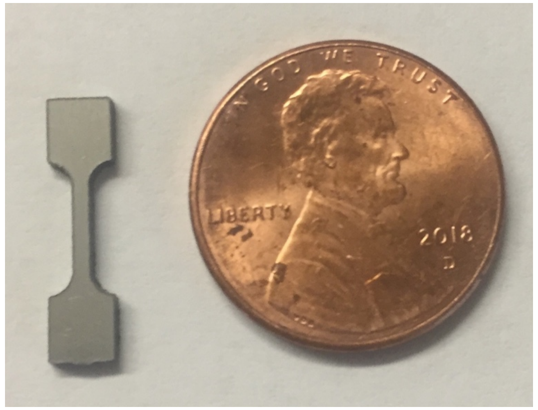
Thermophysical Property Testing Observations

- Stainless steel
  - Unirradiated heat capacities are comparable to reference values
  - Unirradiated thermal diffusivities are higher than reference values
  - Irradiation increased heat capacity and decreased thermal diffusivity
  - The SS-P2 specimens show evidence of anisotropic thermal diffusivity

- Inconel
  - Unirradiated heat capacities are comparable to reference values
  - Unirradiated thermal diffusivities of the Inconel 718 specimens are comparable to reference values
  - Unirradiated thermal diffusivities of the Inconel 625 specimens are higher than reference values
  - Irradiation increased heat capacity and decreased thermal diffusivity

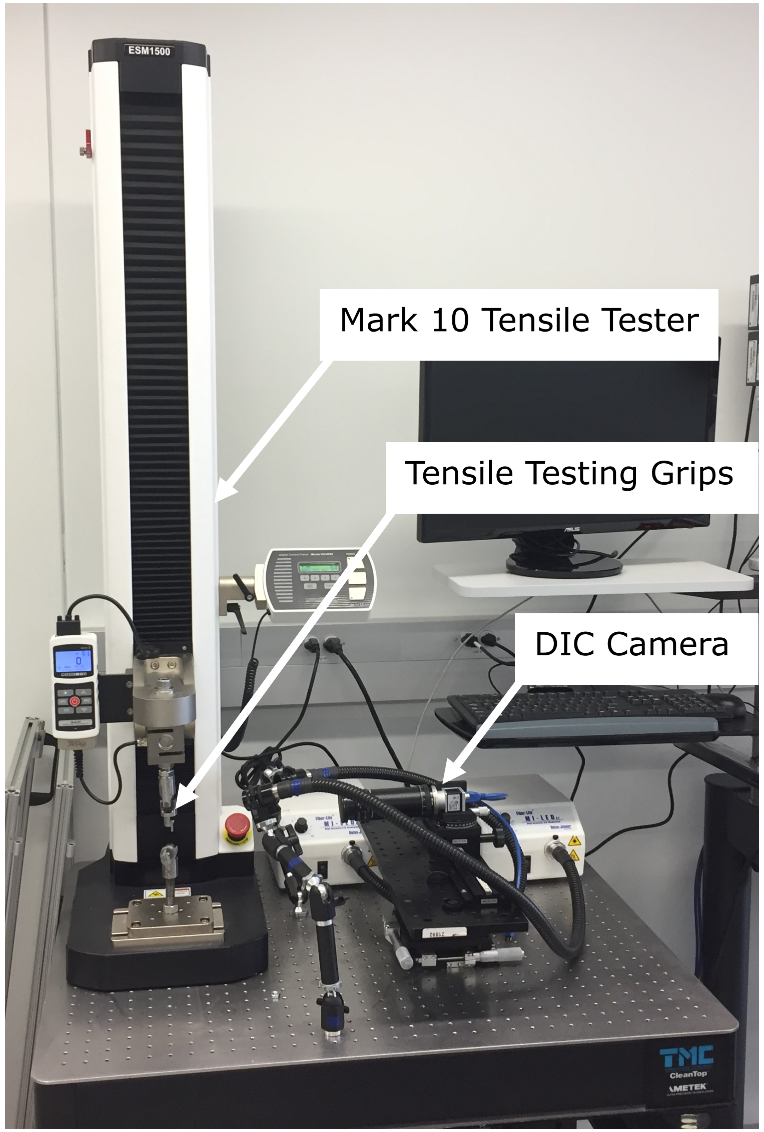
- Additional irradiated specimens need to be run to yield defendable results. (More results to come!)

Pre-Irradiation Mechanical Property Testing Setup

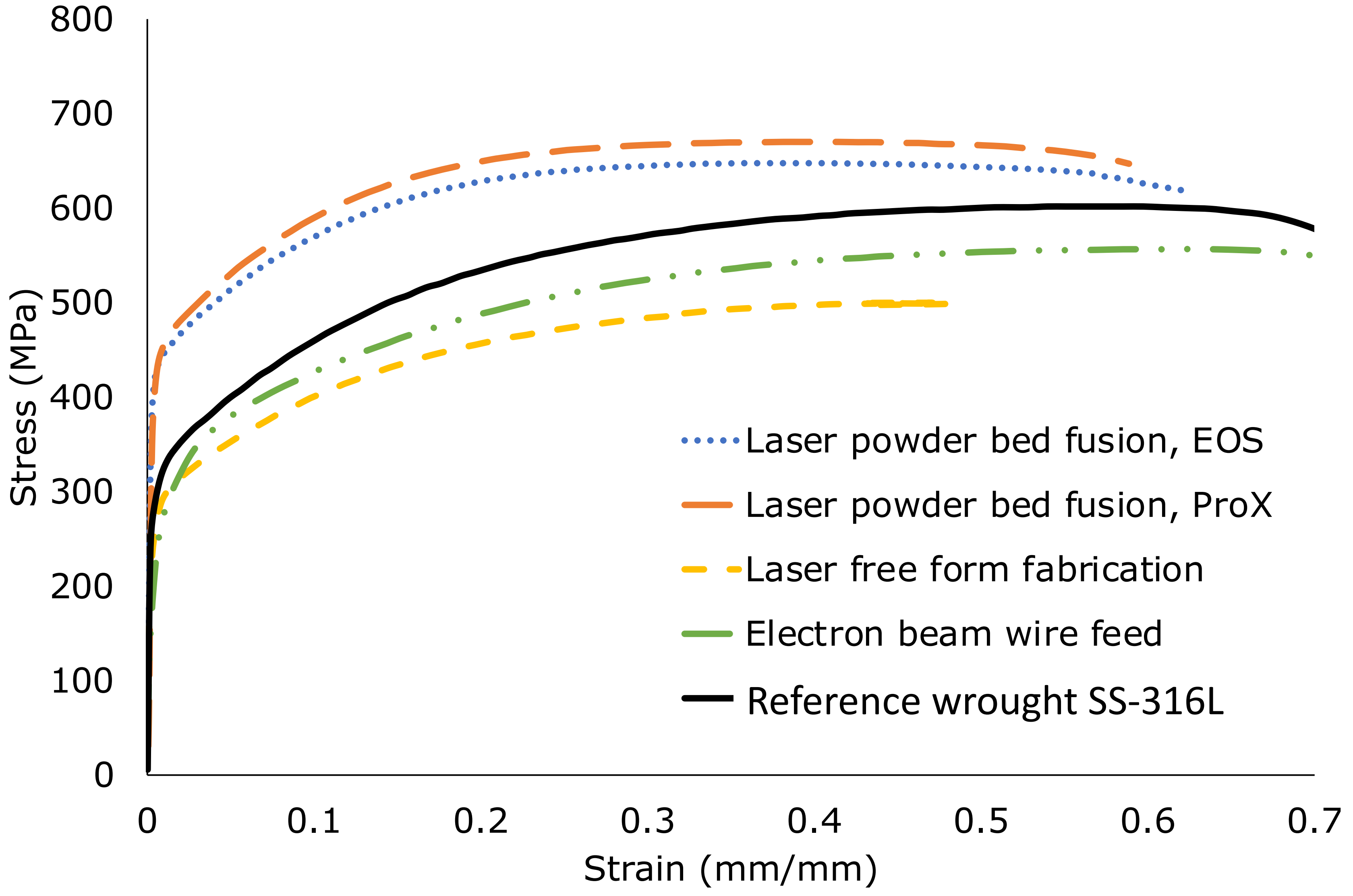


Tensile Specimens

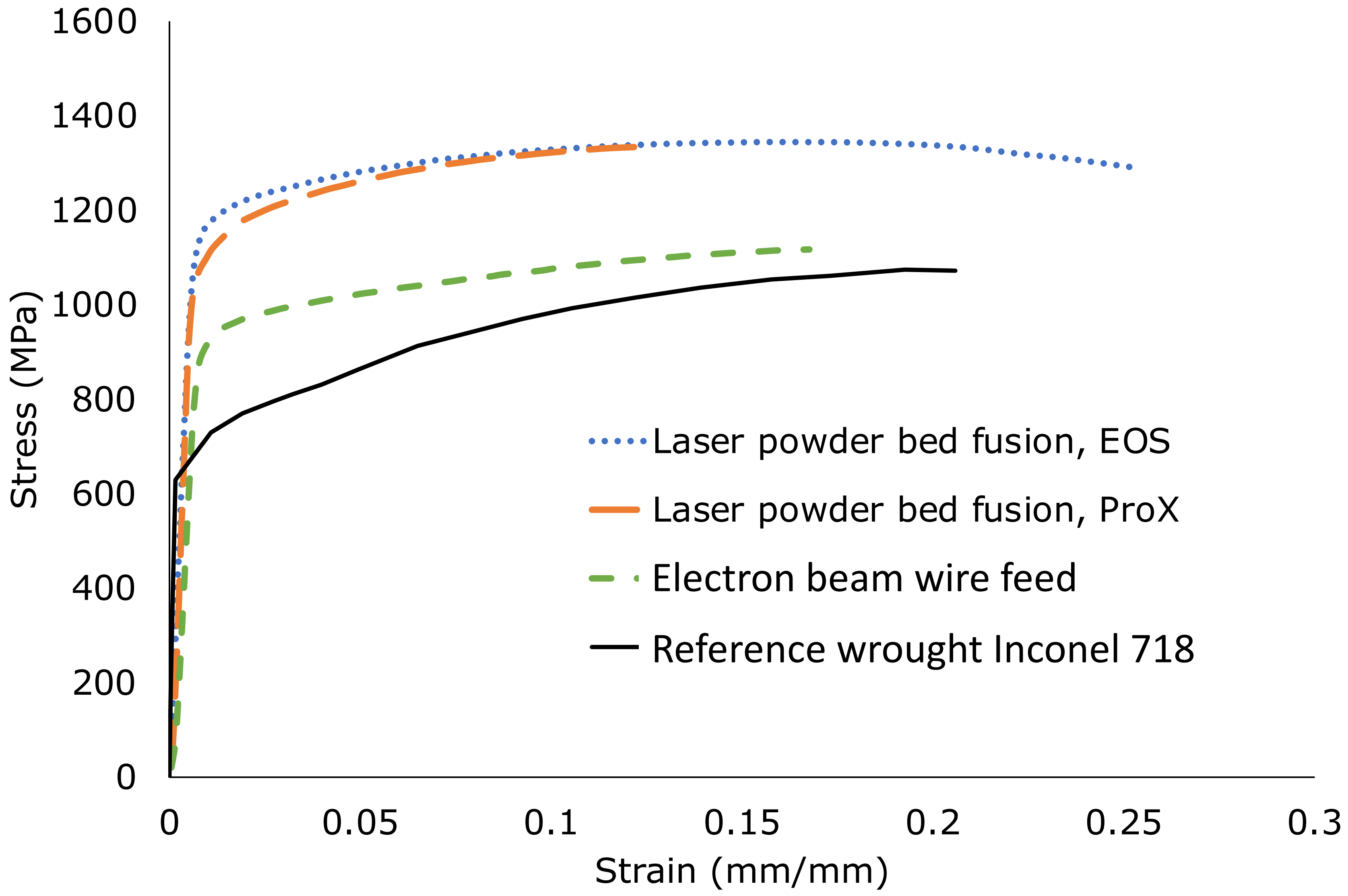
Specimen Holder



Mechanical Test Results (SS-316L)



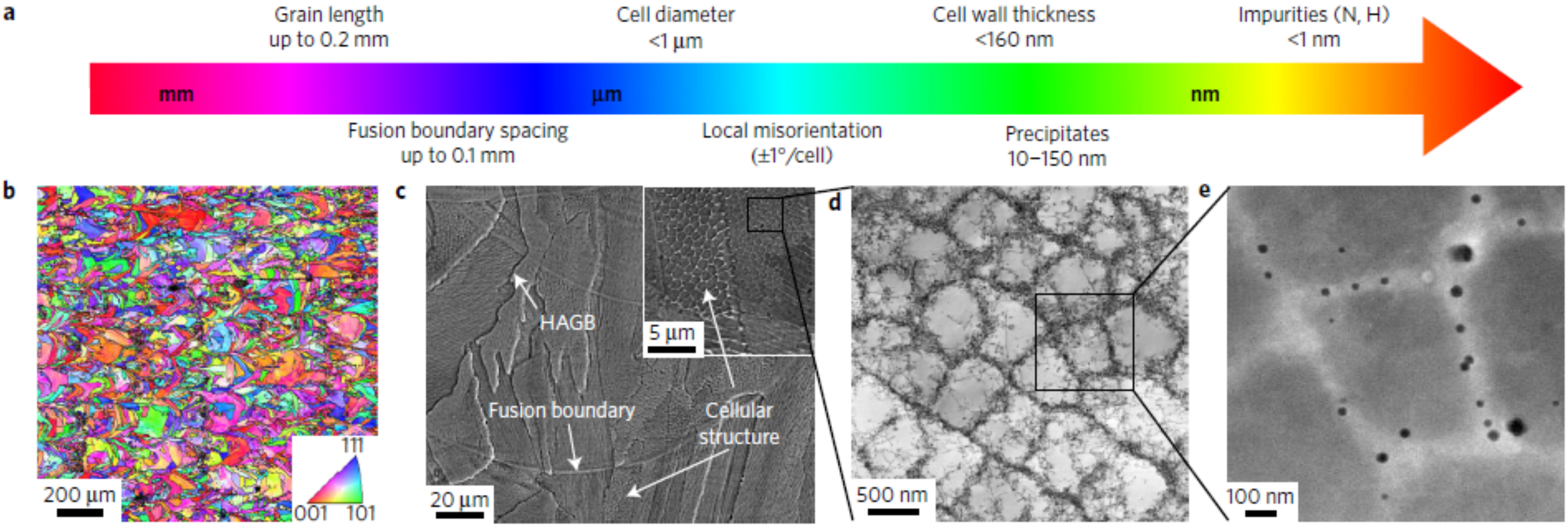
Mechanical Test Results (Inconel 718)



Mechanical Testing Observations

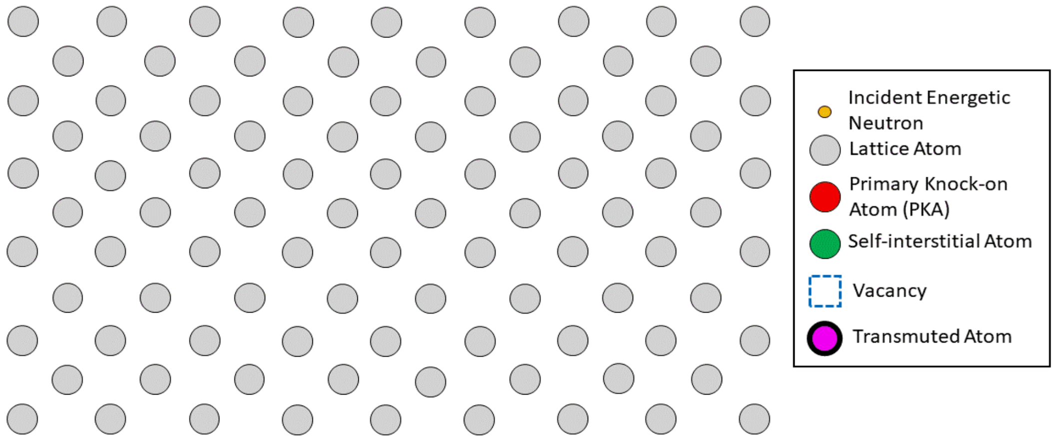
- Stainless steel
  - Both laser powder bed fusion samples exhibited high ultimate tensile strength without a decrease in the ductility
  - The laser free form sample exhibited low ultimate tensile strength
  - The electron beam wire feed sample had a lower modulus of elasticity
- Inconel
  - The laser powder bed fusion samples, both Inconel 718 and Inconel 625, exhibited high ultimate tensile strength without a decrease in ductility
  - The electron beam wire fed Inconel 718 sample exhibited mechanical properties comparable to wrought Inconel 718

Basis For Improved Mechanical Properties

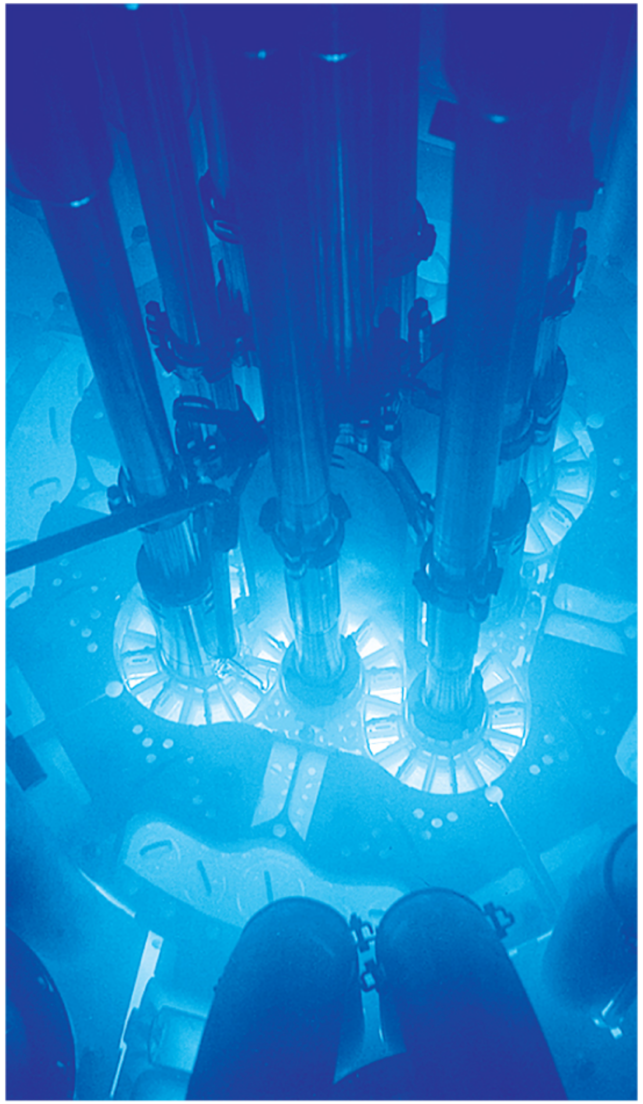


Wang et al., *Nature Materials*, October 2017

The Nuclear Context



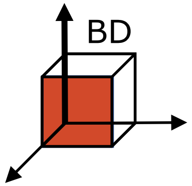
- Radiation damage is driven by ***point defect creation***
  - Build up of defects results in material changes
- Traditionally, grain boundaries act as point defect sinks
  - By optimizing grain boundary character and density, radiation damage can be somewhat mitigated
- **Are the cellular structures stable under irradiation?**
  - How much damage can they accommodate?
  - What impact do the structures have on long-term irradiation performance?

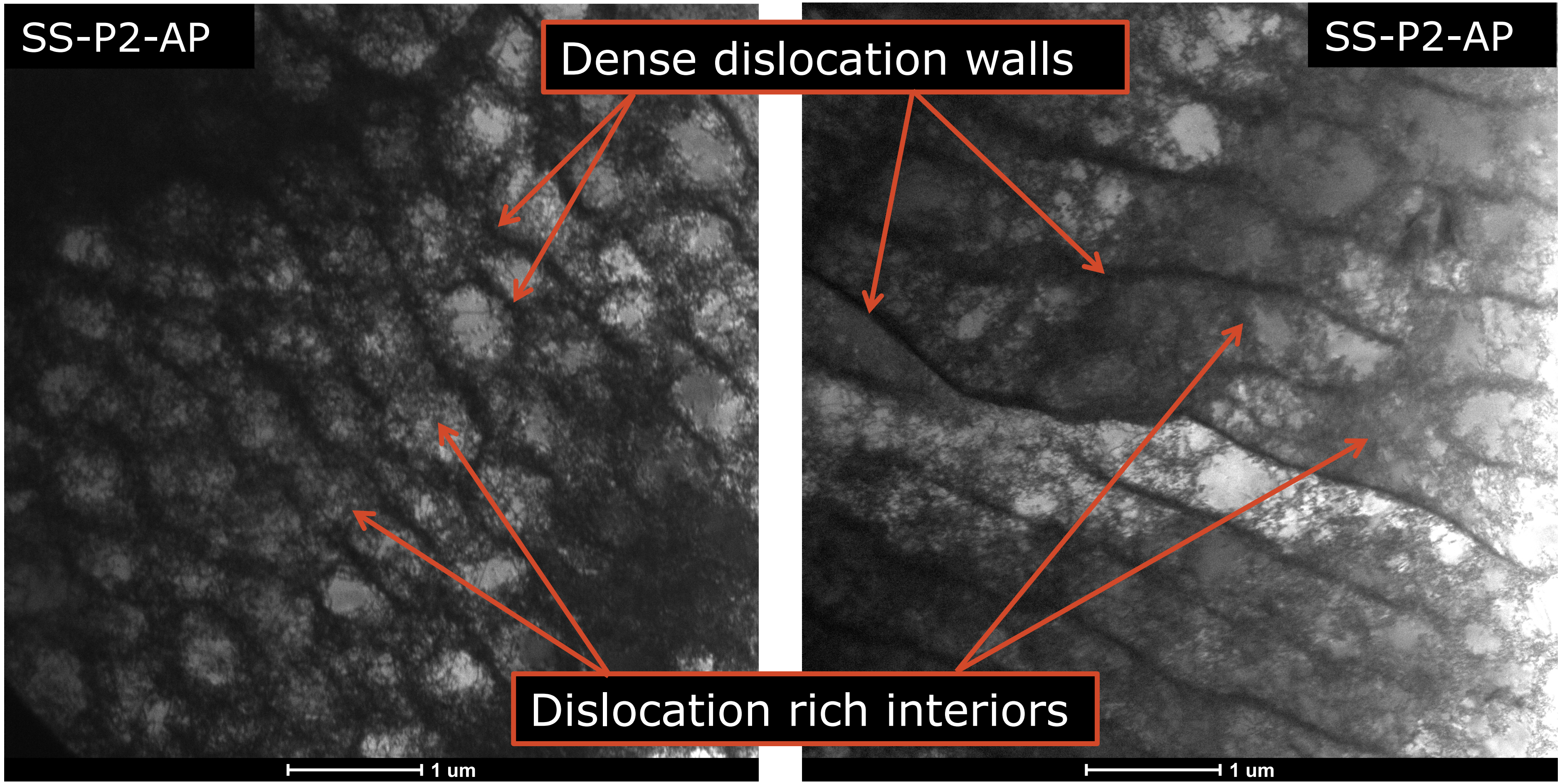


Advanced Test Reactor,
Idaho National Laboratory

Transmission Electron Microscopy

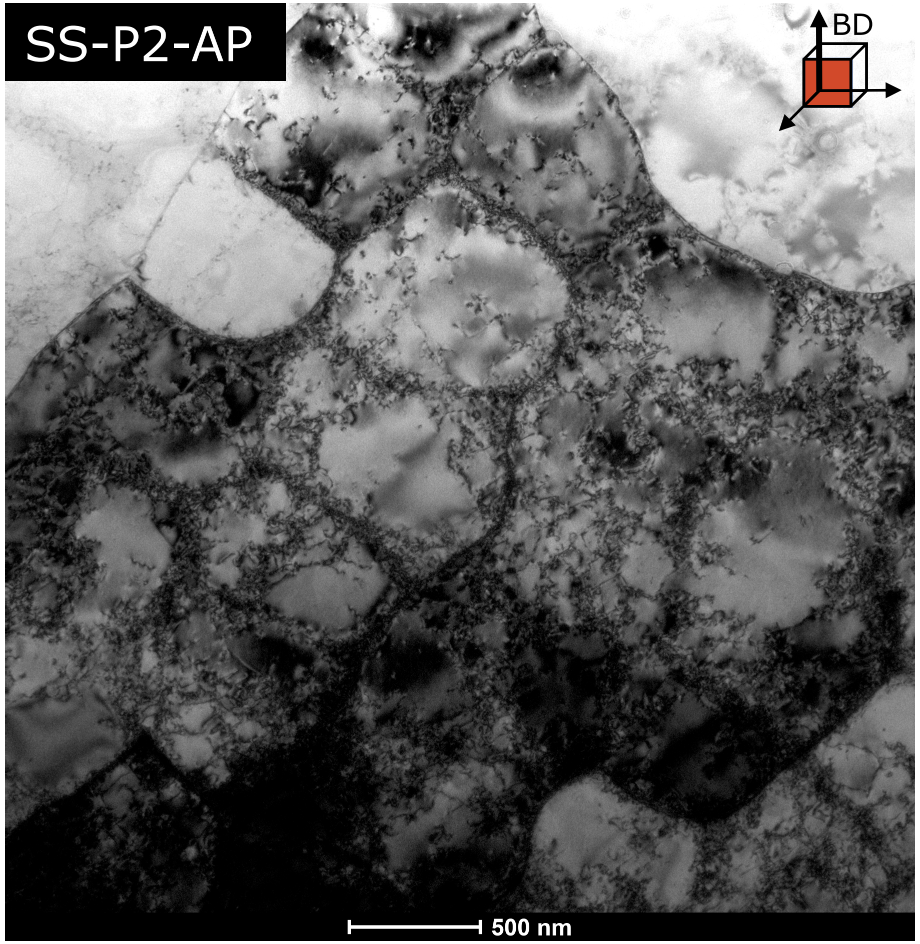
- Investigation of three stainless steel samples in both as-printed and heat-treated conditions
- Cellular structures evident showing dense dislocation walls and decorated with dislocations in the interior

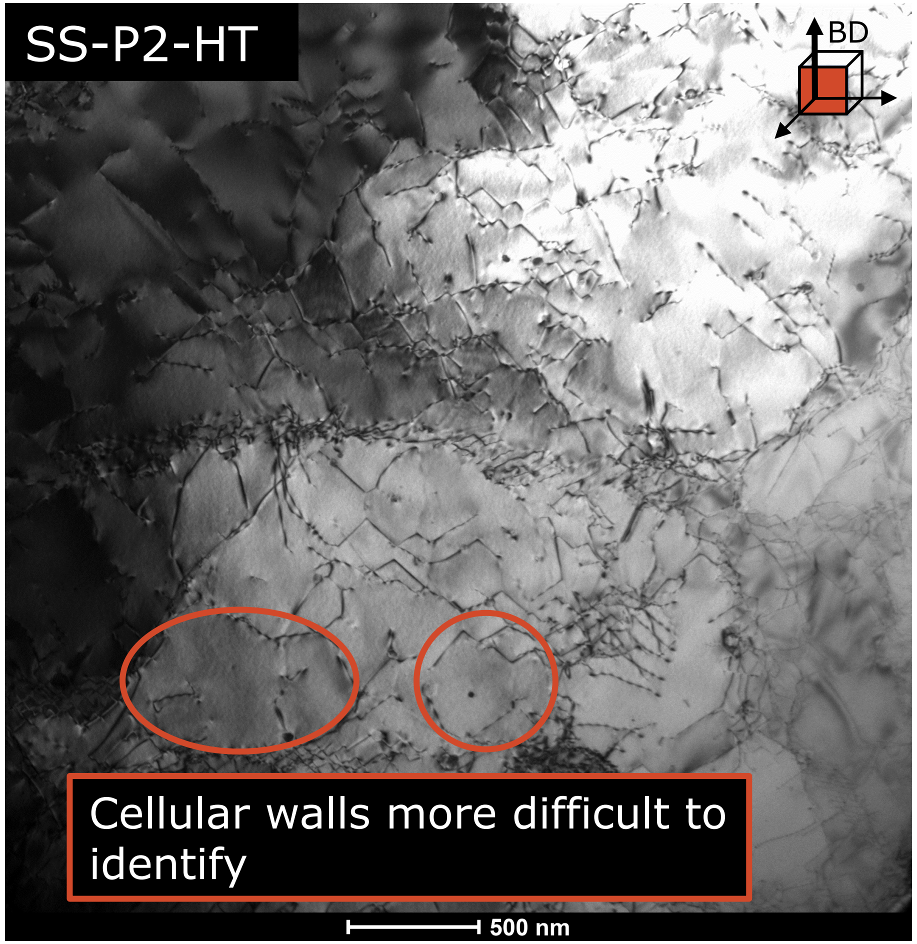




Impact of Heat Treatment

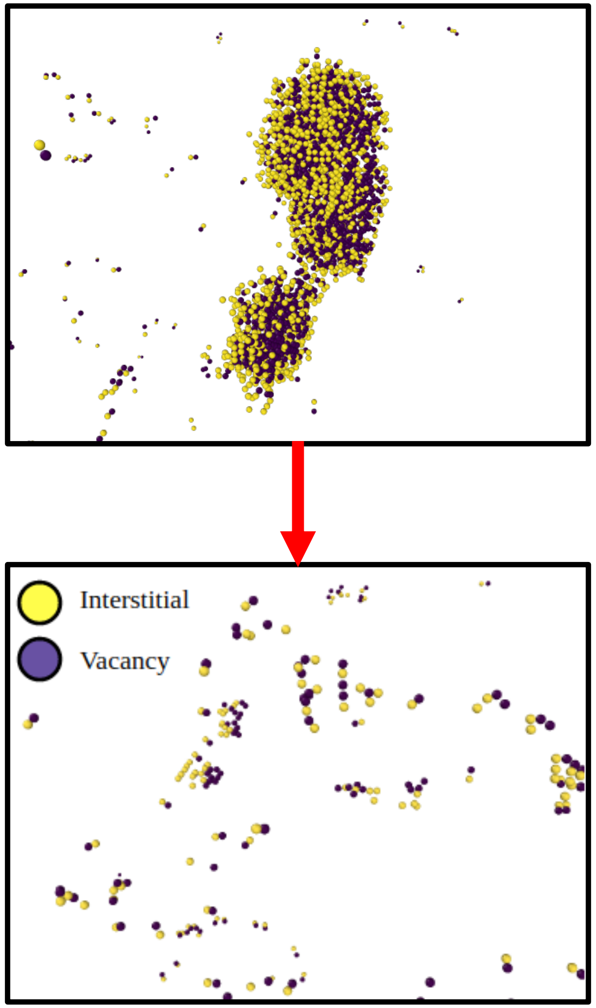
- Dense dislocation walls partially survive heat treatment
- Heat treatment reduced dislocation density by two orders of magnitude ($\sim 10^{16}$ --> $\sim 10^{14}$ dislocations/m^2)



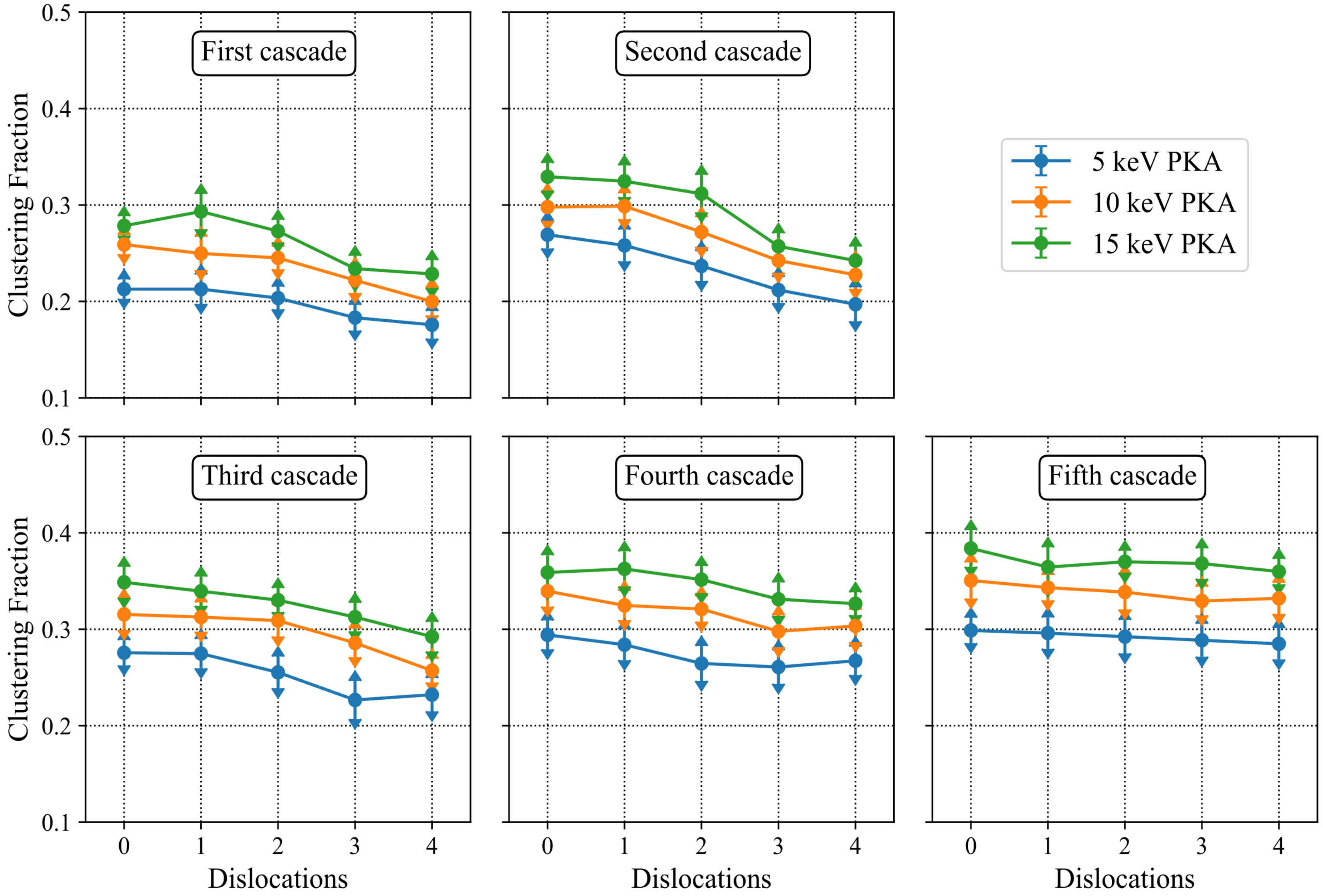


Molecular Dynamics Results

- Molcular dynamics simulations of radiation damage cascades in stainless steel near intersecting edge dislocations suggest that the dislocation tangles will serve as defect sinks, potentially up to 1.5-2 dpa.

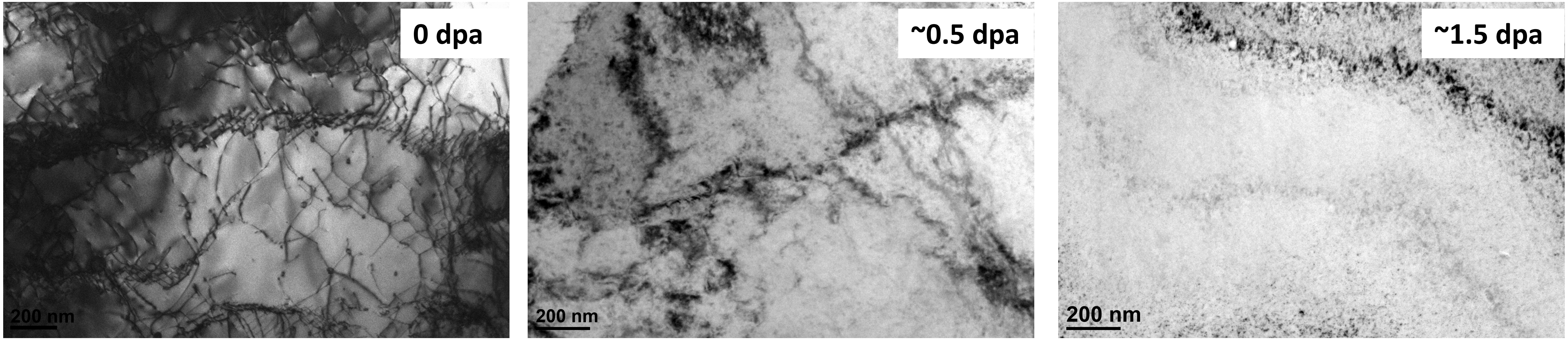


5 keV PKA Cascade

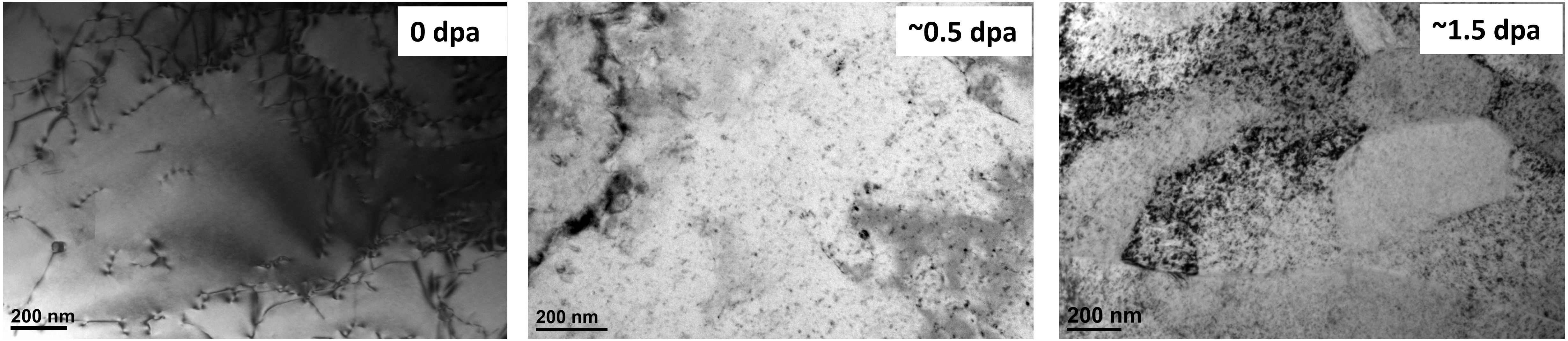


Initial Post-Irradiation TEM Results

SS-P2 (Laser Powder Bed Fusion SS-316L)



SS-P3 (Laser Freeform Fabrication SS-316L)



Caveat lector – this is very early data. Much more to come!

Project Impacts

- Journal Publications
  - 2 invited papers submitted to the *Journal of Nuclear Materials*' "Additive for Nuclear" special issue
- Conference Papers
  - 3 papers published in the *Transactions of the American Nuclear Society*
- Conference Presentations
  - 3 presentations at American Nuclear Society Meetings
- Involvement
  - A total of 4 graduate and 3 undergraduate students have been involved in the project
  - Project will yield 2 PhDs at Mines (one imminent)
- Invitations
  - Semi-regular presentation at the Alliance for the Development of Additive Processing Technologies (ADAPT) member meetings
- Other
  - 4 technical reports documenting the pre-irradiation characterization efforts and data

Milestones and Deliverables for FY-20

- COVID-related NCE granted in FY-20
- Revised project milestones:
  - Baseline Thermophysical Test Results and Microstructure Characterization
    - Original 9/30/19, Revised 3/31/21
    - Completed 9/30/20
  - Post-Irradiation Mechanical and Thermophysical Test Results
    - Original 3/31/20, Revised 9/30/21
  - Post-Irradiation Microstructure Characterization
    - Original 9/30/20, Revised 9/30/21
  - Final Report
    - Original 12/29/20, Revised 12/30/21

Issues and Concerns

- COVID delayed pre-irradiation testing by about 6 months
  - All pre-irradiation work is now complete
- All testing and characterization work at Mines is complete and the Mines budget is fully expended
- COVID delayed post-irradiation testing by at least a year
- All remaining work is at the Nuclear Science User Facilities
  - At present, it appears that the NSUF is on track to complete post-irradiation examination work by the end of current project
  - PI has little control over the scheduling at these facilities

Milestones and Deliverables for FY-21

- Remaining project milestones:
  - Post-Irradiation Mechanical and Thermophysical Test Results
    - Due 9/30/21
  - Post-Irradiation Microstructure Characterization
    - Due 9/30/21
  - Final Report
    - Due 12/30/21

Possible Areas/Industries/Programs (and Readiness) for Adoption

- Not relevant to this project

Contact Information and Questions

- Prof. Jeffrey King
  - Director, Nuclear Science and Engineering Center
  - Colorado School of Mines
  - kingjc@mines.edu

- Acknowledgements
  - Mines Graduate students Ryan Collette, Trace Rimroth, Cliff Ghiglieri, and Mark Graham
  - Mines Undergraduate students Charlie Becquet, Alice Cartes, and Jaden Zymbaluk
  - Mines Research Professor Behnam Amin-Ahmadi
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  - Jeremy Burgener and Yaqiao Wu from CAES