Research and plans on irradiated tungsten at the University of Illinois, Center for Plasma-Material Interactions

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Outline

• PMI/PFC research in irradiated W at Illinois
• Motivation for nanostructured W studies
• Processing of extreme refined-grain W
• In-situ TEM results of dynamic defect behavior in extreme refined-grain W
• High-flux irradiations in Pilot-PSI and Magnum-PSI at DIFFER
• Challenges to characterization and computational modeling of hydrogen isotope interactions in irradiated W
• Summary

Fusion work in irradiated W at Illinois

Process-property-performance relationships studied in well-diagnosed in-situ experiments at Illinois and collaborators worldwide. Emphasis on nanoscale materials design and in-situ testing coupled to computational models

Severe plastic deformation leads to extreme refined grained tungsten

• Irradiations were performed on UFG (ultrafine-grained) and NC (nanocrystalline) samples prepared by large strain extrusion machining1,3
• Coexisting of ultrafine (≤500 nm) and nano-crystalline (≤100 nm) grains adjacent to each other permitted the observation of the behavior of both types of grains and their irradiation tolerance
• Current research focused on processing of full nanocrystalline W grain materials in collaboration with S. Chandrasekar (IE, Purdue)
• Samples size varied depending on characterization and irradiation experiments
  - 3-mm UFG/NC W samples prepared to 300-nm thickness with FIB-SEM
  - 5-mm samples prepared for high-flux irradiation plasmas (DIFFER collab with deTemmerman)

Commercially available lathe tooling

Snapshot of the Process

Extrusion Machining

UFG Tungsten

Observing defect dynamics with in-situ TEM can elucidate effects: couple spatial scale with models

In-situ TEM observation during 2-keV He+ irradiation at 950 C

• Movement of loops occurs between pinning defects
• Irradiation enhanced diffusion (high defect concentration and enhanced mobility) needed for these defects to shuttle between pinning defects

Irradiation of SPC NC-W with 200 eV He+ with moderate fluxes

Irradiation with helium (2x1018 ion.cm-2 or 2x1022 ion.m-2)
Helium energy = 200 eV (no displacement damage)
Temperature = 950 C (both thermal vacancy and interstitial migration are possible)

Nanostructuring of the shear band regions

Fluence from 2-2.4x1019 m-2

In-situ TEM observation during 2-keV He+ irradiation at 950 C

• Movement of loops occurs between pinning defects
• Irradiation enhanced diffusion (high defect concentration and enhanced mobility) needed for these defects to shuttle between pinning defects
Early and latter stages of damage observed with in-situ TEM

2 keV He\(^+\) ion irradiation of tungsten at 950°C

- (a) nanocrystalline (1) and ultraline (2 and 3) grains before irradiation
- (b) at a fluence of \(8\times10^{18}\) ions.m\(^{-2}\) and greater He bubble nucleation (bubbles indicated by yellow arrows)
- (c) after irradiation to a fluence of \(2.4\times10^{19}\) ions.m\(^{-2}\) showing point defect cluster formation (indicated by red arrows) occurred preferentially in grains 2 and 3
- (d) after irradiation to a fluence of \(3.2\times10^{19}\) ions.m\(^{-2}\), a higher areal density of point defect clusters and small dislocation loops evident in grains 2 and 3 while grain 1 demonstrates a uniform distribution of bubbles and a significantly lower areal density of defect clusters and dislocation loops.

Summary of the in-situ TEM studies

- Grain boundaries are He sinks (large bubbles on the grain boundaries).
- Intra-granular bubble and defect formation in relatively large grains (e.g. > 60-nm)
- Grains of less than ~60-nm in size\(^*\) yielded a 50% lower areal bubble density compared to larger grains (60-100 nm) and ultraline grains (100-300 nm). Defect clusters were not observed on those grains.
- Bubbles on grain boundaries were faceted (high He concentration)

Comparison with literature (fuzz formation)

SPD samples (UFG) have higher fuzz formation fluence thresholds, however fuzz thickness growth rate is faster

SEM and TEM micrographs of the ultraline grained tungsten sample irradiated with 30 eV\(^+\) He particles to a fluence of \(1\times10^{19}\) cm\(^{-2}\) at 500 °C

In-situ TEM observation during 2-keV He\(^+\) irradiation

- Fluence for He cluster formation and role of grain boundaries

- No defect clusters were observed in any sample. Only found on large grains.
- The larger the sample, the higher the density of grain boundaries.
- Interstitials were also found in NC tungsten.
- Dislocations growth and formation was indicated in complex nanostructures.

Nanostructure and morphology evolution on SPD-W

- Surface nanostructuring in multiple scales; evidence of He bubble emission at surface
- Crystallographic dependence of irradiation-driven surface patterning; implications for hydrogen isotope interactions

He clusters at grain boundaries of SPD tungsten: comparisons to atomistic modeling

- Work by F. Saffa and B. With et al. open up understanding of self-driven mechanisms for He cluster formation and role of grain boundaries
- How do we couple impurity-driven surface structuring and defect evolution in irradiated materials? How do we close the gap in space and time between models and diagnosis?
Irradiation-driven vs thermal-activated systems: instabilities and self-organization at the plasma-surface interface


Modification ion sources with in-situ tool set

- Conditions: GaSb(100) samples irradiated by Ar+ at 50, 100 and 200 eV, normal incidence with 40-50 μA cm⁻² for fluences up to 10¹⁸ cm⁻²
- We operate in the sputter threshold regime and study early stage growth e.g. ~ 10¹⁵-10¹⁷ cm⁻²

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Summary

- Grain orientation and size have correlated effects on defect formation and surface nano-patterning and morphology evolution
- Defects dominated by high-density clusters within large grains (> 100-200 nm) and faceted He bubbles at grain boundaries in extremely refined-grained W
- In-situ TEM on commercial tungsten samples with micron-level grains and bubble density comparison reveal the efficiency in trapping He atoms at grain boundaries in ultrathin-W and nano-crystalline W (NCW).
- Future work with dual-beam in-situ TEM experiments (He and W) on UFG W (also doped) to investigate hydrogen isotope retention and migration in damaged W
- Computational modeling of He-induced defects in W face serious challenges: multi-scale spatio-temporal defect dynamics that are intimately connected to their nano/microstructure and driven far-from equilibrium in burning plasma fusion device environments
- Role of in-situ diagnosis of irradiated materials and how to close the spatio-temporal gap between measurements and modeling

Tokamak in-situ diagnosis of plasma-material interface: measurement of dynamic response

post-irradiation testing will not elucidate on dynamic effects