INL/EXP-23-74126-Revision-0

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August 2023

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

An accelerated assessment of the creep mechanisms in uranium zirconium model alloys

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Nanoindentation creep was demonstrated on nuclear fuel materials up to 200ºC. Temperature dependency of the obtained creep exponent was observed, agreeing with the creep theory. The load-dependency and stress relaxation were also identified for future investigation.

Creep in nuclear fuel

Creep is generally observed in nuclear fuel, cladding, and structural materials. It limits the lifetime of the nuclear components. Various factors such as high temperature, stress, irradiation, and the material microstructure evolution, simultaneously complicate the deformation mechanism behind the creep phenomena. Thus, understanding the creep on fuel and structural materials in a nuclear reactor is essential for safe reactor operation but remains challenging.

Challenges

Conventional creep measurements are expensive and time consuming. This makes it difficult to gather data quickly and efficiently for new structural and fuel material development. In addition, the microstructural heterogeneity in irradiated fuels prevents conventional testing methods to obtain microstructure-dependent creep properties.

Nanoindentation method

With a smaller amount of sample, nanoindentation creep measurements hold promise as they have been shown to measure the creep stress exponent that is comparable to the macro-scale values but at a significantly reduced time scale. It also gives localized material information regarding a specific area of interest.

Significance

This project combined modeling and nanoindentation creep measurements to better understand the deformation that is taking place under the tip. Specific areas of interest are the examination of the interface between plastic deformation and elastic deformation regions under the indent.

The understanding of the size of the plastic zone and its growth as compared with the elastic zone during the indent would give insights into the deformation process taking place in the material.

Methodology

Creep test

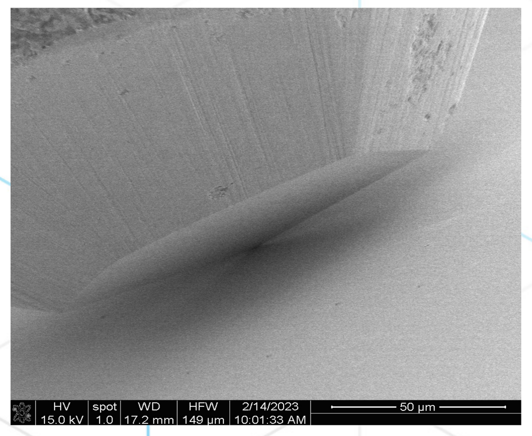
(1) Annealed U-50 wt% Zr samples were polished to a mirror finish for the nanoindentation creep test in vacuumed SEM chamber.
(2) Nanoindentation creep tests were conducted with a Berkovich tip under the force-controlled mode.
(3) The force dependency, temperature dependency, and loading rate dependency were examined.
(4) The data was processed with classic creep theory.

Stress relaxation test

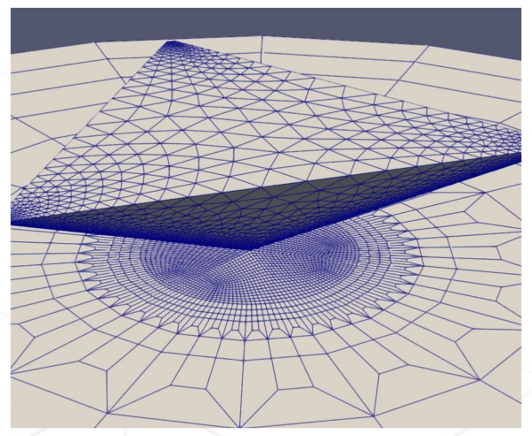
(1) The stress relaxation tests were conducted with a Berkovich tip under the displacement-controlled mode.
(2) Stress relaxation tests were performed on both U-50Zr and pure-aluminum.
(3) The data was processed with power law and general-Maxwell models.

Computational modeling

(1) Modeling and simulation of the indentation process are carried out using MOOSE [1] and the mesoscale code, Marmot [2], for the aluminum and alpha uranium crystal plasticity capabilities, respectively.
(2) The modeling visualized the microstructural evolution and stress distribution under the Berkovich tip.



Berkovich nanoindenter

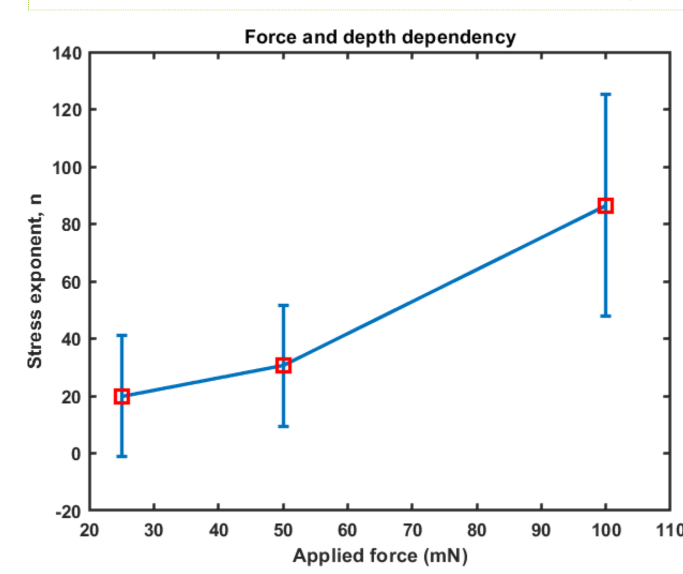


Berkovich tip in modeling

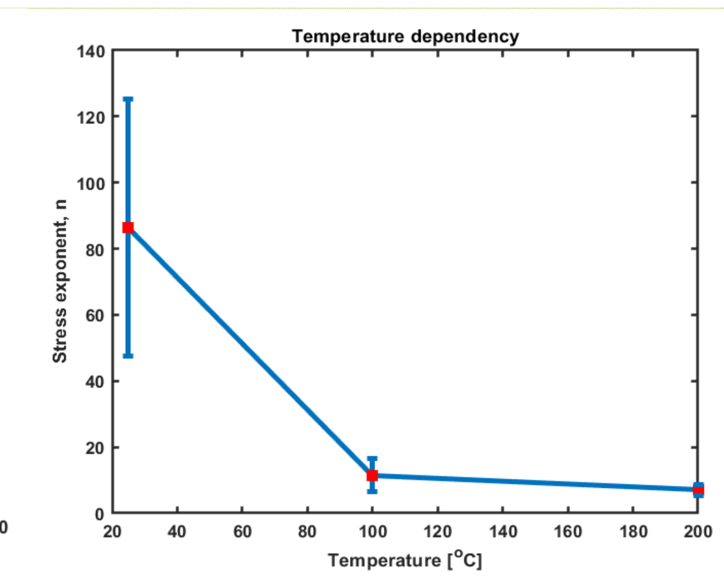
[1] Lindsay, Alexander D., et al. "2.0-MOOSE: Enabling massively parallel multiphysics simulation." SoftwareX 20 (2022): 101202.
[2] Idaho National Laboratory, Virginia Polytechnic Institute and State University "MARMOT Mesoscale Simulation Code" https://inlsoftware.inl.gov/product/marmot

Creep

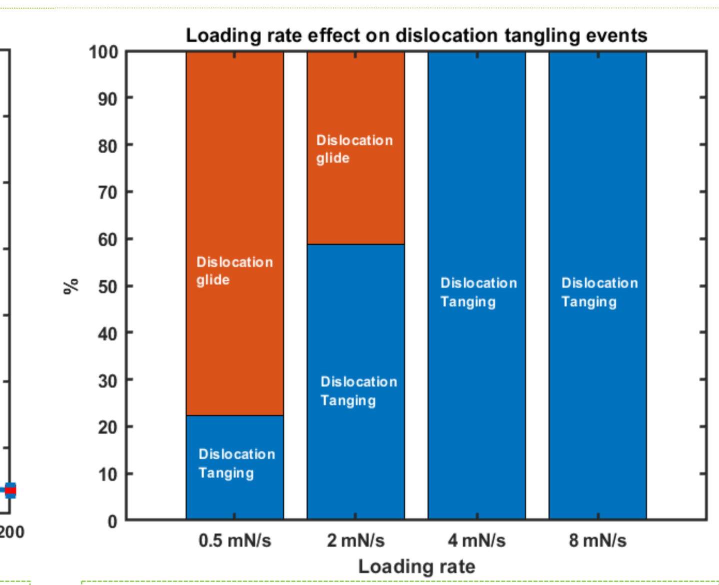
Creep is a time-deformation phenomenon that can relate to stress, temperature, and microstructure. The stress exponent based on the classic creep theory is an experimental value of stress sensitivity used to infer a possible mechanism and structural evolution of the deformation. Our results show a force effect, temperature effect, and loading-rate effect on creep behavior via nanoindentation method.



The force (25mN, 50mN, and 100mN) effect on creep at room temperature shows an increasing stress sensitivity to the deformation rate along with the depth. The dislocation glide is the dominant deformation mechanism.



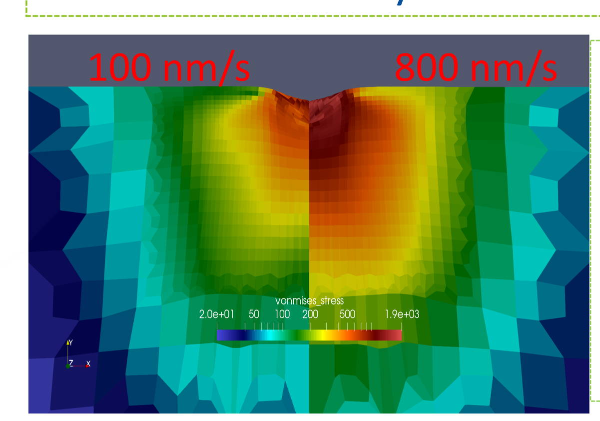
The temperature effect (25°C, 100°C, and 200°C) shows a decreasing stress sensitivity. The higher temperature initial a vacancy diffusion leading to dislocation climb mechanism.



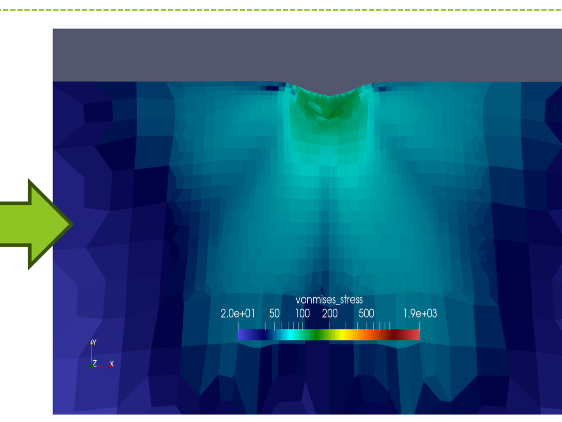
A higher applied loading speed leads a higher chance to dislocation tangling events and thus induces a longer stress relaxation which influences the stress rate sensitivity during steady state creep.

Stress Relaxation

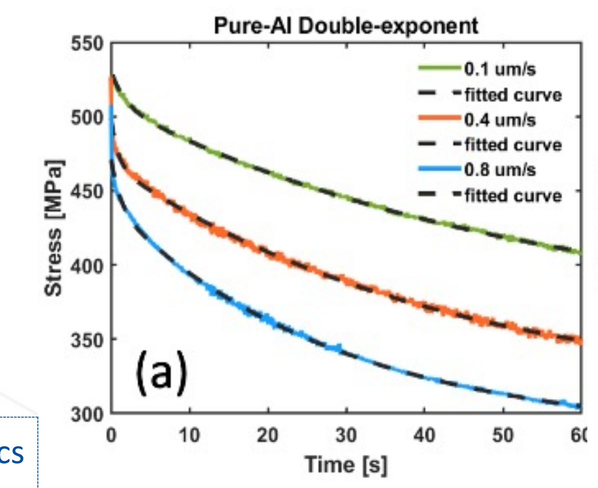
Stress relaxation is a phenomenon of atom re-arrangement during material deformation. Our results from both experiment and modeling show a loading rate dependency on stress relaxation, and a new approach for stress sensitivity estimation is developed.

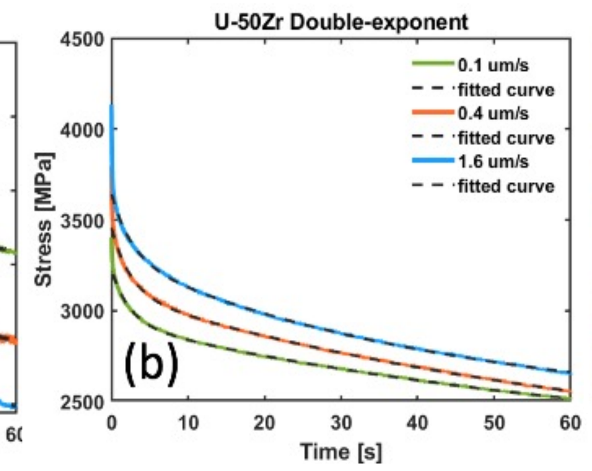


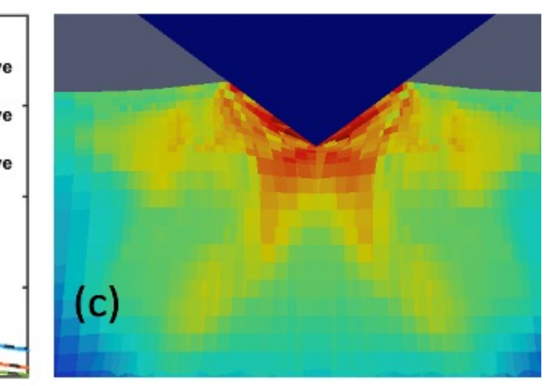
Von Mises stress 0.0 seconds into the holding phase comparing loading rates of 100 and 800 nm/s with a stress exponent of 10. The stress in 800 nm/s is much higher.

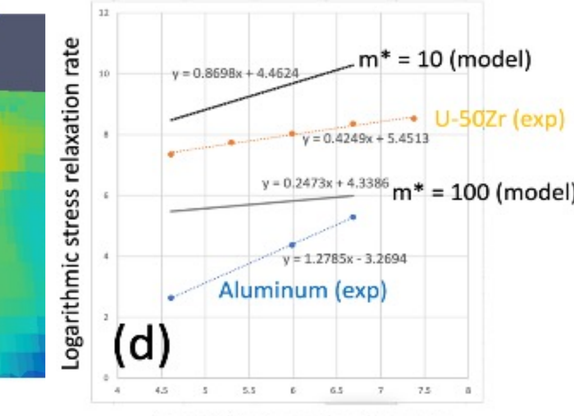


Von Mises stress 2.0 seconds into the holding phase comparing loading rates of 100 and 800 nm/s with a stress exponent of 10. Both loading rates relax to nearly the same stress distribution.









Nanoindentation stress relaxation in aluminum (a) and U-50Zr (b) following different pre-loading displacement rates. This relaxation process was simulated using MOOSE with crystal plasticity model (c) and the relationship between stress relaxation and pre-loading rate is demonstrated as a new approach for stress exponent estimation (d).

Project Number: 22P1068-002FP
LRS Number: INL/EXP-23-74126

Work supported through the INL Laboratory Directed Research & Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517."

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