Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-Base Alloys in A-USC Boilers & Steam Turbines

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NETL Advanced USC Materials Research

- “Addressing Materials Processing Issues in Components for Advanced Power Generation” – Paul Jablonski
- “Materials Performance in USC Steam” – Gordon Holcomb
- “New High Temperature Fe-Based Alloys” – Chris Cowen
- “Materials Life Assessment in Existing Power Plants” – Jeff Hawk
NETL Advanced USC Research Team

- Paul Jablonski
  - Alloy design, melting, casting, thermo-mechanical processing, and heat treatment for microstructure & properties

- Gordon Holcomb
  - Material-environmental interactions to include fireside corrosion, oxidation, & hot corrosion

- Chris Cowen
  - Alloy design, thermo-mechanical processing, and heat treatment for microstructure & properties, and structure-property relationships

- Jeff Hawk
  - Structure-property relationships, non-traditional mechanical testing and life prediction
Worldwide Drivers for a Higher Efficiency (USC) Plant

- National energy security
- Economic & abundant coal supply
- Lower fuel costs
- Significant environmental benefits
  - Fewer emissions of all gases per MWh
  - Less coal mined, transported & fired/gasified
  - Less solid waste for disposal
  - Less water used for cooling

Higher efficiency is limited by materials technology!

Materials Performance in USC Steam

Each 1% increase in efficiency eliminates ~1,000,000 tons of CO₂ emissions over the lifetime of an 800 MW plant.

US-DOE Advanced Power System Goal-
60% efficiency from coal generation
Steam condition: 760°C; 35 MPa

Adapted from: Viswanathan, et al., 2005 & Swanekamp, 2002
The Problem

Consider the following:

- Typical power plant operating at 37% efficiency
- Apply Carbon Capture Storage (CCS) Technologies
  - Immediate plant efficiency reduction of 12% points (worst case scenario), leading to a new overall efficiency of 25%.
  - Consequently, at this new level, the power plant will produce 44% more CO₂ and consume 48% more coal to deliver the same amount of power as the original plant.

Not the best solution for reducing greenhouse gas emissions:
However, by utilizing A-USC power plant technology, it is possible to raise efficiency >48%, which when combined with CCS technology can reduce the net increase in greenhouse gases relative to efficiency reductions.

New Energy Conversion Technologies & High-Temperature Structural Materials

Turbine blade substrate metal temperature (°C) and temperature capability of structural materials.
Requirements for creep rupture strength with increasing pressure and temperature for A-USC main steam pipes.

Use of Ni-Base Alloys for A-USC Applications

Conventional Use

High Temperature
- *Jet Engine Gas Turbines*
- 900-1100°C
- Small Parts (< 10 kg)
- Oxidation Resistant

Low Temperature & Corrosion-Resistant
- *Chemical Equipment, Reactors*
- <500°C
- Large Parts
- Corrosion & Oxidation Resistant
- Weldable
- Long-term service without repair

Advanced-USC

Moderate Temperature, Large Size
- *Large pipes, turbine rotors, etc.*
- 700-800°C
- Large Parts (>5 tons)
- Corrosion & Oxidation Resistant
- Weldable
- Long-term service without repair
- Low thermal expansion

## Summary of Material Requirements for A-USC Power Plant Boilers

<table>
<thead>
<tr>
<th>Properties</th>
<th>Material Requirements &amp; Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Temperature Strength</td>
<td></td>
</tr>
<tr>
<td>Creep</td>
<td>Creep strength at base metal &amp; weldment.</td>
</tr>
<tr>
<td>Thermal Fatigue</td>
<td>For large diameter &amp; heavy wall thickness piping under non-steady thermal start-up &amp; cool-down cycles.</td>
</tr>
<tr>
<td>Creep Fatigue</td>
<td>For piping, thermal expansion at start, steady-state &amp; stop. Creep fatigue interaction &amp; its life assessment - plant design.</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
<td></td>
</tr>
<tr>
<td>Hot Corrosion</td>
<td>Fire side corrosion for superheater tubing.</td>
</tr>
<tr>
<td>Steam Oxidation</td>
<td>Scale thickness &amp; exfoliation behavior of steam oxidation at inner surface of tubing &amp; piping.</td>
</tr>
<tr>
<td>Weldability</td>
<td>Cracking such as solidification cracks, liquefaction, low ductility cracks &amp; HAZ.</td>
</tr>
<tr>
<td>Workability</td>
<td>Hot bending.</td>
</tr>
<tr>
<td>Repair</td>
<td>Weldability of the aged tubing.</td>
</tr>
<tr>
<td>Inspection &amp; QA</td>
<td>Applicability of inspection testing.</td>
</tr>
<tr>
<td>Cost Competitiveness</td>
<td>Materials cost &amp; additional cost for working.</td>
</tr>
</tbody>
</table>

Worldwide Advanced-USC ST Initiatives

European AD 700 Program to achieve Power Plant operating at approximately 700°C

Japanese “Cool Earth” initiative to achieve Power Plant operating at a range of temperatures up to 700°C

US NETL-DOE sponsored 1400°F Boiler and Steam Turbine Program to achieve a Power Plant operating at 760°C
AD700/Thermie – 700 °C & 35 MPa Boiler & Steam Turbine

1. Feasibility study (1998-2004) consisting of:
   a. Process & design studies
   b. Materials development/selection, qualification & demonstration


4. Construction of full-scale demonstration plant (2006 pre-engineering study was started)

5. 2015 target time frame for final design of a 700°C power plant

Targets for boiler materials with respect to mechanical strength:

a. Martensitic alloys: \(100 \text{ MPa @ 650 } ^\circ \text{C for } 10^5 \text{ h}\)
b. Austenitic alloys: \(100 \text{ MPa @ 700 } ^\circ \text{C for } 10^5 \text{ h}\)
c. Nickel-base alloys: \(100 \text{ MPa @ 750 } ^\circ \text{C for } 10^5 \text{ h}\)

Targets were met for austenitic and nickel-base alloys.

Selection of Candidate Alloys Influenced by:

1. Requirement to produce very large components
   a. Large forgings, e.g., Alloys 617, 625, 706 & 718
   b. Large castings, e.g., Alloys 617 & 625

2. Selection based on existing literature/manufacturer data for use at $100 \text{ MPa} @ 750 \text{ C for } 10^5 \text{ h}$.

Nine alloys selected for preliminary investigation:
155, 230, 263, 617, 625, 706, 718, 901 and Waspaloy

Schematic of High Pressure (HP) Steam Turbine

AD700/Thermie – 700 C & 35 MPa Boiler & Steam Turbine (cont.)

• AD700/Thermie have shown very good potential for >700 C power plant technology.
• COMTES have shown utility of alloys operating at 700 C and also problems associated with their use.
• Material supply problems have been identified, mainly for very large forgings and also large nickel castings.

What next? What is needed in terms of materials and properties to go beyond 700 C?

‘Cool Earth’ Innovative Energy Technology Program: Japan

- Initiated in March 2008 to promote international cooperation and contribute to substantial global greenhouse gas emission reduction.
- Advanced Ultra Super Critical (A-USC) pressure power generation.

Commercialize 700°C pulverized coal (PC) power system:
- with 46% power generation efficiency by 2015
- with 48% power generation efficiency by 2020

Possible ‘Cool Earth’ A-USC Turbine Systems

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam Temperature</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main °C</td>
<td>600</td>
<td>630</td>
<td>700</td>
</tr>
<tr>
<td>Reheat °C</td>
<td>600</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td><strong>Steam Pressure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main MPa</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Reheat MPa</td>
<td>5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>Thermal Efficiency</strong></td>
<td>Base</td>
<td>1.03</td>
<td>1.047</td>
</tr>
<tr>
<td><strong>Material (Typical)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPT 10Cr</td>
<td></td>
<td>10Cr</td>
<td>10Cr</td>
</tr>
<tr>
<td>IPT 10Cr</td>
<td>10Cr</td>
<td>10Cr, 25Cr</td>
<td>10Cr, Ni</td>
</tr>
<tr>
<td>Valve Ni</td>
<td></td>
<td>10Cr, 25Cr</td>
<td>Ni</td>
</tr>
<tr>
<td><strong>Development Period</strong></td>
<td>Done</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td><strong>Development Cost</strong></td>
<td>Base</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Operability</strong></td>
<td>Base</td>
<td>Same</td>
<td>Low</td>
</tr>
</tbody>
</table>

Possible ‘Cool Earth’ A-USC Turbine Systems

<table>
<thead>
<tr>
<th></th>
<th>Gas Turbine</th>
<th>IPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Inlet Temperature</td>
<td>°C</td>
<td>1000-1300</td>
</tr>
<tr>
<td>Turbine Inlet Pressure</td>
<td>MPa</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>Rotor Temperature</td>
<td>°C</td>
<td>400-500</td>
</tr>
<tr>
<td>Casing Temperature</td>
<td>°C</td>
<td>200-400</td>
</tr>
<tr>
<td>Blade Material Temperature</td>
<td>°C</td>
<td>600-900</td>
</tr>
<tr>
<td>Nozzle Material Temperature</td>
<td>°C</td>
<td>600-900</td>
</tr>
</tbody>
</table>

Case 2: A possible route to develop a hybrid A-USC steam turbine. This would improve efficiency while allowing development time for Case 3.

# Turbine Rotor Candidate Alloys

<table>
<thead>
<tr>
<th>Materials</th>
<th>Temperature Level</th>
<th>Weight</th>
<th>Development Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fenix-700</td>
<td>700°C</td>
<td>&gt;10 ton</td>
<td>Ni-base material heavier than 10 tons without segregation</td>
</tr>
<tr>
<td>LTES</td>
<td>&gt;700°C</td>
<td>30-40 ton + Welding</td>
<td>10 ton Ni-base material with good weldability to steel</td>
</tr>
<tr>
<td>TOS1X</td>
<td>&gt;720°C</td>
<td>Ni: 10 ton + Steel: 20-30 ton</td>
<td>10 ton Ni-base material with good weldability to steel</td>
</tr>
</tbody>
</table>

NETL-DOE Sponsored A-USC Boiler & ST Program
Phase 1 ST Activities: 2006-2009

Key Issues:
- Welded rotor materials
- Non-welded rotor materials
- Air casting
- Erosion resistance
- Oxidation resistance
NETL-DOE 1400°F Boiler & Steam Turbine

• In order to increase efficiency even further, US consortium assembled to push boiler & steam turbine technology to 1400 F (760 C), and beyond. This would require precipitation strengthened nickel alloys.

• ST materials group looked at current alloys that could meet the following minimum strength requirements for a rotor disk segment:
  • > 400 MPa tensile yield strength at 760 C
  • > 100 MPa creep strength at >10^5 h at 760 C

Yield strength & creep capability are not quite good enough for AD700 rotor alloys at 760 C. The nickel alloys used at 760 C and above must be stronger and microstructurally stable (precipitate coarsening low) for times >10^5 hours.
Candidate Rotor Materials

- Nimonic®105
- Haynes®282 (H282)
- Udimet®720 (U720Li)
- Inconel®740 (IN740)
- Waspaloy

IN740 & Waspaloy were not studied due to availability of data from literature & prior studies.
NETL-DOE 1400°F Boiler & Steam Turbine

- Waspaloy
- IN 740
- Udimet 720Li
- Haynes 282
- Nimonic 105
- Alloy 617

- 2.5 x 10^5 h creep life
- 10^5 h creep life

Stress (MPa)

LMP (C = 20)
Goal A

• Optimize alloy compositions, TMP schedules and/or heat treatment conditions for Haynes 282 and Nimonic 105, and/or other relevant γ′ strengthened nickel superalloys to insure, thermally stable microstructures, and to provide the best combination of tensile strength, creep resistance, and fatigue capability for large steam turbine and boiler components at temperatures \( \geq 1400°F \) (760°C) in dry air and steam.

Tasks

• Characterize peak- and over-aged microstructures for Haynes 282 and Nimonic 105.
• Collate mechanical property data for creep, fatigue and creep-fatigue.
Different Heat-treatments of Haynes282

Solution Annealed

PA = SA + 8h @ 1450 F

OV = PA + 250h @ 1425 F
Determine Long-Term Alloy Stability

Haynes 282 – 0.2%YS at different temperatures for exposure up to 16,000 h.

For H282, the depression in 0.2% YS, for example, is shifted to higher temperatures. Longer term evaluation needed.
Long-Term Alloy Stability

For example, in alloy 718 a change in exposure temperature can lead to a decrease in mechanical properties.
Long-Term Alloy Stability

Alloy 718 – 0.2% YS behavior at 5,000 & 25,000 h as a function of temperature.

For example, in alloy 718 a change in exposure temperature can lead to a decrease in mechanical properties.
As with all aircraft developed alloys, chemistry and heat treatment were designed to provide best combination of properties for short-term, high-strength use. For AD700 program, alloy 718 heat treatment was modified from normal two step age (720°C & 620°C) to one where the temperature of the aging treatments was increased by 30-40°C.

Strengthening Concepts, Microstructural Control & Failure Mechanisms in Steam for Ni-base Alloys in Advanced USC Boilers & Turbines

**Goal B**

- Document the deformation mechanisms in Haynes 282 and Nimonic 105 with respect to microstructural features, and assess the long-term stability of these alloys as a function of exposure temperature and time in order to develop models that can be used to determine the life of a component.

**Tasks**

- Perform selected static (creep) and dynamic (fatigue and creep-fatigue) tests on Haynes 282 and Nimonic 105.
- Document deformation mechanisms in each instance.
- Relate deformation mechanism to specific stress state and chart the changes in the microstructure during testing exposure.
Deformation Mechanisms

Climb / bypass of unit 1/2<110> dislocations

Shearing by <110> superdislocations

Shearing by partial dislocations (1/3<112>)

Micro-twinning (1/6<112>)
### Deformation Mechanisms

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Material</th>
<th>Time</th>
<th>Grain Diameter</th>
<th>Stress (ksi)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-1400°F-3718h</td>
<td>d=142.5</td>
<td>100 nm</td>
<td>37.5</td>
<td>0.01878</td>
<td></td>
</tr>
<tr>
<td>SA-1450°F-13849h</td>
<td>d=238.4</td>
<td>50 nm</td>
<td>15</td>
<td>0.0026</td>
<td></td>
</tr>
<tr>
<td>PA-1400°F-10470h</td>
<td>d=170.4</td>
<td>200 nm</td>
<td>15</td>
<td>0.00042</td>
<td></td>
</tr>
</tbody>
</table>

*Note: The above table is an explanation of the deformation mechanisms observed in different heat treatments.*

![Micrographs showing deformation mechanisms](image)

- **Climb**: The mechanism of climb is observed at 100 nm scale.
- **Twinning**: Twinning mechanisms are evident at 50 nm scale.

*Image descriptions are speculative and need to be verified with actual images.*
1450°F, 0.2% strain, 32.5 ksi
1450°F, 0.2% strain, 32.5 ksi
1450°F, 4% strain, 32.5 ksi
1450°F, 0.2% strain, 27.5 ksi
Summary Microstructural Observations

1. Haynes 282 is almost a classic model alloy.
2. The $\gamma'$ phase has formed in the SA condition, although the precipitates are very small, and subsequent aging coarsens precipitate, but not unduly so.
3. Haynes 282 is a stable alloy in terms of phase formation and phase evolution, i.e., coarsening is relatively slow over time in the temperature range of interest.
4. Deformation mechanisms are also classic:
   a. At high stresses, deformation proceeds primarily via twinning/shearing process.
   b. At lower stresses, deformation proceeds primarily via classic Orowan looping and dislocation climb (cross slip).
Goal C

- Understand the interaction between microstructural development (e.g., alloy chemistry, TMP and heat treatment), deformation and crack growth in steam at 1400°F (760°C) to enable high performance nickel-base alloys to be developed for A-USC power plants.

Tasks

- Design high temperature, steam testing facility.
- Develop creep, fatigue and creep-fatigue testing protocols for life prediction models in dry air and steam.
- Assess literature to establish the effect of steam on creep-, fatigue-, and creep-assisted, fatigue-crack growth in solid solution and particle strengthened nickel-base superalloys.
Milestones

- Procure Haynes 282 & Nimonic 105 to fully implement TMP, heat treatment and mechanical testing matrices (3/31/2010).
- Characterize Haynes 282 and Nimonic 105 microstructures with respect to high temperature strengthening mechanisms with initial assessment as to high temperature strength potential (9/30/2010).
- Finalize design for environmental chamber to test in steam (9/30/2010).