Characterization of INCONEL alloy 740H for Tube, Pipe and Fittings for Advanced-Supercritical CO$_2$ Systems

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Special Metals Corporation
Presentation Outline

• Background – 740H and A-USC
• Metallurgy and Microstructure
• Mill Product Forms and Properties
• Welded Tube
• Fittings and Pipe Bends
• Welding
• Fabrication Experiences
• Where are we now?
Background

- Advanced-USC Programs in Europe and USA
- Service Conditions in USA: 760°C (1400°F), 35MPa (5,076 Psi)
- Creep-Rupture: >100 MPa (14.5 Ks) in 100,000 hr
- Corrosion: <2 mm in 200,000 hr (in coal ash)
- Other attributes: weldability, fabricability, phase stability, damage tolerance, manufacturability
- Modification of an alloy used for gas turbine ducts
- 740H specifically designed for A-USC
- Characterized under many DOE led programs

Nominal Composition of 740H

<table>
<thead>
<tr>
<th>Cr</th>
<th>Co</th>
<th>Mo</th>
<th>Al</th>
<th>Ti</th>
<th>Nb</th>
<th>C</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.5</td>
<td>20</td>
<td>0.5</td>
<td>1.4</td>
<td>1.4</td>
<td>1.5</td>
<td>0.03</td>
<td>Bal</td>
</tr>
</tbody>
</table>

Creep-Rupture Properties of Boiler Materials
Metallurgy and Microstructure

- $\gamma'$ (Ni$_3$M) strengthened by Al, Ti, Nb
- Composition balanced to avoid TCP phases and solidification segregation
- VIM melt and ESR or VAR remelt
- Ingots, 7,000-30,000lb
- Batch process to customer order
- Heat treat: Solution anneal $>1100^\circ$C (2012°F) + age harden 760-816°C (1400-1500°F) 4hr
- Hardness: SA - Rb 85; SA+A Rc 35
- Mill Products: Tube, Pipe, Bar, Sheet, Plate, Weld wire

Optical Micro: Only Carbides Visible

SEM: Grain Boundary Carbides and $\gamma'$ (Xie)

TEM: Reveals $\gamma'$ Structure (Xie)
US A-USC Consortium

• DOE, EIO, EPRI
• Babcock & Wilcox, Foster Wheeler, Riley, Alstom, GE
• Material & Component Supply Chain
  • ORNL, NETL Albany
• ASME Code Design Stress Allowables
  • 740H first age hardened alloy in 2011
• Current Plan of AUSC
  • Demonstrate manufacturing of full scale components

Illustration of minimum wall thickness at constant flow and pressure
sCO$_2$ Systems

- How different
  - No coal ash or steam but other environments such as sCO$_2$, salt
  - Lower pressure
  - Smaller but still big and complex
  - Many systems with different requirements
    - Solar receiver
    - Thermal reservoir
    - Gas fired heater
    - Heat exchanger
    - Transfer piping
    - Valves
    - Turbine components

6th International Supercritical CO2 Power Cycles Symposium
March 27-29, Pittsburgh, Pennsylvania
Tubular Product Sizes

• Cold Worked Tube
  • Extruded, cold drawn or pilgered, heat treated
  • Similar to other “hard” Ni-base alloys

• Extruded Pipe
  • Heavier wall, extruded and heat treated

• Other Tubulars
  • Drilled rods (for short lengths)
  • Roll formed hollows (large diameter/thin wall)
Tube and Pipe Properties

• As Solution Annealed
  • Preferred where bending or flaring will be done
  • Certified with capability heat treatment
  • No defined tensile limits at present
  • Material must be reannealed after bending

• Fully Heat Treated ASME min Tensile
  • YS: 90 Ksi (620 MPa)
  • TS: 150 Ksi (1035 MPa)
  • El in 2”: 20%
Microstructure Stability

• PhaComp Simulation
  • Predicts only γ’ between 650-892°C (1202-1638°F)

• Previous studies on Experimental Material
  • Loss of Toughness in first 1000hr exposure. Gradual recovery after that

• Recent work on boiler tube, 10,000 hr, unstressed exposure at 750°C (1382°F)
  • Room temp
  • 750°C

Annealed & Aged (Xie)

After 10,000 hr Exposure at 750°C (Xie)
Welded Tube Manufacturing

• **Manufacturing Process**
  • **Advantages for small diameter, thin-wall tube**
    • Production cost and time
    • Potential production volume
    • Accepted for molten salt solar receiver (230,625)

• **Issues**
  • Continuous linear structural anomaly
  • No treatment for creep range design in ASME
  • Conflicts with current ASME Code restrictions for 740H

• **First manufacturing demonstration**
  • 0.065” (1.6 mm) thick x 3.02” (76 mm) wide coiled strip
  • 2” (50 mm) dia tube made at RathGibson Tube
Welded Tube Microstructure and Properties

- In-line flash anneal at 1950°F (1066°C)
- Continuous offline re-anneal at 2075°F (1135°C)
- Static Age at 800°C (1472°F)
- Properties consistent with seamless
  - Flare, Flattening, Bend
- Re-annealed weld substantially recrystallized

<table>
<thead>
<tr>
<th>Item</th>
<th>Heat Treatment</th>
<th>Sample</th>
<th>0.2% Offset Yield Strength, ksi(MPa)</th>
<th>Tensile Strength, ksi(MPa)</th>
<th>% Elongation</th>
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</thead>
<tbody>
<tr>
<td>Welded Tube</td>
<td>In-line anneal 1950°F (1066°C)</td>
<td>1</td>
<td>65 (448)</td>
<td>126 (869)</td>
<td>55</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>73 (503)</td>
<td>125 (862)</td>
<td>54</td>
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<tr>
<td>Welded Tube</td>
<td>Cont. Reanneal 2075°F (1135°C)</td>
<td>1</td>
<td>71 (490)</td>
<td>130 (896)</td>
<td>50</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>71 (490)</td>
<td>131 (903)</td>
<td>60</td>
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<tr>
<td>Welded Tube</td>
<td>Reanneal + Static Age</td>
<td>1</td>
<td>110 (758)</td>
<td>168 (1159)</td>
<td>37</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>116 (800)</td>
<td>171 (1179)</td>
<td>34</td>
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<tr>
<td>Seamless Tube*</td>
<td>Cont. Ann 2075°F (1135°C)</td>
<td>1</td>
<td>72 (496)</td>
<td>139 (958)</td>
<td>56</td>
</tr>
<tr>
<td>Seamless Tube*</td>
<td>Cont. Ann + Static Age</td>
<td>1</td>
<td>123 (848)</td>
<td>177 (1220)</td>
<td>43</td>
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<tr>
<td>0.065&quot; Sheet</td>
<td>Continuous Ann 2025°F (1107°C)</td>
<td>1</td>
<td>72 (496)</td>
<td>139 (958)</td>
<td>47</td>
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<tr>
<td></td>
<td>Cont. Ann + Static Age</td>
<td>1</td>
<td>124 (855)</td>
<td>177 (1220)</td>
<td>30</td>
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<tr>
<td>ASME Min</td>
<td></td>
<td></td>
<td>90 (620)</td>
<td>150 (1035)</td>
<td>20</td>
</tr>
</tbody>
</table>

* 0.84 in (21.3 mm) OD x 0.11 in (2.74 mm) W
Age hardening treatment 4 hr at 1472°F (800°C)
• Wide variety of fittings, bolts and valves needed
• Not now available from supplier stock
• Demonstrations at shops with experience in 625
  • Flange made by hammer forging at Maass Flange from 4” bar
  • Elbow by press forge at CB&I APP from 8” pipe
  • Concentric reducer by cold pressing at CB&I
  • Tee by cold hydroforming at CB&I
  • Parts formed with minimal cracking
• Heavy wall rolled ring made at Carlton Forge
  • Application for gas and sCO₂ turbine components
  • Upset press forged from 11” dia. bar
  • Punch center
  • Roll to 34” OD x 25” ID x 6.5” L
Fittings Properties

- All Fittings Surveyed
  - Grain size
  - Hardness
  - Microstructure
  - Room Temp Tensile and Impact at Selected Locations

- Mechanical Properties
  - Exceed ASME mins
  - Variability, process not optimized

- Very Large Fittings
  - Subject to Auto-aging (Wye, Valve body)
  - Demonstration in A-USC ComTest Project in 2018-19
  - Machinability Testing
  - Creep and Fatigue Testing
Tube and Pipe Bends

• Tube Bending
  • Annealed condition recommended
  • Shingledecker Study with pressurized creep test
  • Re-anneal Required

• Pipe Bending
  • Hot Induction Bending
  • 2.87 – 12.75” OD
  • 90° Bends demonstrated
  • Tensile properties exceed ASME mins

<table>
<thead>
<tr>
<th>Pipe OD, in (mm)</th>
<th>Pipe Wall, in/mm</th>
<th>Location</th>
<th>0.2% Offset YS, ksi (MPa)</th>
<th>Tensile Strength, ksi (MPa)</th>
<th>Elongation, %</th>
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<tbody>
<tr>
<td>2.87 (73)</td>
<td>0.55 (14)</td>
<td>Extrados</td>
<td>102 (704)</td>
<td>163 (1121)</td>
<td>42</td>
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<tr>
<td></td>
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<td>Intrados</td>
<td>103 (707)</td>
<td>163 (1121)</td>
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<tr>
<td>5.25 (133)</td>
<td>0.75 (19)</td>
<td>Extrados</td>
<td>104 (717)</td>
<td>162 (1117)</td>
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<td>Intrados</td>
<td>108 (745)</td>
<td>164 (1131)</td>
<td>37</td>
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<tr>
<td>ASME Min</td>
<td></td>
<td></td>
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Heat treatment: Solution Anneal 2100°F (1149°C) + Age 1425°F (774°C)
Welding 740H to Itself

• “Different, but not Difficult”: Sam Kiser
  • Low heat input, bead shape, avoid oxide buildup

• Applicable Methods
  • GTAW, GMAW with matching filler
  • SMAW with 263, qualification testing underway
  • SAW unlikely

• Heat treatment
  • PWHT same as 740H aging treatment
  • Re-anneal qualification testing underway

• Properties
  • Tensile (similar to base metal)
  • 4T Bend specified
  • Creep: WJSRF of 70%
  • Good microstructure stability of weld metal

Header Mockup, Girth
Welding done at Babcock & Wilcox
Welding 740H to Other Alloys

- 740H Used only where Essential
- Alloys Joined
  - P92, P92, 304, 316H, 347, 617, 282
- Filler Metals
  - FM82, WE 182 (Ni-Cr-Mn-Fe-Nb)
  - 617, 282
- Considerations
  - Design PWHT to match requirements of both alloys
- Doosan Experience

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Where Are We Now: What remains to be Done

• Age-hardened nickel-base alloys are new to power piping industry but not to alloy producers

• Manufacturing Mill Products
  • All forms demonstrated and characterized
  • Some size limits
  • Currently TRL 8
  • Needs a full commercial plant order to bring to TRL 9

• Manufacturing Components and Fabricating Systems
  • Basic procedures demonstrated
  • Code enhancements needed for flexibility
  • All welding by specialists so far
  • Forging and machining experience is limited
  • Currently TRL 6
  • Projects underway will bring to TRL 8

• Systems
  • Very limited experience at pilot plant level
  • No experience with damage detection or repair
  • Currently TRL 4

• Sharing of fabrication experiences and data will help to advance technology
Acknowledgements

• Dave O’Donnell – RathGibson
• Kenny Rowley – PCC Energy, now CB&I APP
• Ken Doughty – CB&I APP
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Blue Hole, Lighthouse Reef, Belize