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

Award Number: DE-NE0008907
Award Dates: 10/01/2019 to 09/30/2026
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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

3 m weld, >110 mm thick, 90 min
Why Combine PM-HIP with EB Welding?

Current:
- Forge RPV in Sections, Machining
- 6 months
- 12 months
- 18 months
- 24 months
- 30 months

Proposed:
- PM-HIP RPV
- 40% of $  
- EB Weld
- Arc Welding
- SMR RPV
Project Tasks

Task 1: ATR Irradiation

Task 2: Base, HAZ, Weld Microstructure

Task 3: Shear Punch, Nanoindentation

Task 4: Fracture Testing, DBTT

Task 5: Validate GRIZZLY for DBTT Shift

Guide, Interpret

FEM, CZM

Crystal Plasticity
## Experiment Matrix

<table>
<thead>
<tr>
<th>Processing</th>
<th>Region</th>
<th>Heat treatment</th>
<th>No. of mini CTs</th>
<th>No. of TEM discs</th>
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</thead>
<tbody>
<tr>
<td>PM-HIP</td>
<td>Base</td>
<td>none (as-consolidated)</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>PM-HIP</td>
<td>Base</td>
<td>PWHT</td>
<td>10*</td>
<td>6*</td>
</tr>
<tr>
<td>PM-HIP</td>
<td>Centerline</td>
<td>PWHT</td>
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<td>6</td>
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<tr>
<td>PM-HIP</td>
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<td>PM-HIP</td>
<td>Base</td>
<td>SQNT</td>
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<td>Forging</td>
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<tr>
<td>Total</td>
<td>-</td>
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</table>
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

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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

<table>
<thead>
<tr>
<th>MILESTONE</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
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- 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

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