Mechanical Behavior of UO2 at Sub-grain Length Scales: Quantification of Elastic, Plastic and Creep Properties via Microscale Testing

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ABSTRACT:

Thermo-mechanical behavior of oxide fuels is extremely important, since it is key to understand Pellet-Cladding Mechanical Interactions (PCMI) that can lead to fuel fracture, which in turn can affect fuel performance significantly. In addition, sub-grain scale mechanical behavior, e.g., anisotropy of elastic properties as well as dislocation driven plasticity and creep, can also play a significant role on microstructure evolution of fuels. Therefore, careful measurements of mechanical properties are key to validate robust fuel performance codes able to predict this behavior from inputs at the micro-scale, e.g., MARMOT, and to quantify its effects on other aspects of fuel behavior. In UO2, the thermo-mechanical response at the meso-scale depends strongly on crystallography of individual grains and available datasets are far from complete in terms of temperature, stress and stoichiometry in parameter space. Therefore, a thorough understanding of the mechanical response at the sub-grain level will be key to validate advanced fuel codes with multiscale predictive capabilities. To this end, experiments in large single crystals are ideal, but testing of bulk monocrystalline samples can be costly and complicated, particularly after irradiation. This also makes it difficult to use enough samples to study reproducibility and intrinsic material scatter, which are key to calibrate and validate predictive codes. It is proposed to develop techniques to measure properties at sub-grain scales using depleted Uranium Oxide (d-UO2) samples heat-treated to obtain different grain sizes and oxygen stoichiometries, through three main tasks: 1) sample processing and characterization, 2) microscale and conventional testing and 3) modeling. Grain size and crystallography will be characterized using Scanning Electron Microscopy and Electron Backscattering Diffraction. Grains will then be selected based on their crystallography to perform micromechanical tests with samples machined via Focused Ion Beam, with emphasis on micro-pillar compression and micro-cantilever bending. These experiments will be performed under controlled atmospheres, to insure stoichiometry control, at temperatures up to 700 °C and potentially higher and will allow measurement of properties involving elastic (effective Young's modulus), plastic (critical resolved shear stresses) and creep (creep strain rates) behavior. Conventional compression experiments will be performed simultaneously to validate microscale results and study potential size effects. Modeling will be implemented using finite elements with anisotropic elasticity and inelastic constitutive relations for plasticity and creep based on kinematics and kinetics of diffusion assisted dislocation glide and climb that account for effects of crystal orientation, stress, temperature and stoichiometry. The models will be calibrated and validated using the experimental data. This project will result in correlations between stoichiometry, crystallography and mechanical behavior in advanced oxide fuels, provide experimental data to validate and calibrate meso-scale fuel codes and also a framework to measure sub-grain scale mechanical properties that is suitable for use with irradiated samples due to the small volumes required. The team at ASU will perform sample characterization, select grains and orientations for micromechanical testing, do conventional compression tests, and develop finite element models. The team at UCB will fabricate both micro-pillars and micro-cantilever beams, perform experiments to measure the onset of plastic deformation and creep rates as a function of stress and temperature under controlled atmospheres and assist on data analysis and model formulation. Collaborators at LANL will provide d-UO2 samples.