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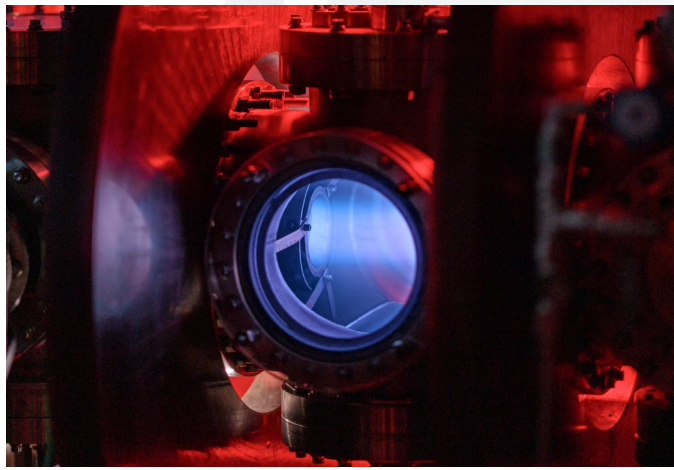
PMI and Materials Science Considerations for Tungsten Plasma-Facing Components in DIII-D

Fusion Materials Science & Technology



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Sandia National Laboratories, Plasma & Reacting Flow Science Department

DIII-D Wall Change Community Forum

12-13 June 2024

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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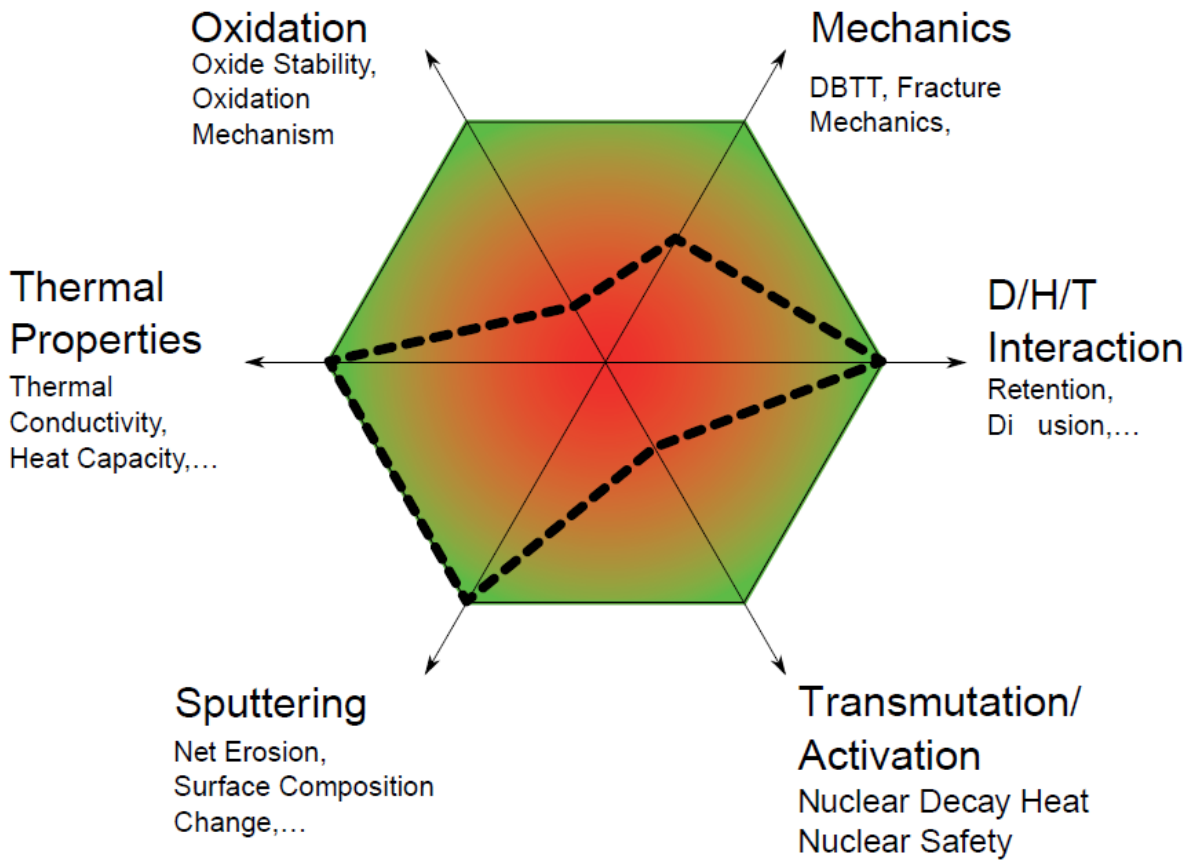
An extensive knowledge base has been developed for high-purity, coarse-grained W as a PFM

Advantages:

- Low sputtering (< 10^{-2} - 10^{-1} at. / ion at E < 5 keV for D, He)
- T_{melt} = 3422°C
- High thermal conductivity (175 W/mK at 25°C)
- High enthalpy of solution for T (1.04 eV), low permeability / trapping
- Extensive modeling tools developed for material performance
- Relatively mature engineering design, fabrication, and joining technologies (TRL 4-5 for “technology demonstration” projects)

Assessment of polycrystalline W performance from an MFE standpoint

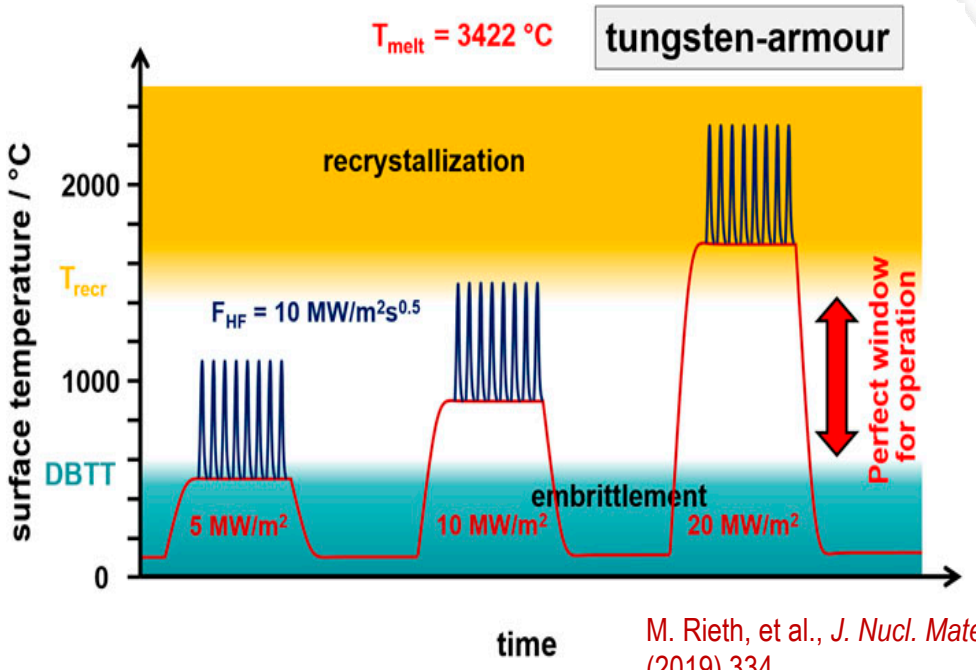


Source: Jan Coenen (Juelich)

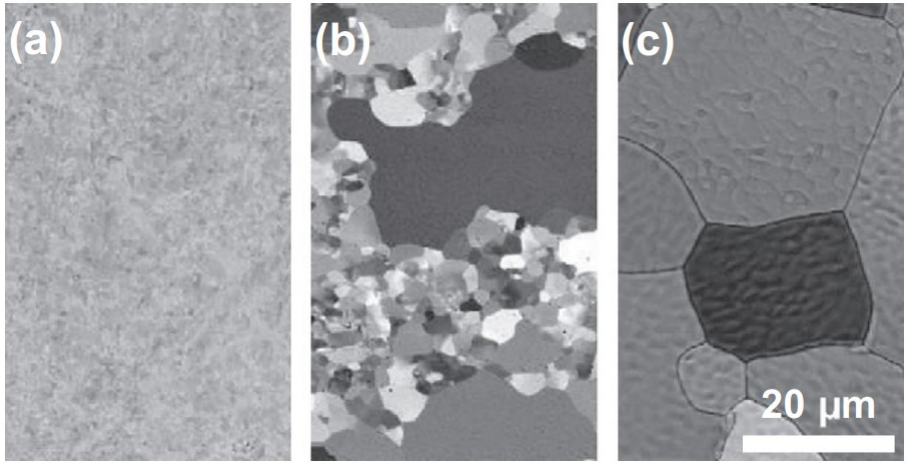
An extensive knowledge base has been developed for high-purity, coarse-grained W as a PFM

Weaknesses:

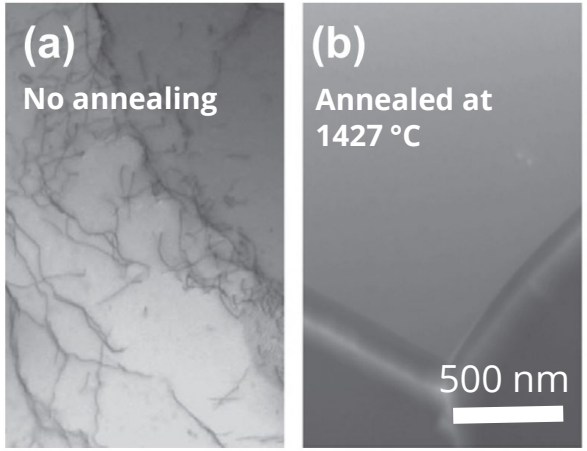
- Thermomechanical properties degradation, transmutation, swelling with neutron exposure
- Rapid grain growth at low temperature (~ 1200°C), coupled with high DBTT, constrains operating temperature window
- Low threshold for crack formation (< 0.3 - 0.6 GW m^{-2} at < 500 °C) during transient loading
- Oxide growth is not self-limiting, could potentially lead to large loss of material in a loss-of-vacuum / up-to-air accident scenario.



M. Rieth, et al., *J. Nucl. Mater.* **519** (2019) 334.



Grain growth at varying temperatures [A. Manhard, *JNM* (2011)].



Annealing of dislocations [A. Manhard, *JNM* (2011)].

Recent W materials development efforts have focused on several strategies to improve the properties of W materials

Recent emphasis:

- decrease ductile - brittle transition temperature (DBTT)
- increase ductility and fracture toughness
- improve microstructural stability, resiliency against neutron damage

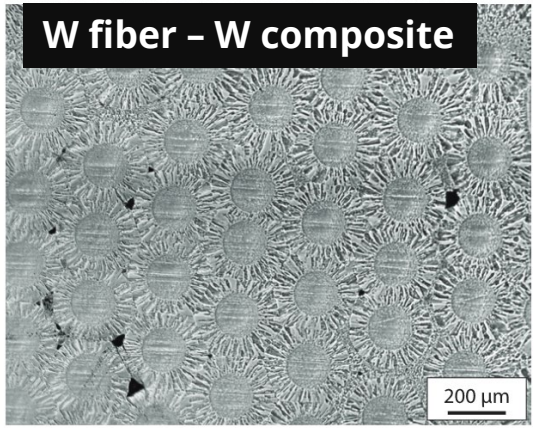
Primary Strategies:

- W solid solution (alloying / doping) (Re, Ta, V, K …)
- ultra-fine grained (UFG) microstructures / nanostructuring
- W composite materials (materials design)

Other areas of R&D:

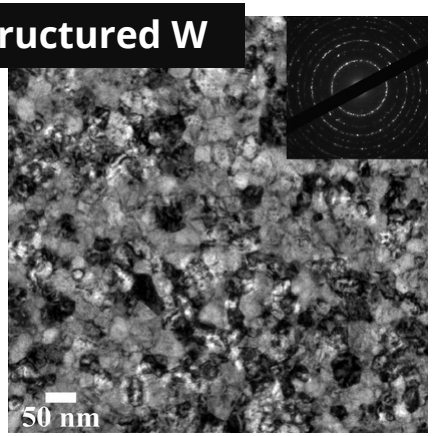
- self-passivating alloys
- high-entropy alloys
- additive manufacturing

W fiber – W composite



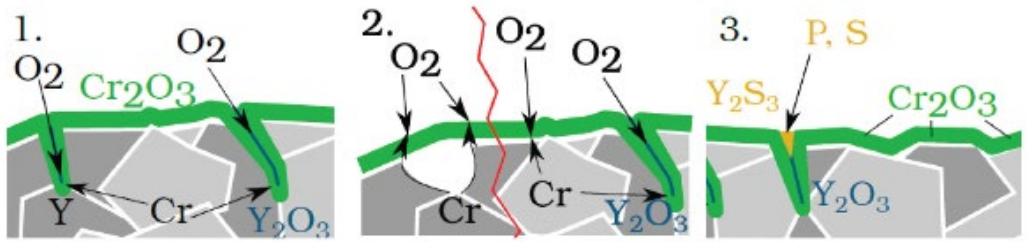
J. Riesch, et al. Max Planck Technical Report 2013

Nanostructured W



W. S. Cunningham, et al Act. Mater **206** (2021) 116629

Self-passivating alloy

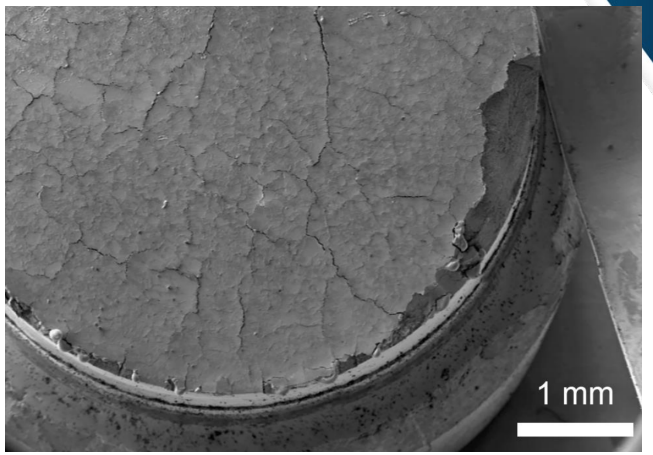


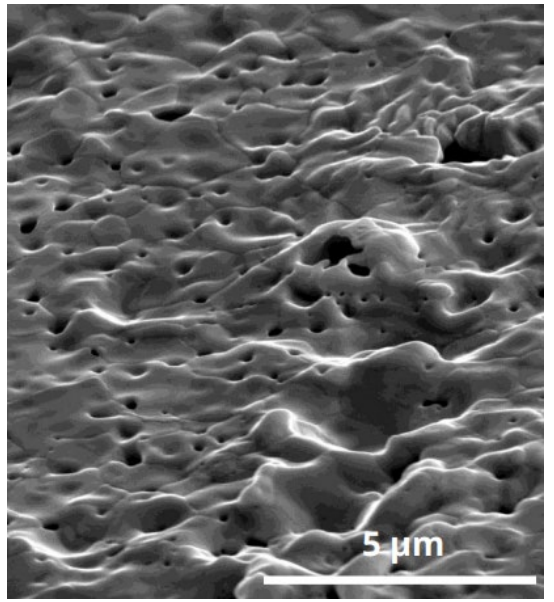
Ch. Linsmeier et al *Nucl. Fusion* **57** (2017) 092007.

Recent W materials development efforts have focused on several strategies to improve the properties of W materials

Potential R&D Themes for DIII-D (linked to critical feasibility issues identified in Fusion Materials Road Map)

- Study effects of transient loading (cracking, recrystallization) **[1A-W-4]**
- Understand effects of complex chemical environment (produced by combination of H, He, B, N and other plasma impurities) on tungsten composite materials **[1A-W-8]**
  - Close linkage between surface composition and H isotope recycling
- Quantify sputtering behavior of tungsten composite materials **[1A-W-10]**
- Assess combined effects of multiple simultaneous loading conditions (high heat / particle flux) **[1A-W-6]**
  - Essential for identifying unforeseen consequences not revealed by laboratory experiments
  - Lack of domestic HHF infrastructure at coupon, cooled subcomponent level is a concern and could be addressed through this experimental work





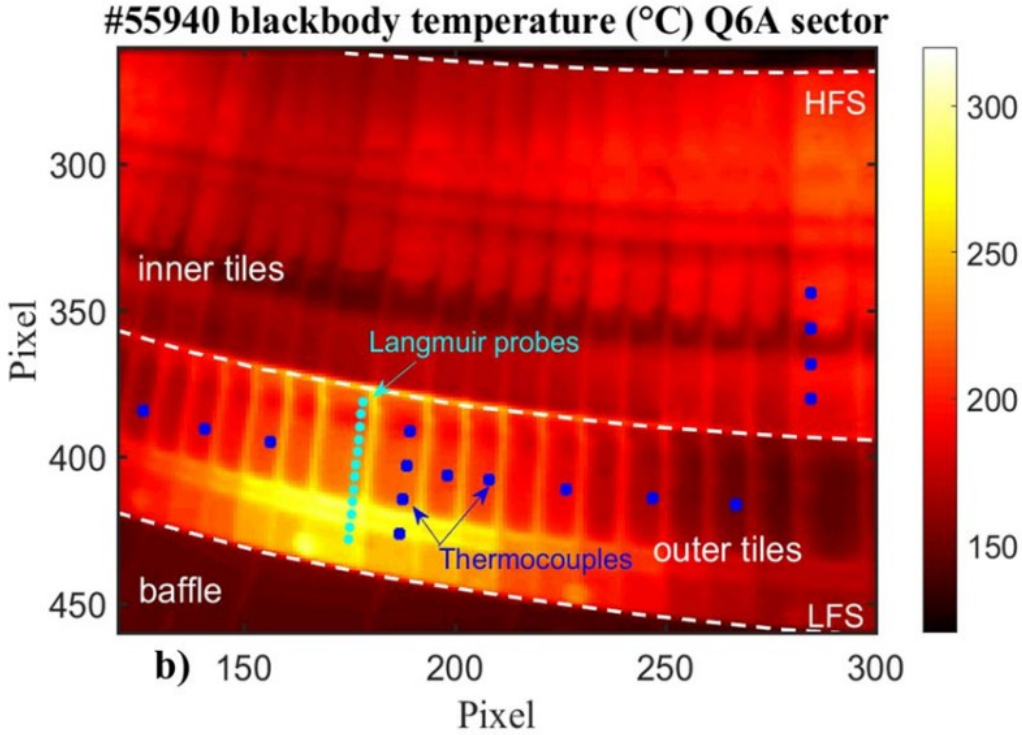
Trade-offs / practical considerations for W PFC's

W coatings on C tiles:
- Comparatively inexpensive, allows W PMI to be studied using existing tile designs
- Thin film microstructure does not resemble bulk metal
- Possible wear-through at strike point, penetration of arc tracks, delamination
- If coatings are pursued, we suggest a small-scale testing beforehand to identify any unforeseen risks.

Bulk W:
- Enables testing of representative components designed for higher power handling
- Established industrial base can supply high purity raw material (ALMT / PLANSEE)
- Design (shaping), machining, and integration of complete tile assemblies much more complex

Diagnostic considerations:

- More extensive coverage with IR cameras, TC's, LP array needed to monitor the condition of the PFC's



J. Gaspar et al, Nucl. Fusion **61** (2021) 096027

Recommendations

- Given the likely engineering and cost constraints, a combination of W coatings / bulk materials may be a reasonable “middle ground” if W PFC’s are selected
- Capabilities exist in industry, national labs, and universities to make novel W materials at the size of single tiles. These materials would be valuable to test alongside pure W materials for performance comparison.
- The wall change-out also provides an opportunity to test more advanced joining technologies, functionally graded interfaces, and cooling strategies.
- New diagnostics will be needed to assess the condition of the W wall materials and should be considered at an early stage in the wall change-out.
- Regardless of material selection, following the first campaign with the new wall, sufficient time should be allocated for tile removal and post-mortem materials characterization
- Only a few facilities in the U.S. are currently capable of performing materials analysis on complete tiles that have been activated. New capabilities for tile analysis may need to be built up in parallel with the wall change-out effort if this is desired.