Low Cost HIP Fabrication of Advanced Power Cycle Components and PM/Wrought Inconel 740H Weld Development

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Background & Motivation

High capital costs offset efficiency gains using $\gamma'$ strengthened Ni-based superalloys in AUSC components

- Limited supply chain of large components using cast or wrought IN740H or HA282
- Extensive machining of complex features
- Technical difficulties in sand casting thick walls or complex shapes

Alternative manufacturing modality for cost reduction
Powder Metallurgy (PM) Near-Net-Shape (NNS) Hot Isostatic Pressing (HIP)

- Reduced 2~3X volume of material vs wrought
- Reduced machining costs
- Reduce welds & weld repair
- Chemical & structural homogeneity
- Ultrasound inspectability

(prior SUNSHOT project: HA282 sand casting trial for turbine case)

Objectives & Impacts

Objectives
• Demonstrate NNS HIP feasibility by a prototype pipe elbow using IN740H powder
• Develop PM/wrought IN740H welding procedure and evaluate microstructure, properties
• Deliver technoeconomic analysis of IN740H NNS HIP components for AUSC power plants

Technical Approach
• Dimension control by accurate design of HIP tooling via modeling non-uniform shrinkage
• HIP cycle and powder size distribution studies to show a clear path for property improvement
• PM/wrought IN740H cross weld microstructure/property evaluations

Anticipated Benefits & Impacts
• 50% cost reduction in manufacturing large components for AUSC power plant
• US manufacturing supply chain for NNS HIP
Pipe Elbow HIP Tooling Design

Schedule 160 pipe elbow, nominal size #8 (OD 8.6”, ID 6.8”, wall 0.9”, center to end 12”)

- HIP densification and shrinkage modeled with the goal of achieving net shape at interior surface
- HIP tooling for pipe elbow designed based on HIP model results
Pipe Elbow NNS HIP Fabrication

- No linear defects by ultrasonic inspection; OD surface roughness 125 RMS; ID surface roughness > 63 RMS
- OD positive stock 0.1~0.22”; ID 0.04” deviation → “net shape” achieved at ID, HIP model validated
• A PM HIP to wrought IN740H welding procedure on 1” thick plates has been successfully qualified to ASME section IX.

• RT cross weld tensile properties pass yield stress > 90ksi, ultimate tensile strength > 150ksi, with reasonable elongation >12%. RT side bend tests pass a 4T minimum bend radius.
PM/Wrought IN740H Weld Development

<table>
<thead>
<tr>
<th>Test I.D.</th>
<th>Weld Process</th>
<th>Weld Filler</th>
<th>Pre-Weld</th>
<th>Post-Weld</th>
<th>0.2% YS (Ksi)</th>
<th>UTS (Ksi)</th>
<th>Elong. (%)</th>
<th>ROA (%)</th>
<th>Failure Location</th>
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<tbody>
<tr>
<td>RTE509711001</td>
<td>GTAW</td>
<td>740H</td>
<td>SA</td>
<td>AG</td>
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<td>162.8</td>
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<td>23.2</td>
<td>Weld</td>
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<td>740H</td>
<td>SA</td>
<td>AG</td>
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<td>162.7</td>
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<td>SA+AG</td>
<td>AG</td>
<td>113.2</td>
<td>146.9</td>
<td>12.2</td>
<td>21.2</td>
<td>Weld</td>
</tr>
<tr>
<td>RTE509811002</td>
<td>SMAW</td>
<td>263</td>
<td>SA+AG</td>
<td>AG</td>
<td>112.3</td>
<td>149.4</td>
<td>13.8</td>
<td>25.6</td>
<td>Weld</td>
</tr>
</tbody>
</table>

- Different weld process, weld filler material, pre-weld heat treatment condition all show good cross-weld tensile properties and side bend test results
- Low risk of thermally induced argon porosity in HAZ or weld (small amount, size within ASME limits)
Prior Particle Boundary (PPB) Particles

• Discrete particles decorating PPB: Nb, Ti rich carbides/carbonitrides and Al rich oxides
• PPB particles effectively pin grain boundary migration, control grain size, influence mechanical properties
Pre-soak Heat Treatments Prior to HIP

- Pre-soak heat treatment applied before HIP to coarsen PPB particles and grain size

Zener Pinning

\[ P_s = 3F_v \gamma / 2r \]

- Particle pinning pressure
- Particle volume fraction
- Boundary of energy per unit area
- Particle radius

Pre-soak time increases
HIP and Pre-soak Heat Treatments

- Grain size distribution measured by EBSD
- Higher pre-soak temperature and time yields larger grain size and wider grain size distribution
Powder Size Distribution

- 5 PSD generated by blending -100 mesh and +100 mesh powder in various fractions
- Powder oxygen varies from 100ppm in fine powder to 55ppm in coarse powder
- Grain size distribution becomes wider and shifts to larger size with increased coarse powder
Effect of Pre-soak HT and PSD on Grain Size

- PSD is not as effective as pre-soak heat treatment to coarsen grain size
- Multiple methods for migrating grain boundaries beyond PPBs (HIP temperature, pre-soak, higher solution temperature) require optimization and avoid thermally induced porosity
Preliminary Tensile Properties

5 Processing conditions

1) Baseline 2200°F HIP with baseline solution and aging: 2200°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hr/AC

2) Higher temperature 2240°F HIP with baseline solution and aging: 2240°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hr/AC

3) 2nd HIP after higher solution: 2200°F/15ksi/3hr HIP + 2250°F/1hr/WQ + 2050°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hrs/AC

4) Higher temperature 2240°F HIP with higher solution and normal aging: 2240°F/15ksi/4hr HIP + 2250°F/1hr/WQ + 1472°F/4hr/AC

5) Pre-soak heat treatment before HIP: pre-soak HT + 2200°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hr/AC

- PM HIP IN740H with processing conditions #1~4 shows higher yield stress than wrought IN740H (likely due to finer grain size)

- Pre-soak before HIP (condition #5) with 32um average grain size and wide distribution shows comparable yield stress as wrought IN740H
Preliminary Tensile Properties

- PM HIP IN740H shows ~10ksi higher UTS at room temperature, comparable UTS at 1292F as wrought IN740H
- Lower tensile ductility than wrought IN740H (likely due to PPB)
• Current data show more than -30% debit in creep stress capability
• Higher solution temperature improves creep, but may result in thermally induced porosity
• No improvement with higher HIP temperature
Preliminary Creep Evaluation

- Creep damages of cavitation and micro-cracking form and progress along PPBs normal to loading direction
**Market Gap**

Challenge to make large ID pipe fittings (tees, wyes) by hot forging or cold hydroforming

- Excessive waste of material and machining from a forged cylinder

**Pipe fitting components considered for cost analysis:**

- 20” elbow (large envelop size)
- 20” tee (more complicated geometry)

- **Powder cost is the key driver for overall costs and more dominant for thicker wall**
- Breakdown cost of each processing step is confirmed by actual cost on the small elbow and quotes from US manufacturers
**Technoeconomic Analysis**

- **Cost-performance analysis:** wall thickness considered from -40% creep capability to wrought IN740H creep capability
- **NNS HIP still shows a significant cost benefit for all wall thicknesses, confirming that >50% cost saving with slight creep improvement is highly achievable**
Technoeconomic Analysis

Pipe Fitting Components by NNS HIP

- Tee, Wye, elbow, nipolet, reducer

LCOE Benefit

- Two USC (600/630 °C) reference plants (600 & 1080MWe): over 130 pipe fittings
- A-USC (>620/630 °C) reduced piping concept: over 80 pipe fittings
- Conservative estimation on only elbows, tees:
  - Over $48/kW reduction in CAPEX for AUSC (Over $13MM per plant)
  - Over $58/kW reduction in CAPEX for USC (Over $39MM per plant)

Summary of the cost savings for NNS HIP piping components

<table>
<thead>
<tr>
<th></th>
<th>Elbows</th>
<th>Tees (Wyes)</th>
<th>Raw Savings</th>
<th>Savings ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USC (660MWe)</td>
<td>88</td>
<td>22</td>
<td>39,589,755</td>
<td>$58.5</td>
</tr>
<tr>
<td>AUSC (250 MWe)</td>
<td>39</td>
<td>12</td>
<td>13,033,978</td>
<td>$48.1</td>
</tr>
</tbody>
</table>
Summary

• Demonstrated feasibility of NNS HIP in IN740H on AUSC pipe fitting components
  • Net shape at inner diameter of pipe elbow achieved
  • HIP model prediction validated
  • PM/wrought GTAW welding procedure qualified
  • Promising tensile properties established

• Applicability of NNS HIP manufacturing to Fossil Energy
  • Cost saving for manufacturing large, complex components in Ni-based alloys for AUSC

• Recommended Future Work (Beyond Phase 1 Project)
  - Creep and ductility improvement by processing optimization
  - ASME code case
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