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Rapid Characterization Methods for Accelerated Innovation for Nuclear Fuel Cladding

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Traditional pathways for understanding the performance of nuclear fuel cladding requires irradiations – either via accelerated ion irradiations or through neutron irradiations – followed by some degree of characterization of the microstructure. These characterization efforts have historically included transmission-based electron microscopy techniques and more recently atom probe tomography (APT) techniques. These methods have inherently laborious components within them such as sample preparation and data collection/analysis. These intensive efforts have retarded the speed of innovation for nuclear fuel cladding even with increases in instrument resolution/efficiency.

Here, we demonstrate two on-going pursuits to reduce or completely eliminate the laborious efforts in characterizing irradiation nuclear fuel cladding. The first pursuit is the application of shielded magnetic small angle neutron scattering (SM-SANS) for replacing (or supplementing) APT characterization efforts of nanoscale precipitates in irradiated cladding. The second is the use of a coupled framework for automated dislocation loop detection and analysis based upon on-zone Scanning Transmission Electron Microscopy (STEM) dislocation imaging with deep learning-based feature detection and tracking algorithms. Both pursuits are centralized on the on-going efforts to innovate and maturate the FeCrAl alloy class for Accident Tolerant Fuel (ATF) nuclear fuel cladding [1].

SM-SANS, shown schematically in Figure 1, uses Pb-shielding to reduce the radiological risk of irradiated cladding specimens on common magnetic-SANS instrument configurations. This novel configuration enables the extraction of both the magnetic and the nuclear-magnetic scattering intensity profiles, Figure 1, while dealing with highly radioactive specimens such as those neutron irradiated to near end-of-life conditions. A free-form size distribution local monodispersed model [2] can then be applied to extract critical microstructure data including nanoclustering size distribution (and metrics), number density, volume fraction, and an inference of composition and structure. All of this can be completed on samples with little to no sample preparation. We will show that the SM-SANS method provides an alternative, rapid method for characterizing nanoscale clustering compared to APT-based techniques.

Until recently, the de facto methods for dislocation loop imaging is the application of either 2-beam imaging and/or weak beam dark field imaging [3]. On-zone STEM imaging is quickly replacing these difficult-to-configure imaging conditions due to the simplicity of obtaining the correct imaging conditions coupled with excellent signal-to-background micrographs [4]. This easy to obtain (which accelerates data collection) and high-quality micrographs are idealized for the application of deep learning-based feature detection and tracking algorithms. Here, we show that the application of the Faster R-CNN method [5] in a detection and analysis framework, Figure 2, can be applied to provide human-like levels of performance in characterizing on-zone STEM images (e.g. F1 scores >0.80). An example of our frameworks output is shown in Figure 2. This greatly simplified data collection and automated analysis methods significantly cuts down the time (e.g. two-three orders of magnitude) from irradiation to data that can be used to accelerate the informed decision-making process during alloy development or fuel-cladding qualification efforts [6].

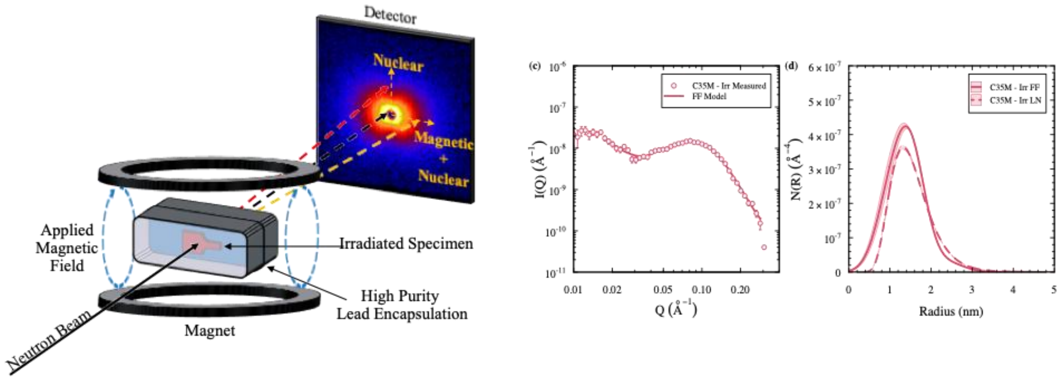

Figure 1. Schematic of the SM-SANS configuration (left) and extracted 1D scattering profiles from an irradiated FeCrAl alloy and resulting size distributions based on the free-form model (right).

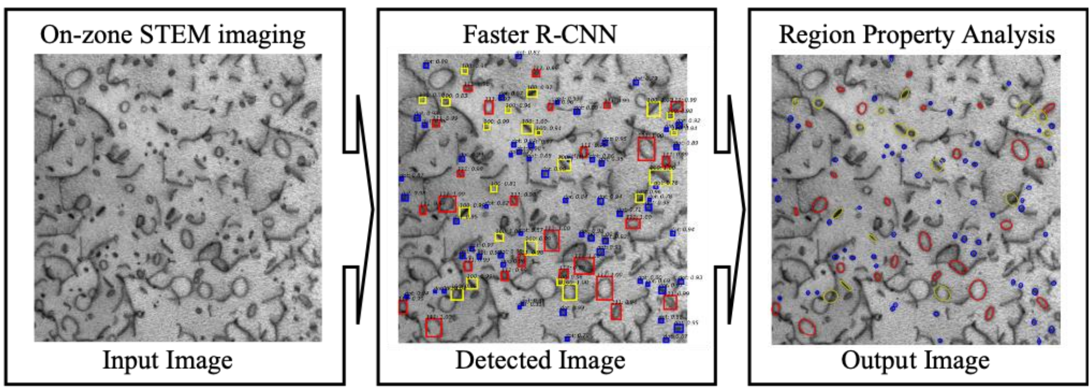

Figure 2. Automated detection and analysis framework using on-zone STEM imaging, the Faster R-CNN detection algorithm and a custom property analysis algorithm for dislocation loops in FeCrAl alloys.

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