Benchmarking Microscale Ductility Measurements

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ABSTRACT:

Conventional macroscale experimentation is generally considered to be straightforward with few limitations. Conversely, micro/nanoscale experimentation presents numerous challenges in loading device design, sample preparation and handling, as well as accurate understanding of grain size and local texture effects on recorded measurements. Despite these challenges, nanopillar compression, MEMs based micro-tension, and nanoindentation approaches have been able to provide fundamental contributions to the understanding of material behavior at small lengthscales. However, the overarching shortcoming of these micro/nanoscale experimentation approaches, is the inability to directly translate measurements evaluated at the nm and µm length scales (e.g., hardness) to macroscale tensile material behavior (i.e., elastic modulus, yield strength, and ductility).

The objectives of the proposed study are, 1) to establish best practices for obtaining tensile microscale ductility measurements, and 2) to validate methodologies to for comparing microscale ductility measurements to macroscale ductility measurements. In order to achieve these objectives, a multi-lengthscale, multi-temperature testing protocol and simulation framework will be executed first on copper as a model material to validate the following approach, and second on reactor grade Zircaloy-2.

Experiments are conducted on specimens extracted from the same test piece to ensure nominally identical grain size and texture from specimens to specimen. Motivated by the need to isolate the contribution of size-effects on obtained mechanical property measurements, specimens are manufactured with thicknesses at the micro- (1-10 µm), meso- (10-100's µm), and macroscales (sub-sized ASTM E8). In-situ full-field deformation techniques (scanning electron microscopy (SEM) grid methods and optical DIC) are incorporated into testing at each specimen length-scale to capture plasticity localization and evolution. Experimental testing for all specimens is conducted at both room temperature (25°C) and elevated temperatures (100,200, or 300°C) to probe the role of thermal activation on plastic deformation accommodation processes. Post-mortem TEM will be conducted to examine dislocation activity and defect structures.

Simulation efforts focus on examining the mechanical behavior of microscale specimens using a finite element approach with explicitly resolved grain morphologies, and an embedded RPI crystal plasticity model. The cost-efficient implementation method allows for the modeling of a statistically significant number of both real (i.e., digital twin) and generated microstructures to obtain an understanding of the interrelationships between specimen microstructure and geometric variables (grain size, texture, specimen geometry, etc.) on microscale mechanical behavior.

Anticipated outcomes of the project are: 1) measurement of grain and sub-grain localization processes at the micro, micro and macroscales; 2) establishment of best practices for microtensile experimentation; 3) identification statistically significant relationships between specimen geometry, microstructure variables and mechanical behavior, 4) modified phenomenological elongation based ductility models to enable direct upscaling of microscale ductility measurements to macroscopic ductility measurements; and 5) the education, training and development of four graduate students in the area of nuclear materials research.