INCONEL alloy 740H for High Temperature and High Pressure Power Applications

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Introduction

- **PCC organisation**
  - Manufacturing group

- **INCONEL alloy 740H**
  - High temp. properties
  - Corrosion resistance

- **Fabrication**
  - Project activity
  - Product supply
  - Welding
  - Stress Relaxation
  - Applications – Steam, uSCO₂

- **Summary**
Power Applications

- **Steam Cycle for improved efficiency**
  - 760C & 35MPa steam pressure
  - Large pipe, tube and valve structures
  - Reduced CO₂ emissions
  - Flexible plant

- **Ultra Super Critical CO₂**
  - 760C & 35 MPa CO₂ pressure
  - High plant efficiency
  - Compact design
  - Low water consumption
  - CCS compatible CO₂
Organisation

30,500 people
162 manufacturing sites
Acquired by Berkshire Hathaway in 2016
Single Integrated Solution

Vertically integrated, global manufacturer of metallic products and complementary technologies

MELT  FORM  FINISH

Portfolio of world-class brands delivering a fully integrated solution to the energy industry

- Special Metals
- TIMET
- Schulz Group
- RathGibson

- Wyman Gordon
- Hackney Ladish
- Rollmet
- Texas Honing

- Pipe & Tube
- Fittings
- Forgings
- Cladding

- Plate
- Bar
- Sheet
- Welding Wire
PCC Metals locations

- RathGibson – Janesville, WI
- TIMET – Toronto, OH
- SMC – Huntington, WV
- SMC – Burnaugh, KY
- SMC – Elkhart, IN
- TIMET – Henderson, NV
- Rollmet – Irvine, CA
- Hackney Ladish - Russelville, AR
- Hackney Ladish – Enid, OK
- Greenville Tube - Clarksville, AR
- THI – Pearland, TX
- SXP USA - Houston, TX
- Wyman Gordon – Houston, TX
- SMC – New Hartford, NY
- SMC – Dunkirk, NY
- RathGibson - North Branch, NJ
- TIMET – Morgantown, PA
- SMC - Hereford, England
- Timet, Witton, England
- Wyman Gordon - Livingston, Scotland
- Schulz - Krefeld, Germany
- SMC WASA – Canning Vale, Australia
- SXP USA – Tunica, MS
- SMC – Huntington, NY
History of INCONEL alloy 740H

- Advanced-USC fossil fuel Programs in Europe and USA
- Service Conditions in USA: 760°C (1400°F), 35MPa (5,076 Psi)
  - Creep-Rupture: >100 MPa (14.5 Ksi) in 100,000hr
  - Corrosion: <2 mm in 200,000 hr (in coal ash)
- Other attributes: weldability, fabricability, phase stability, damage tolerance, manufacturability
- 740H specifically designed for A-USC
- Characterized under many global R&D programs

```
Cr  Co  Mo  Al  Ti  Nb  C  Ni
24.5 20  0.5  1.4  1.4  1.5 0.03 Bal
```

Nominal Composition of 740H

Creep-Rupture Properties of Boiler Materials
Special Metals development of INCONEL alloy 740H

- Nickel-base alloy strengthened by precipitation of γ'
- High Cr and low Mo for fuel ash corrosion resistance
- Composition balanced to avoid TCP phases and solidification segregation
- Heat treat: Solution anneal >1100°C (2012°F) + age harden 760-816°C (1400-1500°F) 4hr
- 740H resistance to weld liquation cracking & stable

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Co</th>
<th>Al</th>
<th>Ti</th>
<th>Nb</th>
<th>Si</th>
<th>% γ' at 700°C</th>
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<tbody>
<tr>
<td>617</td>
<td>0.08</td>
<td>22</td>
<td>9</td>
<td>12</td>
<td>1.2</td>
<td>0.4</td>
<td>0.002B</td>
<td>0.1</td>
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<td>263</td>
<td>0.06</td>
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<td>6</td>
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<td>2.2</td>
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<tr>
<td>740</td>
<td>0.03</td>
<td>25</td>
<td>0.5</td>
<td>20</td>
<td>0.9</td>
<td>1.8</td>
<td>2</td>
<td>0.5</td>
<td>19</td>
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<tr>
<td>740H</td>
<td>0.03</td>
<td>25</td>
<td>0.5</td>
<td>20</td>
<td>1.4</td>
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<td>1.5</td>
<td>0.15</td>
<td>19</td>
</tr>
</tbody>
</table>

- Coal ash corrosion resistance
- Microstructure Stability
- Thick – section weldability

740, 10000hr @ 750°C

740H, 10000hr @ 750°C
Microstructural 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. Followed by gradual recovery
  - Unstressed exposure for 20,000hrs at 725°C (1382°F)
  - As received (Sln & Aged) – 68J and 39J exposed

740H Annealed & Aged
After 10,000 hr Exposure at 750°C
Very high steam oxidation resistance

Barry steam exposures for 17,000 hrs
All Nickel alloys showed low metal loss, very thin oxide scale and some internal degradation, no exfoliation

Depth of attack 800C with 10 % controlled water vapor air oxidation test
Excellent fuel ash corrosion resistance

Gas: N₂ - 15% CO₂ - 3.5% O₂ - 0.25% SO₂; Coating: [5% Na₂SO₄ - 5% K₂SO₄ - 90% (Fe₂O₃ - Al₂O₃ - SiO₂ in 1:1:1 ratio by weight)]

Demonstrated Excellent Stress Corrosion Cracking Resistance

- Laboratory and in-plant test loop experience shows alloy differences
- Alloys with high Mo content show accelerated pitting attack
DOE consortium- EIO, EPRI, Babcock & Wilcox, Foster Wheeler, Riley, Alstom, GE

ASME Code Design Stress Allowables
- 740H first age hardened alloy in 2011

Mechanical Property Evaluations
- Creep data exceeds 60,000hrs

Current Plan of AUSC
- Code improvements
- Demonstrate manufacturing of full scale components
Double steam line design for 617 & 740H compared with single design for 740H. Steam temperature 732/760°C (1350/1400°F)

<table>
<thead>
<tr>
<th>Pipe length</th>
<th>Pipe ID (mm)</th>
<th>MS Weight (kg/m)</th>
<th>HRH Weight (kg/m)</th>
<th>Weight (Tonnes)</th>
<th>Total Welds</th>
<th>Welding (hrs)</th>
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<tbody>
<tr>
<td>617(2)</td>
<td>97</td>
<td>249</td>
<td>467</td>
<td>361</td>
<td>34</td>
<td>50</td>
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<tr>
<td>740H(2)</td>
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<td>249</td>
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<td>180</td>
<td>29</td>
<td>37</td>
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<tr>
<td>740H(1)</td>
<td>69</td>
<td>353</td>
<td>660</td>
<td>180</td>
<td>20</td>
<td>19</td>
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</tbody>
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Specifications

- ASME
  - Section 1, Case 2702-3, (Original 26 Sept. 2011)
  - B31.1, Case 190, 12 Nov, 2012
  - B31.3, to be requested
  - B16.34 Valves, approved
  - ASME VIII to be requested
- ASTM
  - B983-13a, Tube and Pipe, 19 Nov. 2013
  - B637, Forgings,
  - B1007-17 Welded Tube,
  - Sheet, Plate products; ASTM documents pending
- AWS
  - A5.14-ERNiCrCo-1
Alloy 740H Strain LCF

- Strain LCF at 725°C
  - R=0 and R= -1, triangular, 6%/min.
- NIBALO725 fatigue, creep fatigue testing underway at 725, 750°C
- EPRI data at RT, 450C, 600C

Zhang & Takashi, CRIEPI
Evaluation of High Temperature Strength of a Ni-base alloy 740H for AUSC plant, Advances in materials technology for fossil power plants
Proceedings 7th international conference
October 22-25, 2013, Hawaii, USA
Extrusion of large pipe

- Large diameter heavy wall pipe required for steam transfer to the turbine of AUSC
- Feasibility demonstrations for 740H done at Wyman-Gordon, Houston TX
  - Used 825 mm dia., 8700 kg ingot
  - Established pipe extrusion process capability
  - Process size limit projected to be about 711 mm OD x 50 mm wt
  - Properties of heat-treated pipe met ASME code requirements with good weldability

378mm OD x 88mm W x 4.4m L alloy 740H pipe

Wyman Gordon 14KT blocking & 35KT extrusion press
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)

Smallest tube made at RathGibson
Cold Worked 323.8mm OD x 9mm wt

Pipe sizes made to date

Graphs showing wall thickness vs. outer diameter for tube and pipe sizes.
Wide variety of fittings, bolts and valves needed
- Made to order via supplier
- Demonstrations at shops with experience in 625
  - Flange made by hammer forging from 4” bar
  - Elbow by press forge at CB&I APP from 8” pipe
  - Concentric reducer by cold pressing
  - Tee by cold hydroforming
  - Parts formed with minimal cracking
- Heavy wall rolled ring made at Carlton Forge
  - Application for gas and sCO$_2$ turbine components
  - Upset press forged from 11” dia. bar
  - Punch center
  - Roll to 34” OD x 25” ID x 6.5” L
    (864mm OD x 635mm ID x 165mm wt)
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 (73mm – 324mm OD)
  - 90° 3D 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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<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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<tr>
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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>
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<td>20</td>
</tr>
</tbody>
</table>

Heat treatment: Solution Anneal 2100°F (1149°C) + Age 1425°F (774°C)
“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

Heat treatment
- PWHT same as 740H aging treatment

Properties
- Mechanicals similar to base, 4T Bend
- Creep: WJSRF of 70%
- Good microstructure stability of weld metal
- No Stress relief of liquation cracking

Header Mockup, Girth Welding done at Babcock & Wilcox
- Stress relaxation cracking in 617 pipe (COMTES)
- 740H has not cracked in restrained thick sections
- Borland test used by Special Metals to characterize sensitivity to longer term cracking
- Kang & Dupont ranked moderately susceptible
- PWHT reduces residual stress
Weld residual stress measurement using contour method

- Dr. F. Uzun & Prof A. Korsunsky
- Measure residual stress using contour method
  - As-welded and PWHT plate
  - Wire EDM, CMM coordinate measurement
  - Data analysis & FEM modelling
Fabrication of 2.5MW uSCO2 Heater by Thar Energy

- uSCO2 2.5MW microtube heater
- Recuperated Brayton Cycle
- Heater air – sCO2 HX – air @ 715C
- 6000m of 7mm OD tube with 1.5D cold bends
- 2.5” sch XXS manifold piping & 90° elbows in 740H
- 1.5D cold bending tube in the solution annealed condition
Dissimilar Welding INCONEL alloy 740H

- 740H used for efficiency gains, cost saving
- Alloys Joined
  - P91, P92, 304, 316H, 347, 617
  - FM82, WE 182 (Ni-Cr-Mn-Fe-Nb)
  - Stress relief compatible with steels
  - Design PWHT to match requirements of both alloys
- Doosan Transition Pipe

![Schematic of joint](image)

- 304 Fins resistance welded to 740H, Optimus, Chanute, KA

![Macro of weld joint](image)
Doosan transition piece design of P92/740H/316H Joint

- INCONEL 740H selection
- High Strength & Fatigue Resistance
- Stress relief P92 compatible with 740H
- Low COE
- Available in large pipe
- Qualification - DBA
  - Creep & mechanical tests
  - Stress relaxation
  - Fatigue data
  - DWM creep tests
  - FE Model
Summary: INCONEL alloy 740H

Nickel PH alloy developed for > 700C power plant applications

Characterised mechanical and corrosion properties

Developed welding & fabrication techniques for aged material

Manufactured components and fabricated systems

Coal, uSC02 and renewable power applications

Large scale forging and reheat pipe development planned