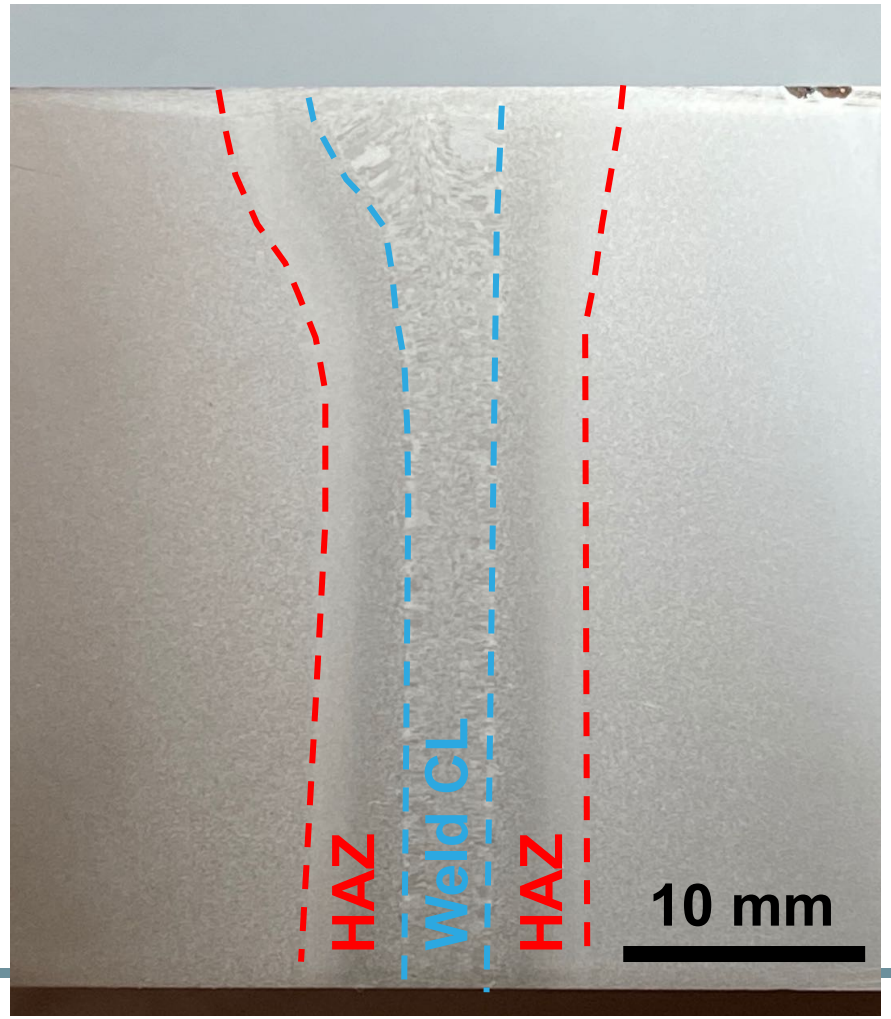
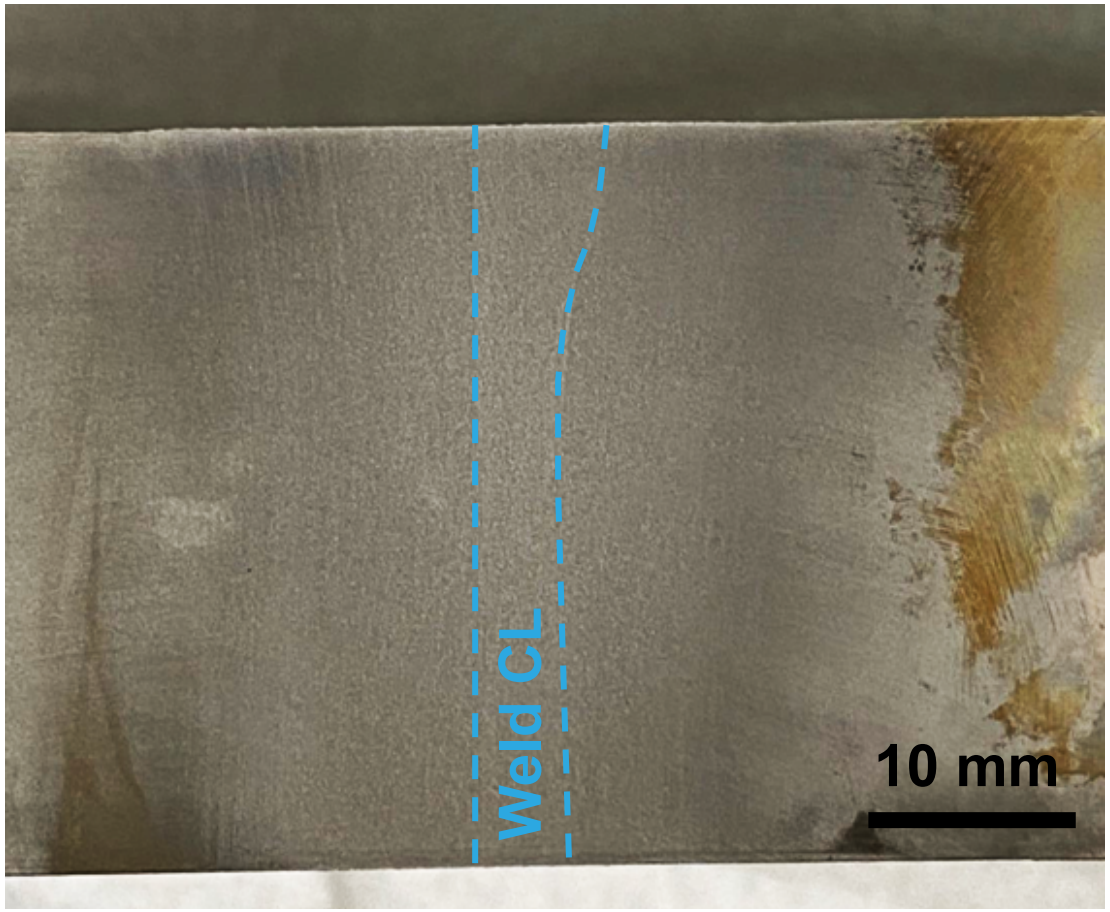
- Alloys fabricated; PWHT and SQNT completed
- Specimen machining in progress
  - INL will be cutting the miniature CTs, and they will be ready to ship to INL next week
  - Will then pre-crack at external vendor
- ATR ATR Final Design Review completed August 2020

Technical Progress/Accomplishments

HIP + Weld + PWHT



HIP + Weld + SQNT



Project Impacts

- No publications or presentations yet

Milestones and Deliverables for FY-20

	MILESTONE	Year 1				Year 2				Year 3				Year 4				Year 5			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Task 1	1.1: Irradiation capsule design and sample preparation																				
	1.2: Dimensional qualification of samples, load samples into capsules																				
	1.3: Carry out ATR neutron irradiations																				
	1.4: Disassemble capsules, ship samples to PIE facilities																				
Task 2	2.1: SEM/TEM microstructure characterization of unirradiated samples																				
	2.2: SEM/TEM microstructure characterization of irradiated samples																				
	2.3: APT nanostructure characterization of irradiated samples																				
Task 3	3.1: Shear punch testing of unirradiated samples																				
	3.2: Nanoindentation of unirradiated samples																				
	3.3: Shear punch testing of irradiated samples																				
	3.4: Nanoindentation of irradiated samples																				
Task 4	4.1: Fracture testing of unirradiated samples																				
	4.2: Fracture testing of irradiated samples																				
	4.3: Fracture surface examination by SEM																				
Task 5	5.1: Validate GRIZZLY CZM for unirradiated samples																				
	5.2: Validate GRIZZLY CZM for irradiated samples																				
	5.3: Validate GRIZZLY crystal plasticity model based on microstructure																				

Location of work:
- ATR
- CAES/IMCL
- Westinghouse
- Purdue

- Original proposal was 5 years; extended to 7 years upon award
- COVID-19 shutdown at Nuclear AMRC slowed alloy fabrication by ~2-3 months, but little impact on overall timeline

Issues and Concerns

- If specimen machining can proceed without too much delay at INL, and precracking can proceed without much delay, should be able to meet ATR insertion timeline (Summer 2021)

Milestones and Deliverables for FY-21

- Complete specimen fabrication
- Insert specimens into ATR
- Conduct initial characterization of weld cross-sections
  - SEM
  - Nanoindentation
  - Possible TEM

Possible Areas/Industries/Programs (and Readiness) for Adoption

- Small Modular Reactor (SMR) manufacturing – especially pressure vessels
- NuScale working with EPRI on pressure vessel manufacturing
- Estimated Technology Readiness Level (TRL) ~4.5

Contact Information and Questions

Janelle Wharry

Associate Professor, Materials Engineering

Purdue University

jwharry@purdue.edu