Nickel-Base Superalloys for Advanced Power Systems

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The 4th International Symposium – Supercritical CO₂ Power Cycles
September 9-10, 2014, Pittsburgh PA
Presentation Outline

- Superalloys – from Aerospace to Energy
- Mechanical Properties
- Microstructure Stability
- Corrosion Properties
- Manufacturing Mill Forms
- Fabrication
- What remains to be done?
Why Superalloys?

- **USC to A-USC**
  - 100/150°C temp Increase
  - Oxidation/corrosion rate increases significantly

- **Materials**
  - Ferritic Stainless Steel
  - Austenitic SS/Nickel-Base
  - Superalloys

- **Cost**

- **Availability**

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Superalloys = Age-Hardened Nickel Base Alloys

- Gamma prime (γ') Strengthened Alloys
  - Soft and ductile in annealed condition
  - Age-harden to increase strength
  - Ni₃(Al,Ti,Nb) precipitate
  - Cubic, coherent, sub-micron size
  - Stable at high temperature
- Phase diagram
- Adjust other elements for specific properties (Cr, Mo, Co)

<table>
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<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Co</th>
<th>Al</th>
<th>Ti</th>
<th>Nb</th>
<th>Si</th>
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<td>25</td>
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<td>25</td>
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<td>20</td>
<td>1.35</td>
<td>1.35</td>
<td>1.5</td>
<td>0.15</td>
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TEM Showing fine γ' particles (Xie)

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Tensile Properties

- ASME code requirement based on room temperature tensile test
- Impact and creep properties for information
- ASME minima
  - YS: 90 ksi (620 MPa)
  - TS: 150 ksi (1035 MPa)
  - EI: 20%

**Standard Heat Treatment for 740H**
- SA: 1100°C (min), 1 h/it, WQ
- AH: 800°C, 4 h (min) +, AC

Ambient and elevated temperature tensile properties of tube and pipe
Creep Properties

- US Consortium data generated at ORNL
- Recent data to 45,000 h
- Tests now running will exceed 100,000 h

Stress Rupture Data

Sample from shoulder, rupture in 1087.4 h at 750°C and 280 MPa

Sample from reduced section

Composite data from US Consortium and SMC Tests

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Microstructure

- Amount of $\gamma'$ decreases with increasing temp.
- Size of $\gamma'$ increases with time and Temp.
- Particles remain cubic
- Volume fraction and size affect strength

JMatPro prediction of $\gamma'$ volume

Rockwell C Hardness

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Microstructure Stability

- Isothermal stress-free aging studies conducted for 10,000 h
- No $\eta$-phase or G-phase detected

Thermo-Calc predicted equilibrium diagram for alloy 740H showing restricted stability for $\eta$-phase

$\eta$ range: 974-1003°C

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Impact Toughness

- As-aged, CVN ambient temp impact toughness high
- Initial drop possibly due to increased carbide coverage at grain boundary
- Toughness stabilizes after 1000 h
- Fracture path largely inter-granular after exposure
Oxidation and Corrosion

- Air Oxidation
- Steam Oxidation
- Coal Ash Corrosion
- Supercritical CO₂
- Metal Dusting
- Stress-Corrosion

Pit depth, base metal and matching weld metal. 1000 h at 750°C in simulated Chinese coal ash

Mass change in 50% H₂O-50% Air at 760°C

Pit depth after exposure in H₂O-20% CO₂ at 621°C
Manufacturing – Ingot Production

- Vacuum Induction Melting
  - Cleanliness, Composition Control
- Vacuum Arc Remelt
  - Cast Structure Control
- Large Ingots (27,000 lb/ 12,250 kg) have been produced

Head macro-etch slice of homogenized 750 mm diameter VAR ingot

<table>
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<th>Element</th>
<th>Edge</th>
<th>Mid-Radius</th>
<th>Center</th>
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<tr>
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Manufacturing Tube

- Forge bar, machine and trepan billet, extrude shell
- Pilger, draw or roll form tube
- Heat treat (SA vs SA + A)
- Sizes made:
  - 21.3 mm (0.83 in) OD x 2.7 mm (0.10 in) W to
  - 50.8 mm (2 in) OD x 8 mm (0.31 in W)
- Possible size range:
  - 12.7 mm (0.5 in) OD to
  - 280 mm (11 in) OD

Tube shell emerging from extrusion press

Finished, bundled tube

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Manufacturing Pipe

- Forge rod, cut mult, block & pierce, machine billet, vertical extrude
- Condition
- Heat-treat
- Sizes made:
  - 323 mm (12.7 in) OD x 22.5 mm (0.88 in) W and
  - 378 mm (14.8 in) OD x 88 mm (3.46 in) W
- Sizes possible:
  - 254 mm (10 in) OD x 25.4 mm (1.0 in) W to
  - 790 mm (31 in) OD x 63.5 mm (2.5 in) W
  - Many other OD/W combinations

Wyman-Gordon 15 kT blocking press and 35 kT extrusion press

378 mm (14.8 in) OD x 88 mm (3.5 in) W x 10 m (33 ft) L extruded 740H pipe
Tube and Pipe Bends

• Tube bending
  – Cold or hot
  – Cold workability similar to 625
  – If strain > 5%, assembly must be re-annealed
  – Bending in the aged condition is not recommended

• Pipe bending
  – Must be done hot (>1950°F) due to the high strength of the alloy
  – Induction bend to be demonstrated later this year
Small Forged Fittings

- Flanges, nipples, saddles, weldolets, reducers, tees and wyes
- Hammer or press forge
- Example weld-neck flange made at Maass Flange (Houston TX)
- Properties of heat-treated forging met ASME Code requirements
- More difficult shapes will be demonstrated in future

As-forged weld neck flange

Etched cross-section

Machined flange

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Large Forged Shapes

• Valve bodies, large wyes and tees, turbine casings and nozzle guide vanes
• Press forged or ring rolled
• Flow stress of 740H less than most superalloys
• Due to auto-aging, large forgings must be given spheroidizing treatment before machining
• Properties of heavy forged bar being determined

Peak compressive flow stress at strain rate of 1 sec⁻¹

CCT diagram simulated using JMatPro
Welding

- Welding has been a major focus for 740H development
- Procedures have been developed for GTAW and GMAW welding processes
- SMAW and SAW processes are not recommended due to low recovery of reactive (strengthening) elements
- ASME requires tube and pipe to be joined in aged condition. Welding in annealed condition is possible but not now code approved.
- Qualified welds have been made in material with wide range of thickness: 6.4 mm (0.25 in) to 88 mm (3.5 in)
- Best welding practices include control of shielding gas, close thermal management, control of bead geometry and interpass surface grinding
- ASME applies a WJSRF of 0.70 for longitudinal welds in creep limited applications.

HW/NG GTAW welding of 740H pipe
A-USC Header Pipe

- Simulated header made from 355 mm OD x 76 mm W pipe
- Hot-Wire Narrow-groove GTAW process for girth weld (at B&W)
- Nipples welded internally with rotary GTAW torch, externally with manual GTAW
- Stress relieved (aged) at 800°C using external ceramic heating blanket

Appearance of finished header pipe segment

Cross-section of pipe weld with 1 degree bevel

Weld metal after 10,000 h exposure at 700°C

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Stress Relaxation Cracking

- Delayed cracking is seen in many creep-resistant alloy welds
- Strain aging mechanism
- Partial mitigation via stress relief treatments
- Ramirez showed 740H is similar to 718 in gleeble simulations
- No stress relief cracking reported in any 740H restrained weldment
- SMC Borland Test studies
  - No Cracking in 5000 h at 700°C

Gleeble tests. Specimens preheated to 1250°C, cooled to RT, heated at 50°C/s to test temp. and static loaded to % UTS (Ramirez/EWI)

Appearance of Borland test soecimens of 617 and 740H after 5,000 h.

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Dissimilar Metal Welds

- 740H will only be used in the hottest section of the A-USC plant
- Welded to ferritic or austenitic steel
- Experimental welds made to P92 and 316SS with FM82 and EPRI P87 fillers
- Qualification testing completed (bends and tensile tests) with tensile failure in steel
What Remains to be Done?

• Wide range of tube and pipe made to code requirements
  – Refine manufacturing processes to reduce variability
  – Demonstrate 0.78 m OD pipe capability
• Excellent corrosion resistance in many environments
  – Generate data for more specific environments (Salt, CO2, Bio-mass)
• Fittings and forged components
  – Develop process and property data for representative components
• Fabrication
  – Improve weld creep-strength
  – Fully characterize stress relaxation cracking resistance
  – Develop repair welding capability
• Characterize damage tolerance of base metal and welds