Advanced Structural Materials for Non-Light Water Reactors

Steven J. Zinkle\textsuperscript{1,2}

\textsuperscript{1}Dept. Nuclear Engineering and Dept. Materials Science & Engineering, University of Tennessee, Knoxville, TN, USA
\textsuperscript{2}Oak Ridge National Laboratory, Oak Ridge, TN, USA

Workshop on Advanced Non-Light Water Reactors: Materials and Component Integrity
Nuclear Regulatory Commission
December 9-11, 2019
Overview

- High sink strength has been a long-standing scientific tenet for superior radiation resistance in structural alloys
  - Cold-worked and Ti-modified SS alloys (e.g., D9) developed by LMFBR program in the 1970s

- Improved structural materials are needed for nuclear power to fully achieve its promise
  - High burnup, accident tolerant LWRs
  - Fusion and Gen IV reactors

- Nanostructured alloys enable simultaneous achievement of radiation resistance and high performance (strength)
  - Radiation resistance ("sink strength"): $S \sim 4\pi R N$
  - Dispersed barrier hardening: $\Delta \sigma_y \sim \alpha \mu b (2NR)^{1/2}$
  
  $\Rightarrow$ For a given precipitate volume $f = 4\pi R^3/3$, best radiation resistance and mechanical strength simultaneously occurs for high $N$, small $R$

  $\Rightarrow$ High density of uniformly distributed nanoscale precipitates preferred
Thermal creep and void swelling in sodium-cooled fast reactor cladding is problematic for conventional steels.

Current “either/or” dilemma if structural alloy selection is limited to conventional steels.

Effect of initial sink strength on the volumetric void swelling of irradiated FeCrNi austenitic alloys

For void swelling resistance, sink strengths $>10^{15}/m^2$ are generally sufficient for fission reactors; fusion reactor irradiation may require even higher sink strengths ($>10^{16}/m^2$?) due to transmutant He production.

Dramatic reduction in void swelling occurs when average spacing between voids is $>10x$ average spacing between defect sinks.

$N_v^{-1/3} > 10 S_{tot}^{-1/2}$
ODS steels provide improved void swelling resistance compared to standard ferritic/martensitic steels.

S.J. Zinkle et al., *Nucl. Fusion* **57** (2017) 092005
Effect of Initial Sink Strength on the Radiation Hardening of Ferritic/martensitic Steels

Current steels

Next-generation (TMT, ODS) steels

Dramatic reduction in radiation hardening occurs when average spacing between defect cluster nuclei (dislocation loops, etc.) is much greater than average spacing between defect sinks

\[ N_{\text{loop}}^{-1/3} \gg S_{\text{tot}}^{-1/2} \]

or equivalently,

\[ S_{\text{tot}} \gg S_{\text{rad defects}} \]
Creep rupture behavior for TMT vs. conventional 9Cr steels

Thermo-mechanical treatment (TMT) 9Cr steels designed using computational thermodynamics

50-100% improvement in creep rupture strength for newly designed reduced activation steels

Predicted improvement in radiation resistance as well due to high precipitate density
Creep rupture behavior for ODS vs. conventional 9Cr steels

~100% improvement in creep rupture strength for ODS steels

Predicted improvement in radiation resistance as well due to high dispersoid density

S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005
Conclusions

• Nanostructured (high sink strength) alloys are promising options for the structural materials in next-generation fission reactors
  • Enables simultaneous superior radiation resistance and superior mechanical property performance

• ASME code qualification is needed to enable their deployment
  • Currently in “boutique” materials stage
Since the 1960s, there has been relatively little modification of materials aspects for LWRs.

Evolution in light duty personal vehicles

Greatly improved safety, along with improved performance (horsepower, fuel economy)

Source: US Dept. of Transportation and Environmental Protection Agency
New Propulsion Materials and Architectures Have Driven Marked Improvements in Jet Engine Fuel Efficiency

Plus: 40x improvement in durability; 10x improvement in in-flight shutdown rate

R.E. Schafrik, personal communication

W.G. Roeseler et al., in 16th Int. Conf. on Composite Materials, Kyoto, Japan (2007)
Near-term Importance of Advanced Steam

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Conditions</th>
<th>Net plant efficiency (%)</th>
<th>Net plant heat rate (HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcritical</td>
<td>2,400 psi</td>
<td>35</td>
<td>9,751 Btu/kWh</td>
</tr>
<tr>
<td></td>
<td>1,050F/1,050F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supercritical</td>
<td>&gt;3,600 psi</td>
<td>38</td>
<td>8,981 Btu/kWh</td>
</tr>
<tr>
<td></td>
<td>1,050F/1,075F</td>
<td>&gt;42</td>
<td>8,126 Btu/kWh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;45</td>
<td>7,757 Btu/kWh</td>
</tr>
</tbody>
</table>

Fuel; ash; NO\(_x\); SO\(_x\); CO\(_2\); Hg...

Source: Electric Power Research Institute

essential to reduce cost of CCS
Advanced Steam Conditions Push Metallurgical Limits of Alloys in Use Today

Improvement in Energy Efficiency


2400/1005/1005

3480 psi / 1005°F / 1050°F

3600/1050/1085

4000/1085/1100

4000/1100/1150

4000/1165/1200

5400/1300/1325/1325

R&D ongoing (Ni-based)

Current Market introduction

Market introduction by Japan R&D ongoing (COST) in Europe

Cost-Effective Materials Are Key

Illustration: EPRI
Data: Alstom
Tubing/piping materials for advanced ultra-supercritical (A-USC) steam (760°C, 350 bar)

- Objective: qualify/develop advanced alloys to enable reliable, high efficiency operation of A-USC plants

- Key Deliverables:
  - Generate alloy properties database for U.S. boiler manufacturers to enable component design and fabrication
  - Qualification of fabrication/welding techniques for use with specific alloys
  - ASME Boiler and Pressure Vessel Code case for Inconel 740
  - Evaluate environmental compatibility

Cast nickel-base alloys for steam turbine casings
Qualification of new, commercial ODS alloys for use in advanced FE processes

Objective: Determine capabilities of new commercially-produced ODS alloys for application at temperatures up to 1200°C in advanced fossil combustion and conversion processes

Key Deliverables
- Data on the full range of properties required to qualify the alloy for fossil applications
- Evaluate joining technologies
- Feasibility of employing a less costly route for producing ODS alloy powders

25 mm diam x 4 m long ODS FeCrAl tubes used in British Gas/COST 501 1100°C air heater demonstrator
Historical development of improved high-temperature steels has exhibited slow and steady progress


Diagram showing the maximum use temperature for different generations of high-temperature steels from 1920 to 2020, with an average increase of 2.5°C per year.