Diffraction-Based Quantification of Plasma-Induced Microstructural Evolution in Tungsten

S.A. Pitts[1], H. Gietl[2], N.L. France[1], M.M. Swisher[1], Z. Hua[1], P. Agrawal[1], B.S. Newell[1] M.A. Muntaha[1], S. Biswas[1], T. Feng[3], Q. Xu[3], S. Blondel[4], P. King[4]

1 Idaho National Laboratory, 2 Max Planck Institute for Plasma Physics, 3 University of Utah, 4 University of Tennessee, Knoxville

brian.newell@inl.gov

The extreme operating environment of fusion reactors imposes stringent requirements on plasma-facing materials (PFMs). Tungsten is the leading candidate due to its high melting temperature, favorable thermal conductivity, and low sputtering yield. However, exposure to plasma and neutron irradiation drives significant microstructural evolution, including defect cluster formation, dislocation network development, and near-surface plastic deformation. These processes alter thermal, electrical, and mechanical properties, ultimately affecting material reliability under fusion-relevant conditions [1].

Here we present an integrated experimental–computational framework linking diffraction-derived microstructural metrics with multiphysics simulations of plasma-induced defect evolution in tungsten. The simulation capability is implemented within the open-source Multiphysics Object-Oriented Simulation Environment (MOOSE), where a phase-field microstructure model is coupled with the cluster-dynamics code Xolotl to simulate irradiation-driven defect formation and evolution.

Diffraction methods provide quantitative measurements of defect structures for model validation. X-ray diffraction (XRD) peak broadening is analyzed using line profile analysis and Williamson–Hall methods to separate crystallite size and microstrain contributions [2]. Diffraction-based dislocation density determination is performed using the modified Williamson–Hall approach and the Ungár dislocation model for strain broadening [3,4]. These analyses enable estimation of dislocation densities and defect-induced lattice distortions during thermal and plasma exposure. Complementary microscopy techniques—including scanning electron microscopy (SEM), transmission electron microscopy (TEM), and laser scanning confocal microscopy (LSCM)—provide spatially resolved observations of grain morphology and defect structures.

Separate-effects experiments isolate the influence of thermal loading and plasma exposure in tungsten. Samples are annealed between 500–1500 °C under protective atmosphere, while plasma exposure experiments are conducted in the Tritium Plasma Experiment at Idaho National Laboratory under a deuterium flux of ~10^{22} D m^{-2} s^{-1}. Preliminary results demonstrate how diffraction-based quantification of defect density and microstrain constrains multiphysics simulations of plasma-induced microstructural evolution.

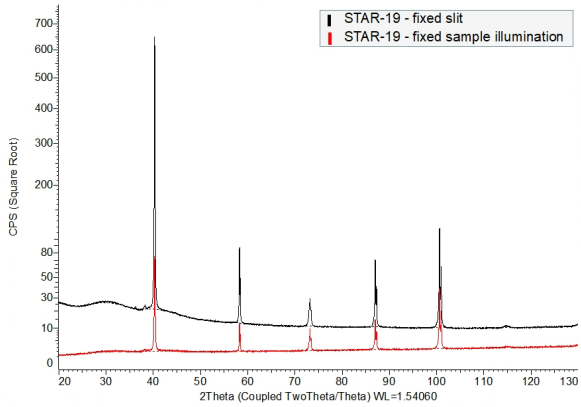


Figure 1. *XRD of STAR-19 with fixed slit (black) and fixed sample illumination (red).*

[1] M. Rieth, *et al.*, J. Nucl. Mater. (2013). 432, 482-500.
[2] G. K. Williamson, W. H. Hall, Acta Metall. (1959). 1, 22-31.
[3] T. Ungár, A. Borbély, H. Rietveld, Appl. Phys. Lett. (1996). 69, 3173-3175.
[4] T. Ungár, Script. Mater. (2004). 51, 777-781.