Structural materials for advanced nuclear reactors

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Comparison of Gen IV and Fusion Structural Materials Environments with different power conversion systems

All Gen IV and Fusion concepts pose severe materials challenges

New steels designed with computational thermodynamics exhibit superior mechanical properties compared to conventional steel

- Three new reduced activation FM steel heats (1537, 1538, 1539) and an optimized-Gr.92 heat (C3=mod-NF616) were investigated
- Tensile strengths of the new thermomechanical treated (TMT) steels were much higher than conventional steels
- Dramatic improvement in thermal creep strength also observed

New Thermomechanical treatment (TMT) Applied to Commercial 9-12%Cr Steels Yields Improved Microstructure

- Commercial 9Cr-1Mo and 12 Cr steels were processed
- TMT (hot rolling) on 25.4-mm plates
  - Several TMT conditions were investigated
- Precipitates formed on dislocations introduced by hot rolling
- Precipitate dispersion is much finer than observed in conventionally processed 9-12Cr steel
  - Up to 1000X increase in density (TMT precipitate density is 0.2-1x10^{22}/m^{3}; d~4-8 nm)

Creep rupture behavior for TMT vs. conventional 9Cr steels

S.J. Zinkle et al., Nucl. Fusion (2016) in press
Development of New Alumina-Forming, Creep Resistant Austenitic Stainless Steel

- Designed for 600-800°C structural use under aggressive oxidizing conditions
  - superior oxidation resistance to conventional chromia-forming alloys
- Comparable cost to current heat-resistant austenitic stainless steels

Options for designing radiation resistance

Three general strategies for radiation resistance can be envisioned:

- Utilize materials with negligible point defect mobility at desired operating temperatures
  - Amorphization with an accompanying volume change may occur if all point defects are immobile => select temperature range where vacancies are immobile but interstitials are mobile
- Use materials with intrinsic resistance to radiation damage accumulation (e.g., BCC alloys, high entropy alloys?, noncrystalline materials?)
- Materials with a high density of nanoscale recombination centers
  - Volumetrically-distributed precipitates or nanolayered structures
Effect of Sink Strength on the Volumetric Void Swelling of Irradiated FeCrNi Austenitic Alloys

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

$$N_v^{-1/3} > 10 \ S_{tot}^{-1/2}$$

Internal multilayers in MAX phase ceramics: Example for Ti$_5$Al$_2$C$_3$

Bulk nanolaminates: If interfaces are ideal point defect sinks, S > 10$^{19}$/m$^2$
Approaches for radiation resistance 1: Immobile defects

- Defect accumulation is limited if one or more defect types are immobile
  - Utilize materials with negligible point defect mobility at desired operating temperatures
  - A key potential consequence (particularly in ordered alloys and ceramics) is amorphization, with accompanying significant volumetric and property changes

- Regime with intrinsically high point defect recombination typically occurs at too low of temperatures for power generation applications (except SiC and possibly Al₂O₃, W, Re)

Radiation resistance depends on temperature: example of swelling in SiC

Good radiation stability when interstitials are immobile & vacancies mobile: $S > 10^{19}/m^2$. Similar behavior occurs in MAX phase ceramics, etc.


L.L. Snead et al., JNM 367-370 (2007) 677
Conclusions

• Advances in materials science have paved the way for a suite of new materials with significant performance improvements
  – E.g., >50% improvement in creep rupture strength or >10X improvement in creep rupture lifetime for ferritic/martensitic steels

• The same microstructural features that provide good mechanical properties also provide superior radiation resistance

• Enhanced performance, durability and safety is possible

• Looking forward to working with reactor design teams to implement these high-performance cost-effective materials