SHORT COMMUNICATIONS

Ion Irradiation for High Fidelity Simulation of High Dose Neutron Irradiation

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Traditionally, research to understand radiation-induced changes in materials is conducted via radiation effects experiments in test reactors, followed by a comprehensive post-irradiation characterization plan. Ion irradiations have been developed to the point where temperature is extremely well controlled and monitored, and damage rate and total damage are also measured continuously throughout the irradiation and with great accuracy. The objective of this project is to demonstrate the capability to predict the properties of structural materials in reactor and at high doses, using ion irradiation as a surrogate for reactor irradiations.

Experimental or Technical Approach

Dual ion irradiations were performed on T91 steel utilizing the dual beam configuration at the Michigan Ion Beam Laboratory using 5 MeV iron ions with a helium co-injection rate of about 4 appm He/dpa to a total damage of up to 35 dpa at temperatures of 406–570°C to complement irradiation of the same alloy in the BOR-60 reactor up to 35 dpa at temperatures from 360–525°C. Additional single beam ion irradiations were conducted on T91 to isolate the role of irradiation damage rate and co-injected helium. These experiments were used in conjunction with rate theory models of cavity evolution, helium portioning, and a more detailed cluster dynamics model.

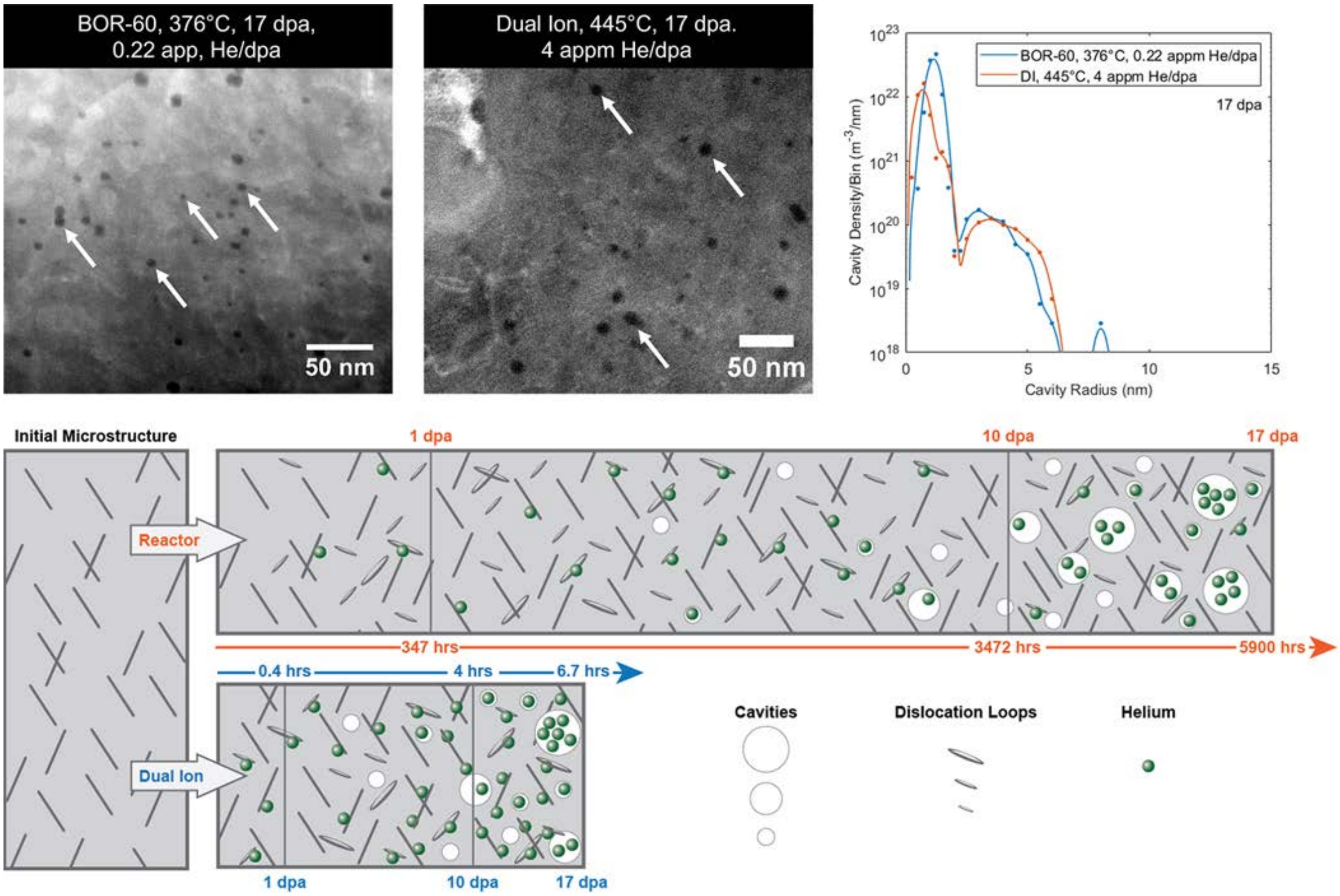

Figure 1. A comparison of scanning transmission electron microscopy high-angle annular dark field (STEM HAADF) images of T91 from BOR-60 irradiation and complementary dual ion irradiation with corresponding cavity size distributions (above) and schematic of the time-dependent helium trapping and release behavior under reactor and ion irradiation conditions (below).

Results

The microstructure from the dual ion irradiation was characterized using transmission electron microscopy (TEM) and compared with the BOR-60 irradiated steel. Cavities were characterized using high angle annular dark field scanning TEM. Additional characterization was performed to identify cavities smaller than 2 nm in radius using over focused and under focused bright field TEM imaging with a Gatan OneView 16-megapixel charge-coupled device (CCD) camera capable of 4K resolution with 0.25 nm point-to-point resolution. Hand counting techniques were used with the FIJI image software to measure the cavity diameter to convert to a cavity radius and estimate the density of cavities from resulting images. Images for cavities can be found in the supplemental materials for Taller and Was' 2020 article [1]. Dislocation loops were imaged using on-zone STEM BF imaging near the [001] or [011] zone axis to view dislocation loops on edge, or nearly on edge, to distinguish between a < 100 > dislocation loops, a/2 < 111 > dislocation loops, and dislocation lines. The dislocation and cavity microstructures of dual ion irradiated T91 and T91 irradiated in the BOR-60 fast reactor matched extremely well using a temperature shift of +60–70°C and an increase in the helium injection ratio.

Discussion/Conclusion

Higher damage rates in ion irradiation require higher irradiation temperatures to maintain a balance between defect production and loss; however, with helium transmutation, the temperature shift is less than predicted by invariance relationships. Higher rates of helium implantation are required in dual ion irradiations to compensate for the reduced irradiation time that impacts the distribution of helium among the microstructural features. The temperature dependence of swelling is governed by both the thermal evaporation of small vacancy clusters and helium trapping at damage rate independent trapping sites. These conclusions provide a guiding "formula" for predicting the complex radiation induced phenomenon of cavity nucleation and growth at an accelerated damage rate.

References

[1.] S. Taller, and G. S. Was. "Understanding Bubble and Void Nucleation in Dual Ion Irradiated T91 Steel using Single Parameter Experiments." *Acta Materialia*. Vol. 198. October 1, 2020. pp. 47–60, https://doi.org/10.1016/j.actamat.2020.07.060.

[2.] Taller, S., and G. S. Was. "Understanding Bubble and Void Nucleation in Dual Ion Irradiated T91 Steel using Single Parameter Experiments." *Acta Materialia*. vol. 198. October 1, 2020. pp. 47–60, https://doi.org/10.1016/j.actamat.2020.07.060.

[3.] Taller, S., F. Naab, and G. S. Was. "A Methodology for Customizing Implantation Profiles of Light Ions Using a Single Thin Foil Energy Degrader." *Nuclear Inst. and Methods in Physics Research: B*. vol. 478. September 1, 2020. pp. 274–283. https://doi.org/10.1016/j.nimb.2020.07.017.

Publications

[1.] Taller, S., G. VanCoevering, B. D. Wirth, and G. S. Was. "Predicting Structural Material Degradation in Advanced Nuclear Reactors with Ion Irradiation." *Scientific Reports*, vol. 11. 2949. 2021, https://doi.org/10.1038/s41598-021-82512-w.

Distributed Partnership at a Glance

NSUF Institution	Facilities and Capabilities
University of Michigan	Michigan Ion Beam Laboratory
Collaborators	
University of Michigan	Stephen Taller (collaborator), Valentin Pauly (collaborator), Gabriella Bruno (collaborator), George Jiao (collaborator), Kevin Field (collaborator)