Advanced Methods for Manufacturing

DEC 2 – 3, 2020

Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

Award Number: DE-NE0008590

Award Dates: 10/2016 to 9/2021

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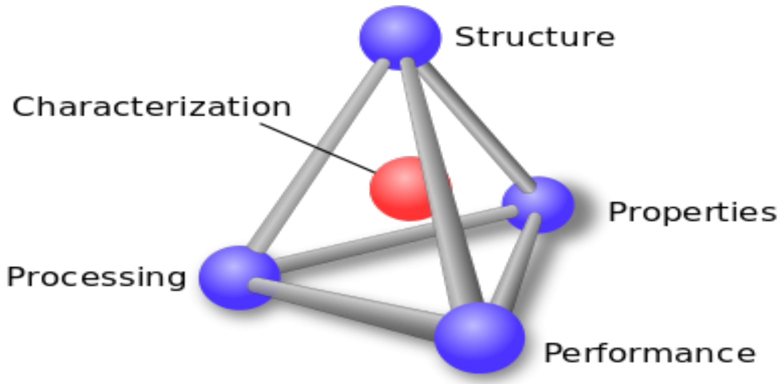
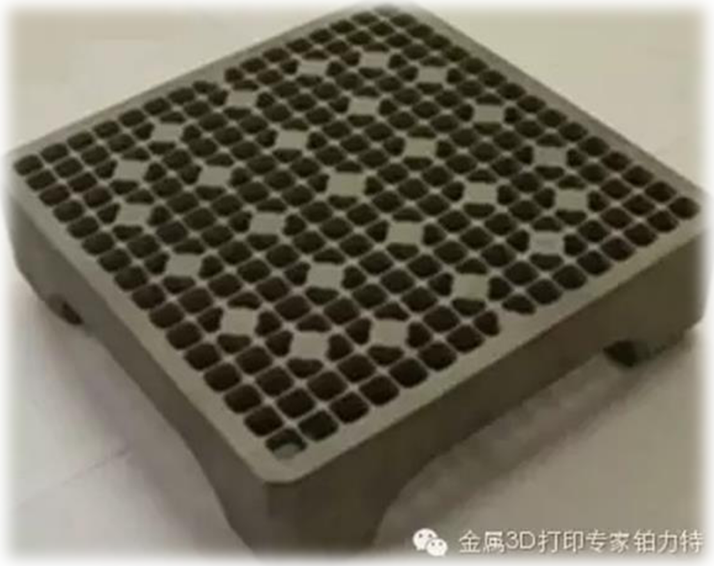
Team Members: Colorado School of Mines, King Research Group

COLORADO SCHOOL OF MINES

Motivation

- Additive manufacturiung can circumvent conventional constraints
  - Unique geometries
  - Rapid prototyping
  - Legacy parts
- The nuclear industry is likely to benefit from additive manufacturing
  - Power conversion (small capillary heat exchangers, pipes, turbine blades)
  - Structural components (core plate assembly, channel grids, spacers, nozzles, plugs)
  - Fuel & Cladding (optimized geometries)
- Nuclear industry implementation is limited by a lack of understanding regarding AM processing-structure-property relationships
  - Particularly related to irradiation performance





AM-produced grid plate for the CAP1400 nuclear fuel assembly (China National Nuclear Corporation)

AM-produced heat exchanger (GE)

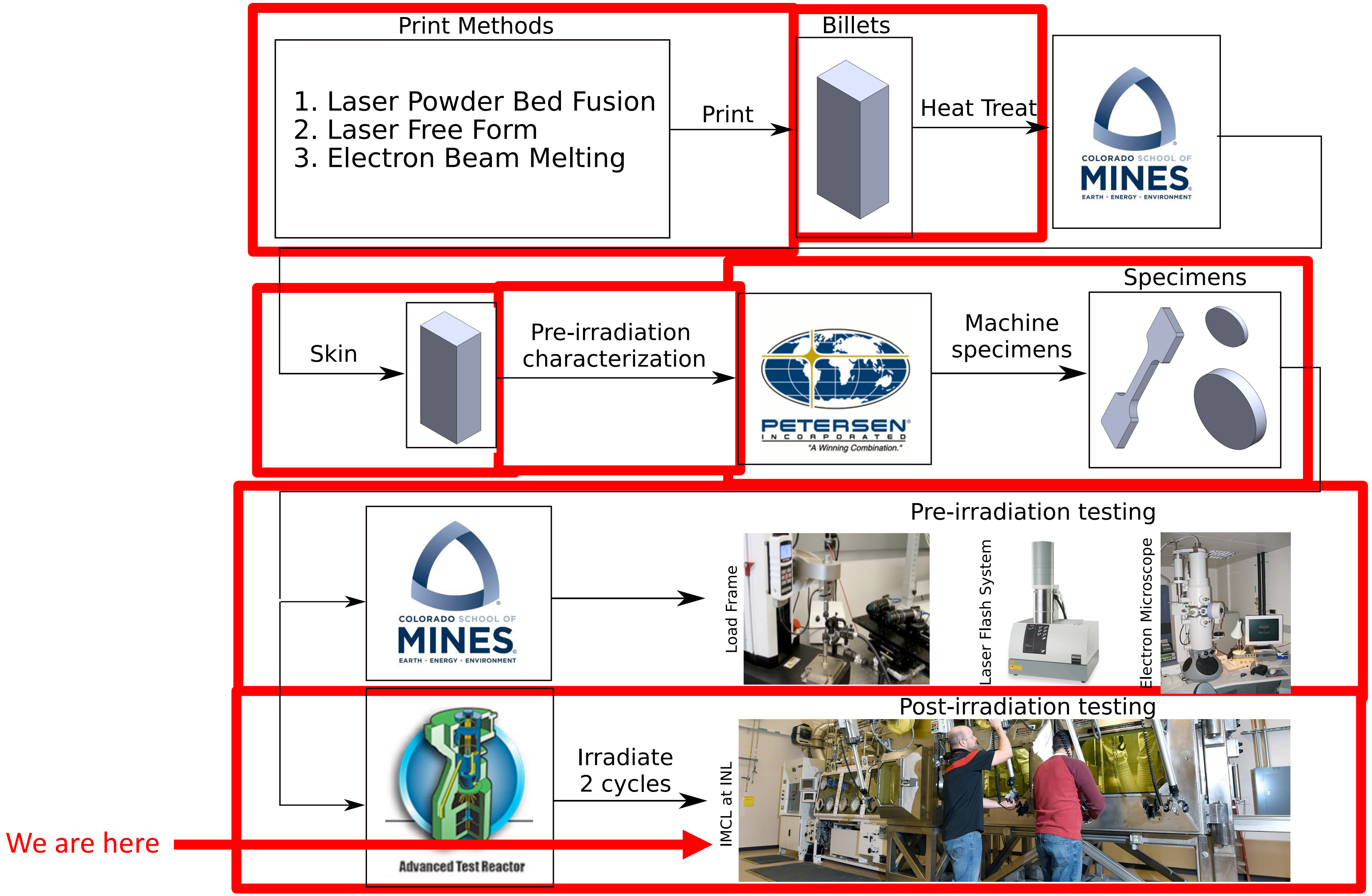
Project Objectives

- The project is collecting irradiation performance data for Stainless Steel 316L and Inconel (718 and 625) specimens produced using different additive manufacturing techniques. The project seeks to elucidate the link between the microstructures produced by additive manufacturing and the impact of neutron irradiation on the mechanical and thermo-physical properties of the specimens.

- Determine as-manufactured properties of SS-316L and Inconel specimens
- Determine impact of irradiation up to 1.6 DPA on specimen properties
- Correlate relationships between manufacturing technique and irradiation damage

Project Plan

- Test the performance of "commercially-available" AM materials in an irradiation environment



Specimen Matrix

- Goal - test the performance of “commercially-available” AM materials in an irradiation environment

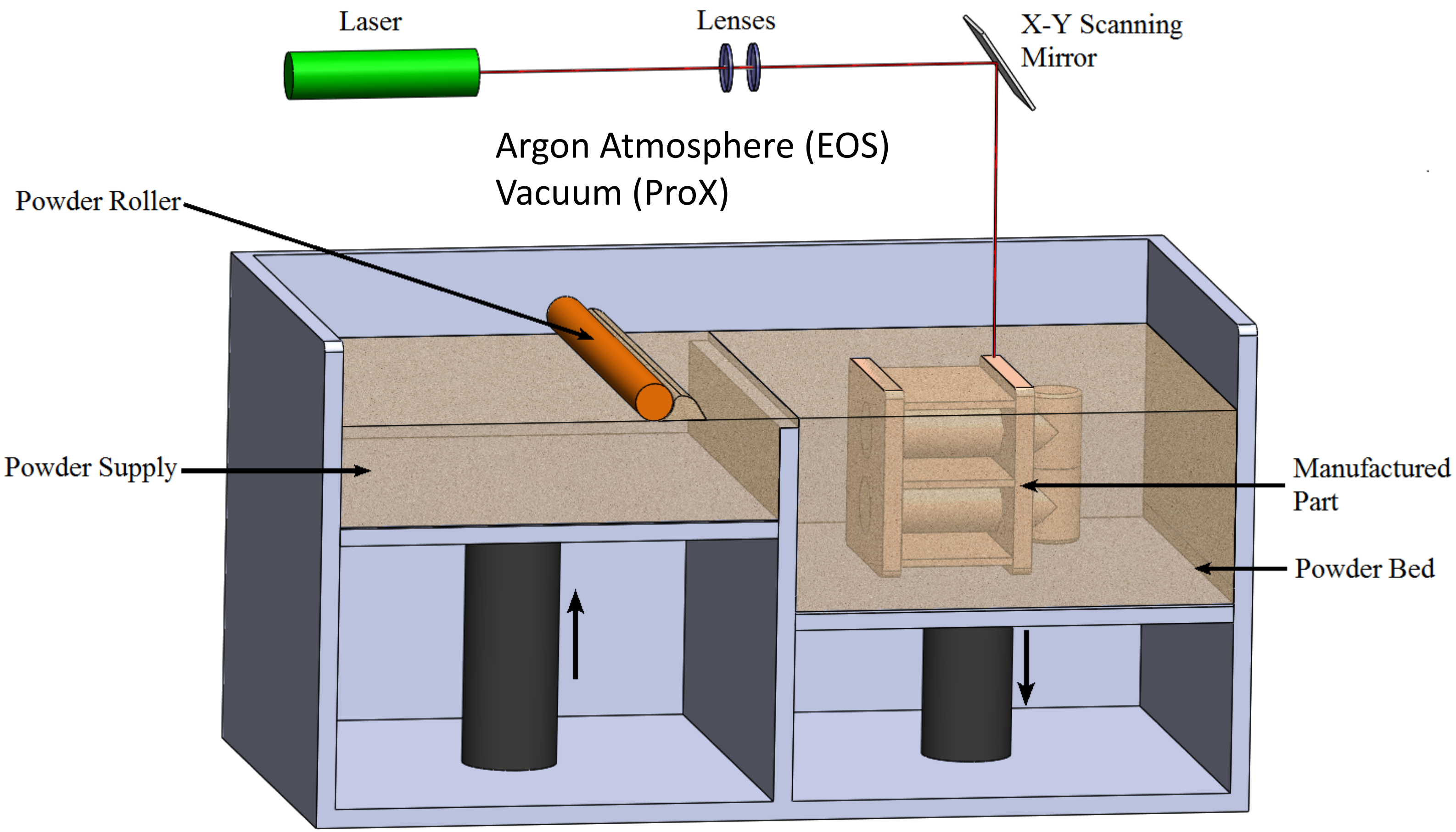
Specimen ID	Material	Method	Atmosphere	Feed Type
SS-P1	SS-316L	Laser Powder Bed	Argon	Powder
SS-P2	SS-316L	Laser Powder Bed	Vacuum	Powder
SS-P3	SS-316L	Laser Free Form	Argon	Powder
SS-P4	SS-316L	E-Beam Wire Feed	Vacuum	Wire

SR1 - Stress relieved @ 1650 F for 3.25 hours, air cool

Specimen ID	Material	Method	Atmosphere	Feed Type
IN-P1	Inconel 718	Laser Powder Bed	Argon	Powder
IN-P2	Inconel 718	Laser Powder Bed	Vacuum	Powder
IN-P3	Inconel 625	Laser Powder Bed	Argon	Powder
IN-P4	Inconel 718	E-Beam Wire Feed	Vacuum	Wire

AMS 5664 - Heat treat per AMS 5664 (solution anneal and aging)
AN1- Anneal at 870 °C for 1-hour, rapid cool

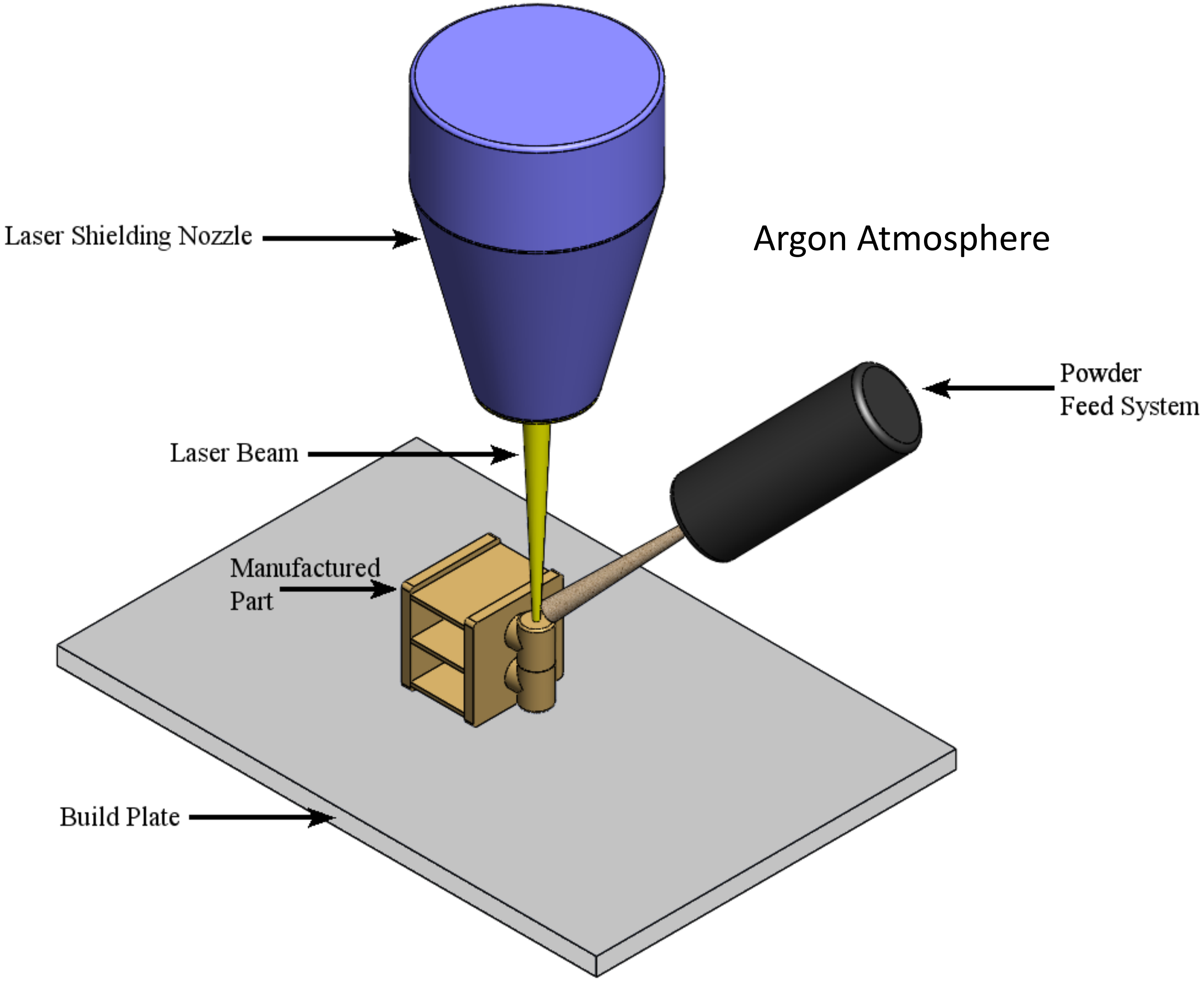
Laser Powder Bed Fusion



EOS M 290

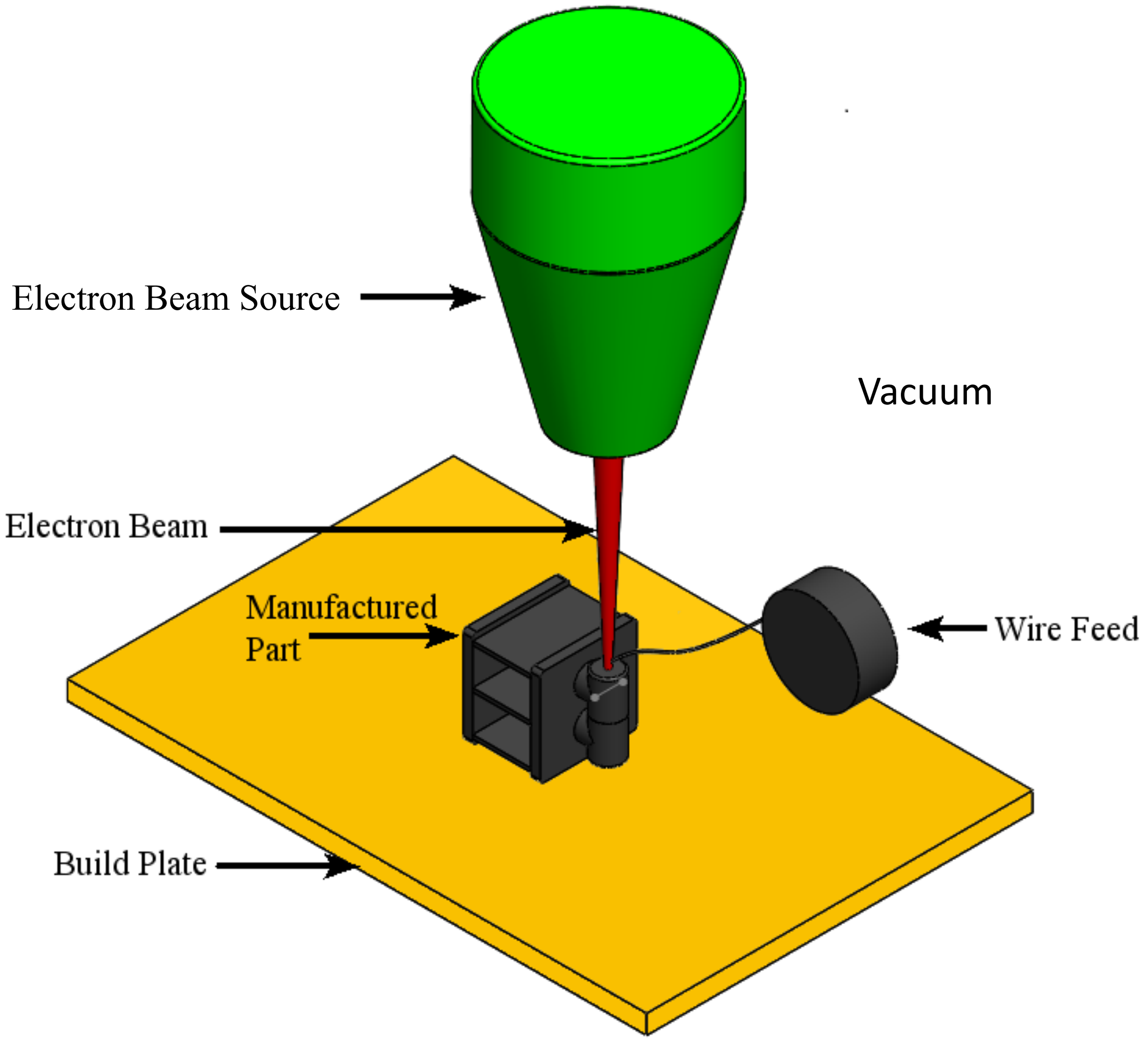
ProX320B

Laser Powder Free Form (Directed Energy Deposition)



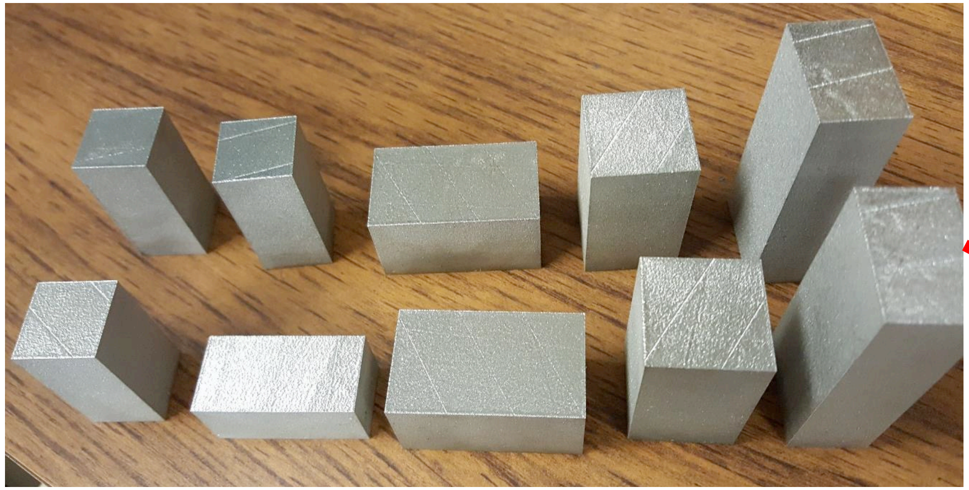
Optomec MR7

Electron Beam Wire Feed (Directed Energy Deposition)

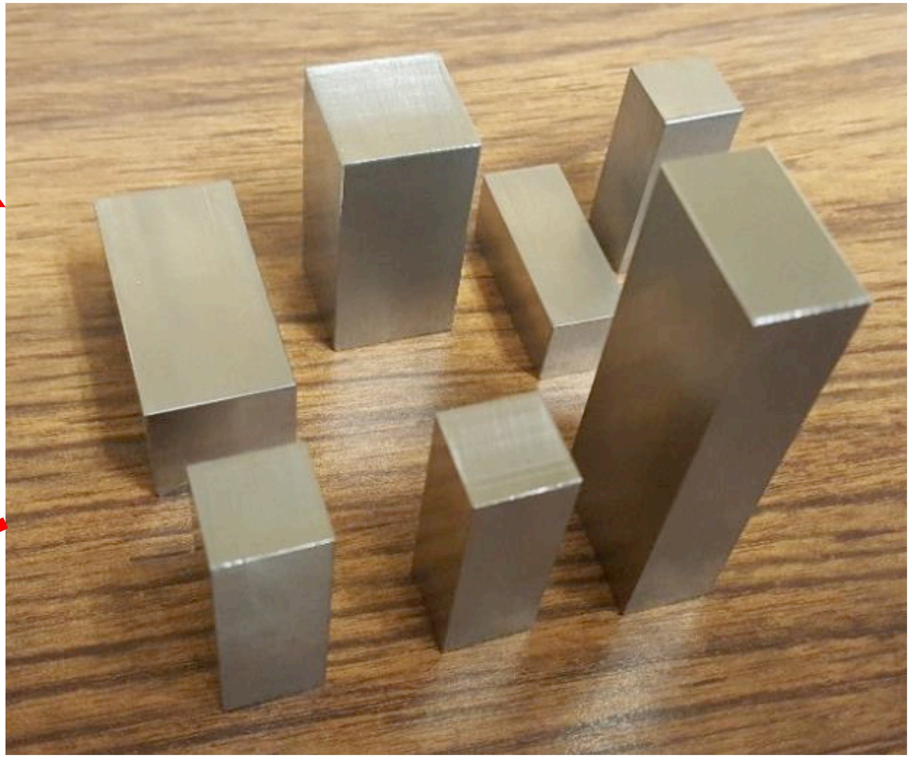


Sciaky

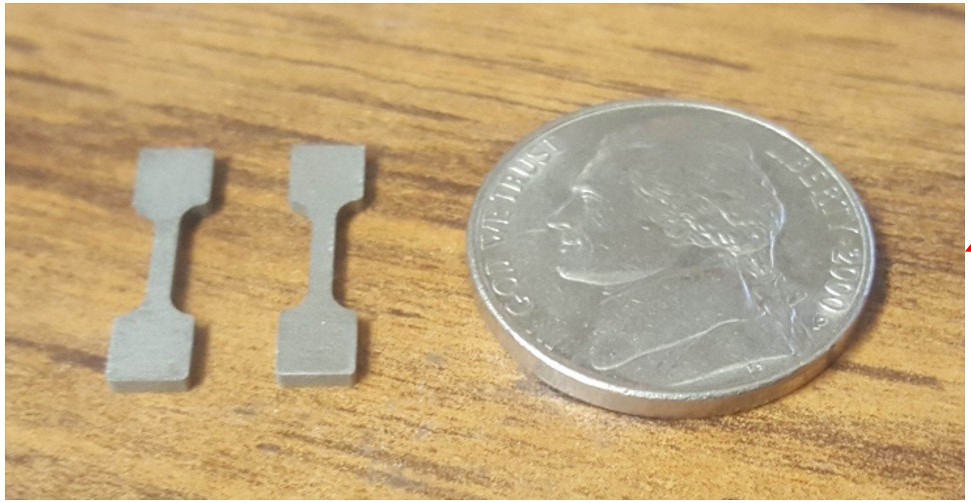
Source Materials and Specimens



As-built billets

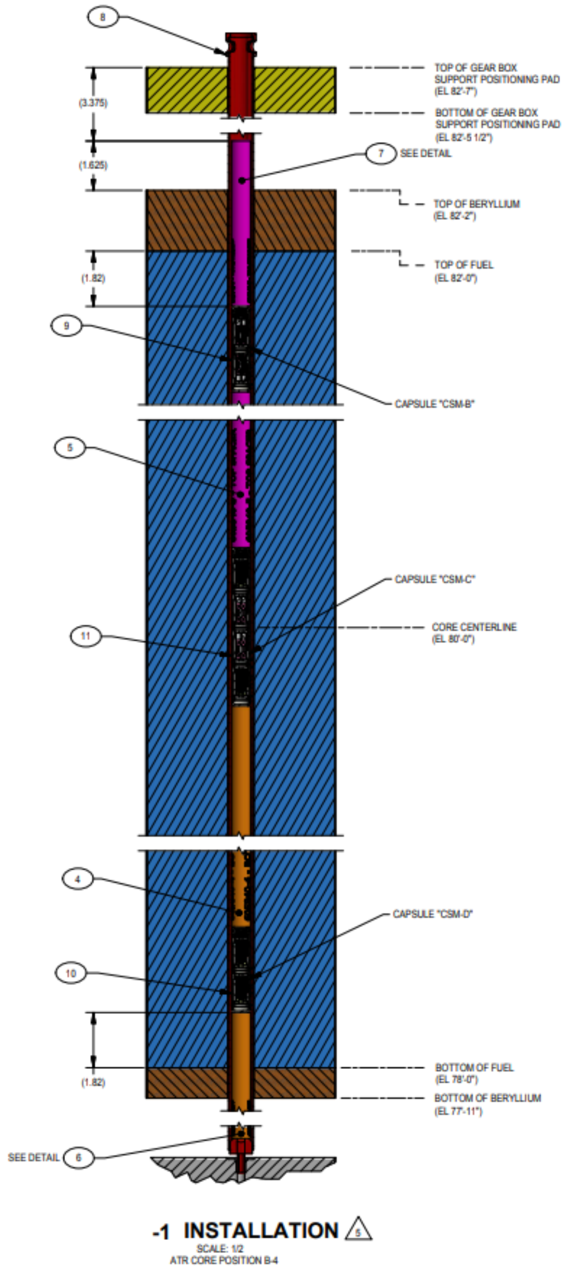


Skinned billets

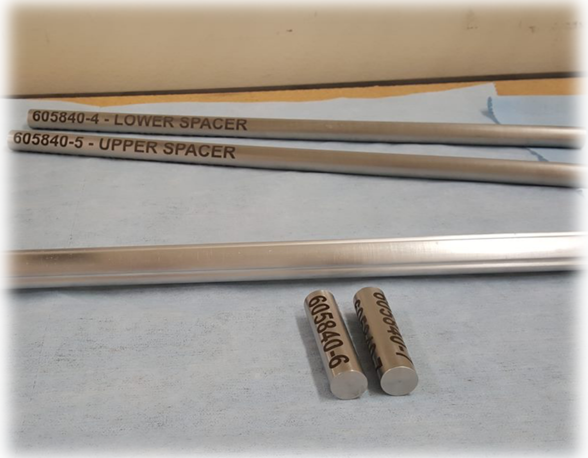


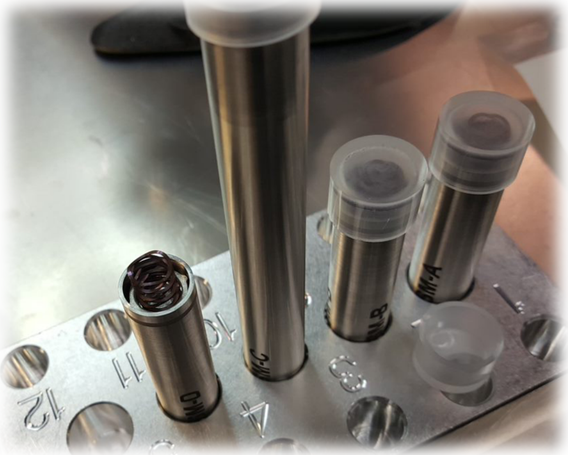
Tensile specimens

Irradiation Experiment



- Specimens irradiated in the Advanced Test Reactor resulting in damage accumulation ranging from 0.11-1.63 dpa

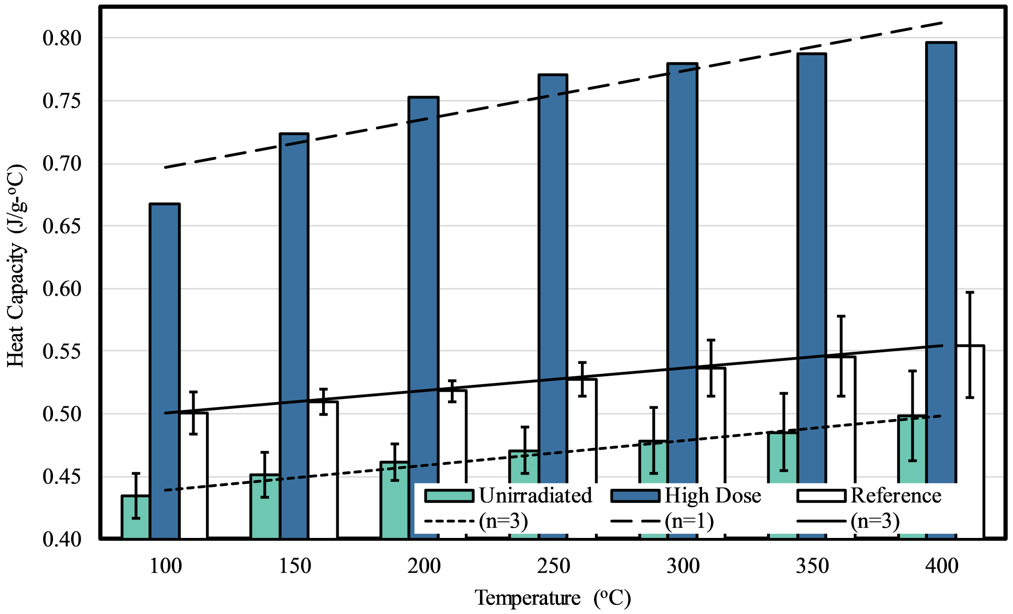




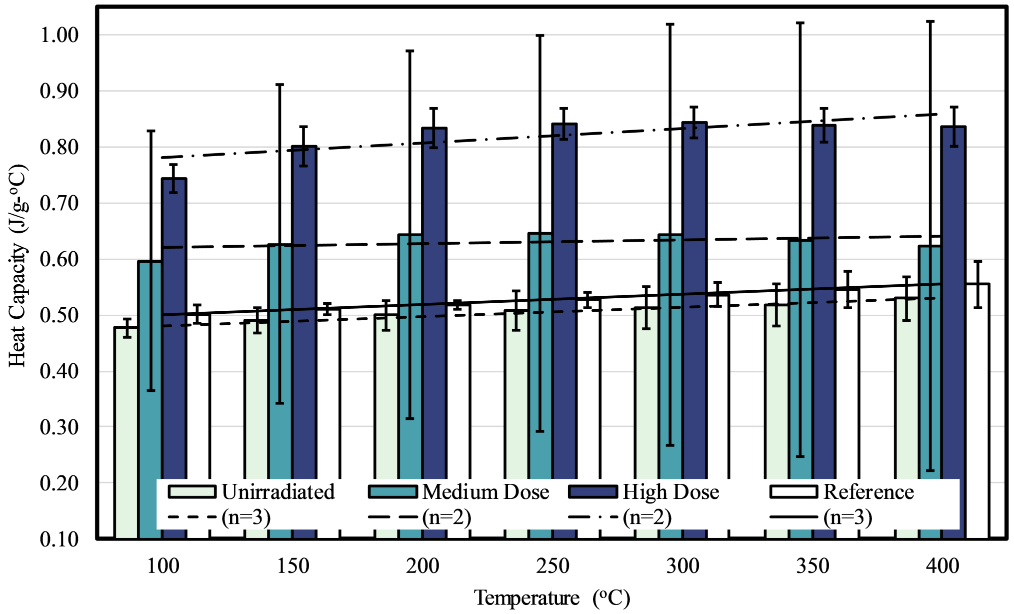
FY 20 Technical Progress/Accomplishments

- Completed pre-irradiation characterization
  - Thermophysical properties
    - Heat capacity, thermal diffusivity, thermal conductivity
  - Mechanical properties
    - Yield strength, elastic modulus, ultimate tensile strength
  - Microstructure
- Completed first round of irradiated thermophysical property testing at INL
- Completed TEM imaging of selected irradiated specimens at INL
  - Analysis is in progress
- Mechanical testing is about to begin at ORNL

Heat Capacity Results (Stainless Steel)

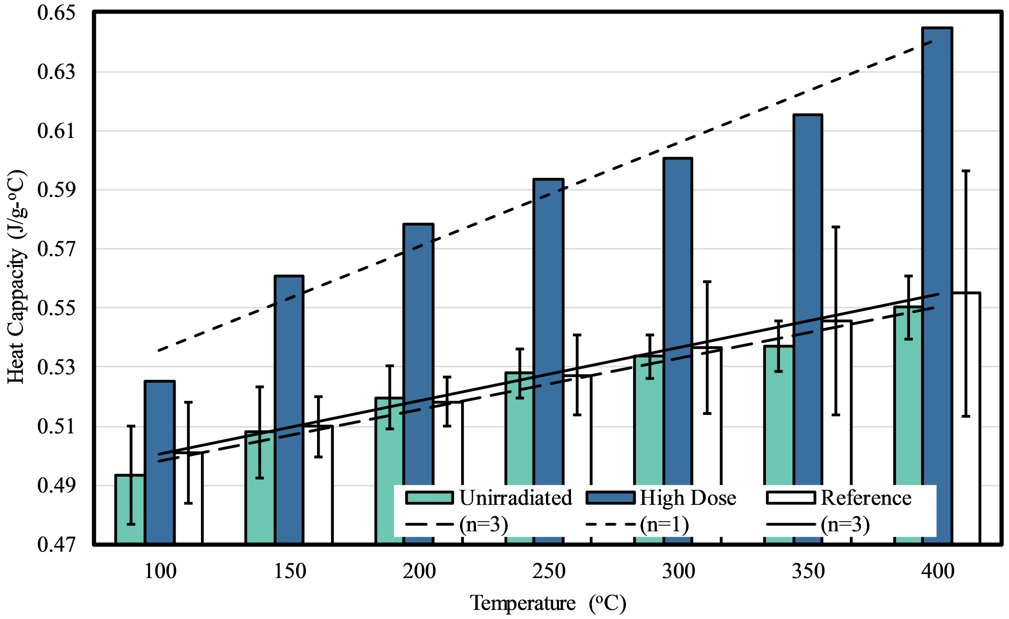


SS-P1 (LPBF-argon)



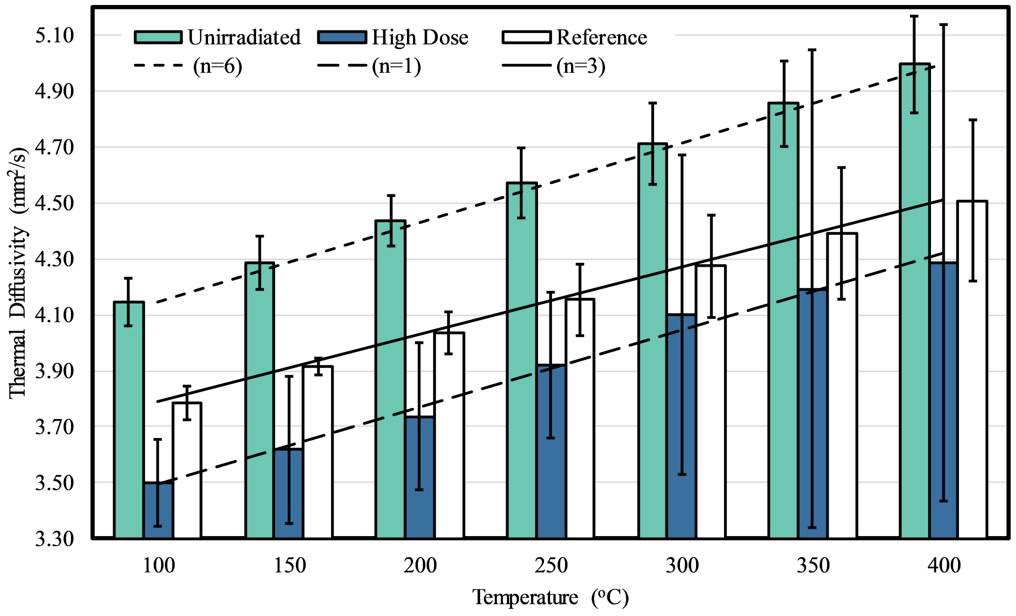
SS-P2 (LPBF-vacuum)

Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

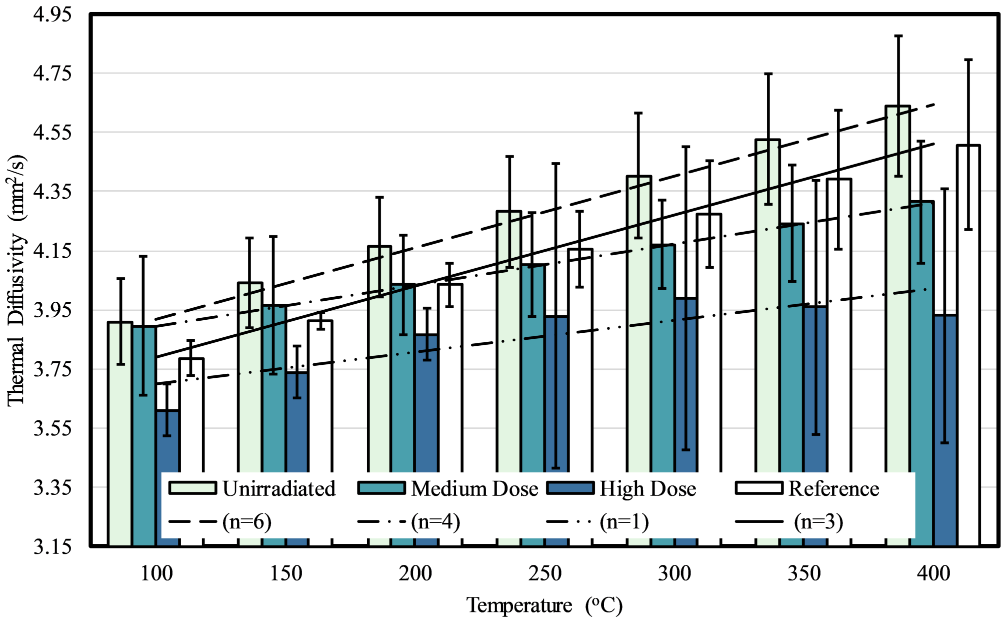


SS-P3 (LFF-argon)

Thermal Diffusivity Results (Stainless Steel)



SS-P1 (LPBF-argon)



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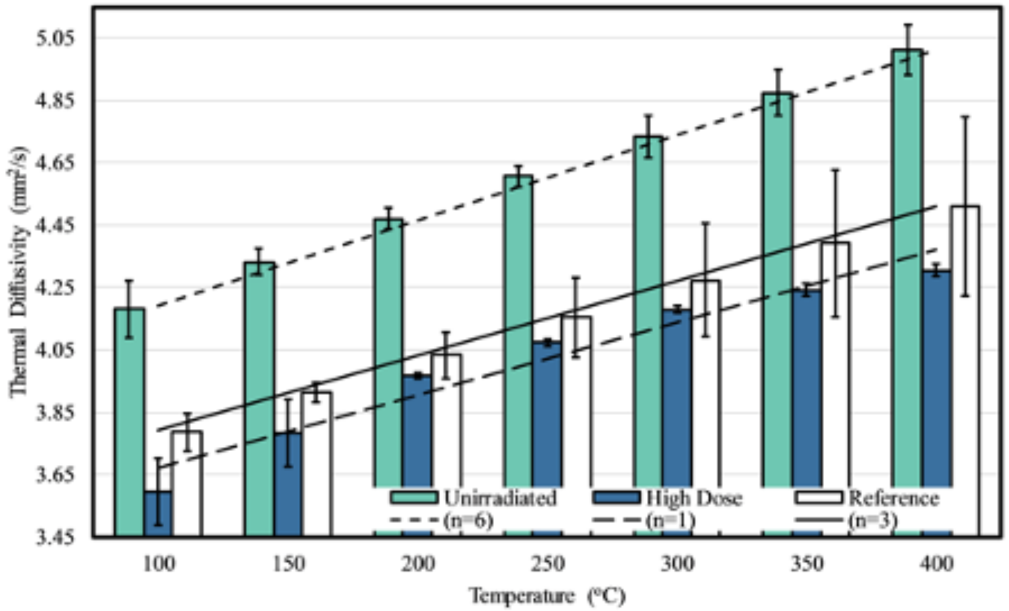
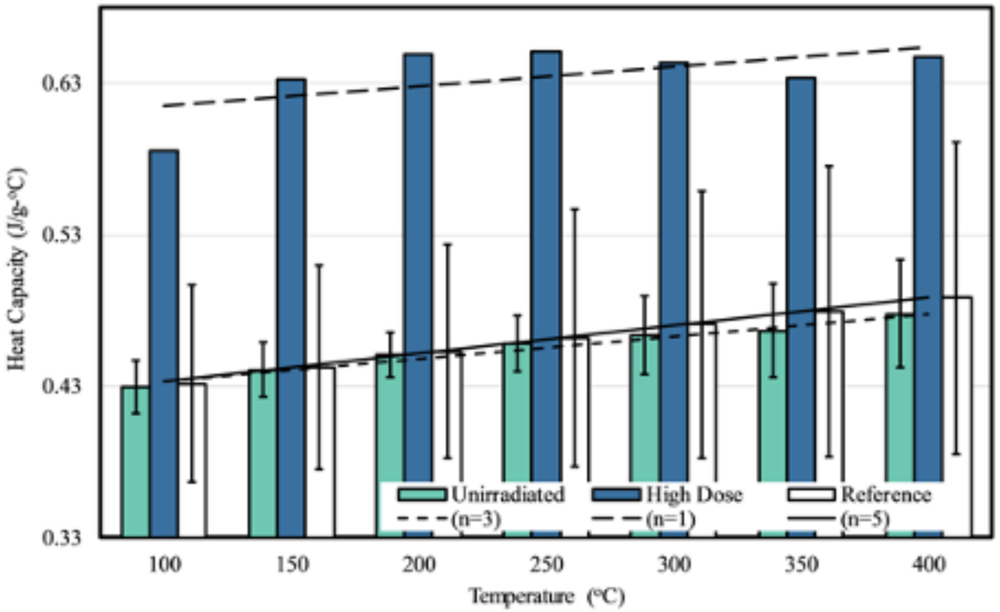
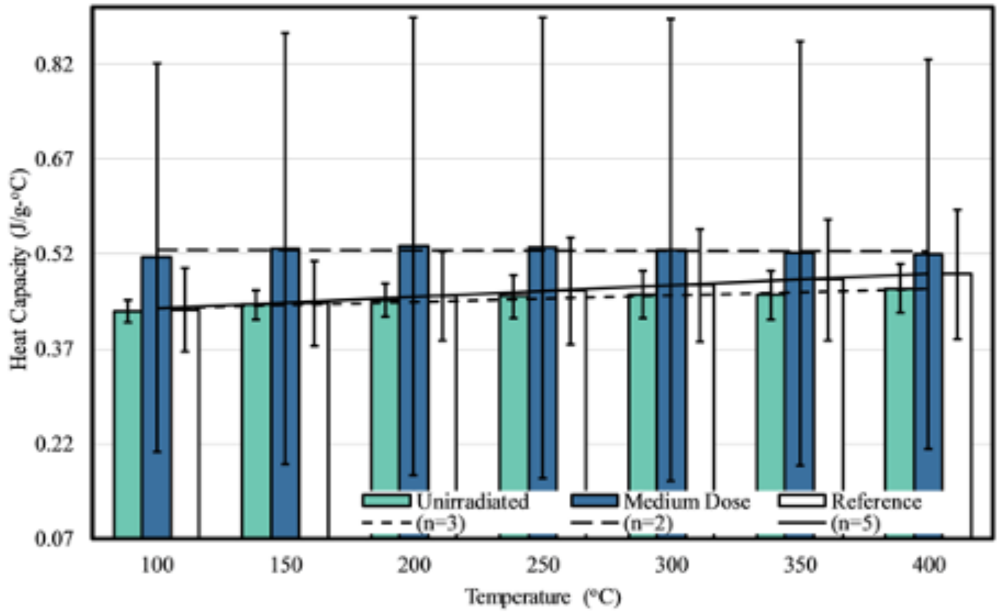


SS-P3 (LFF-argon)

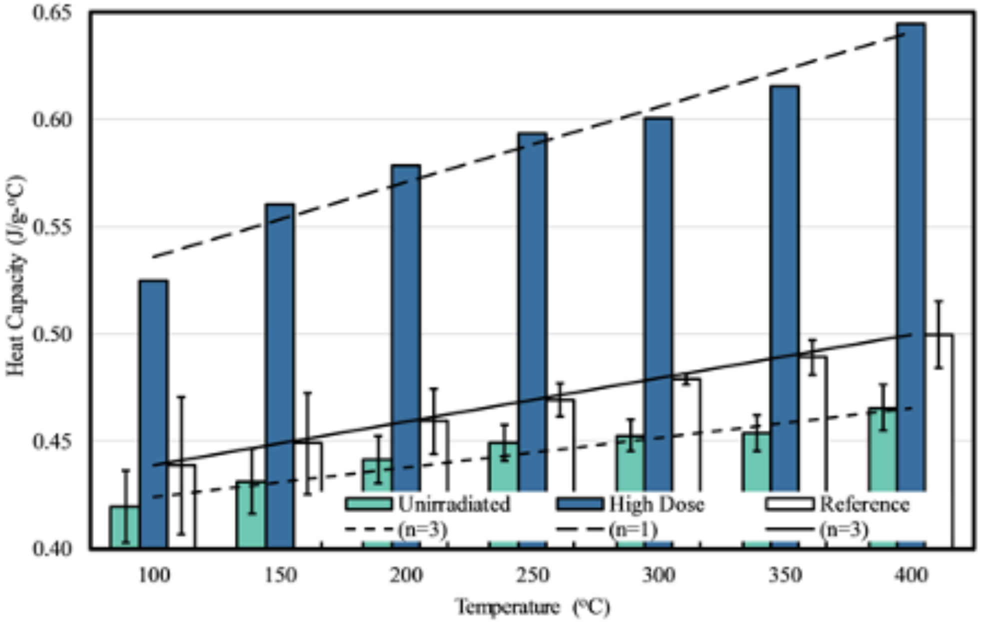
Heat Capacity Results (Inconel)



IN-P1 (718, LPBF-argon)



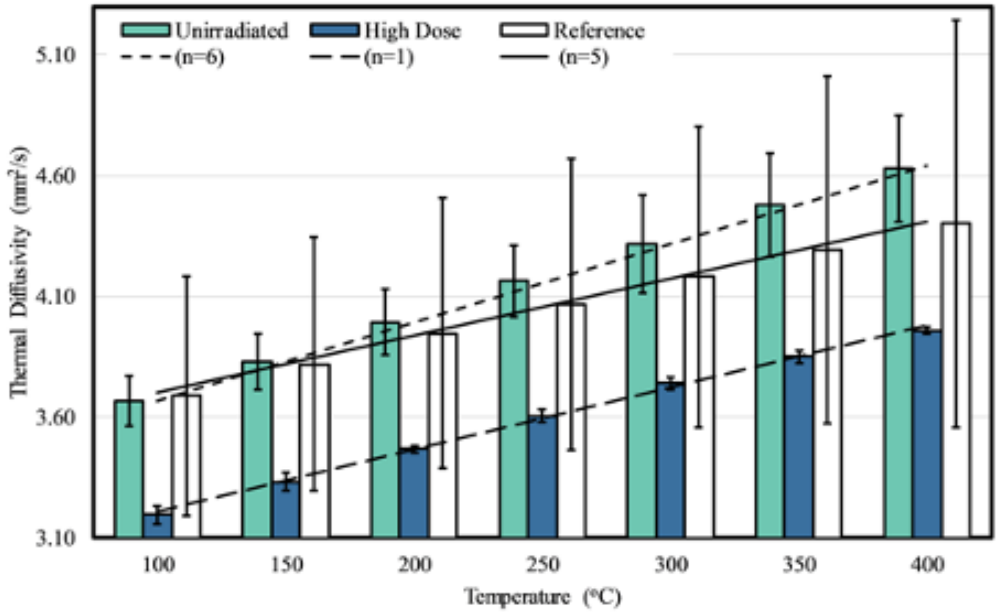
IN-P2 (718, LPBF-vacuum)



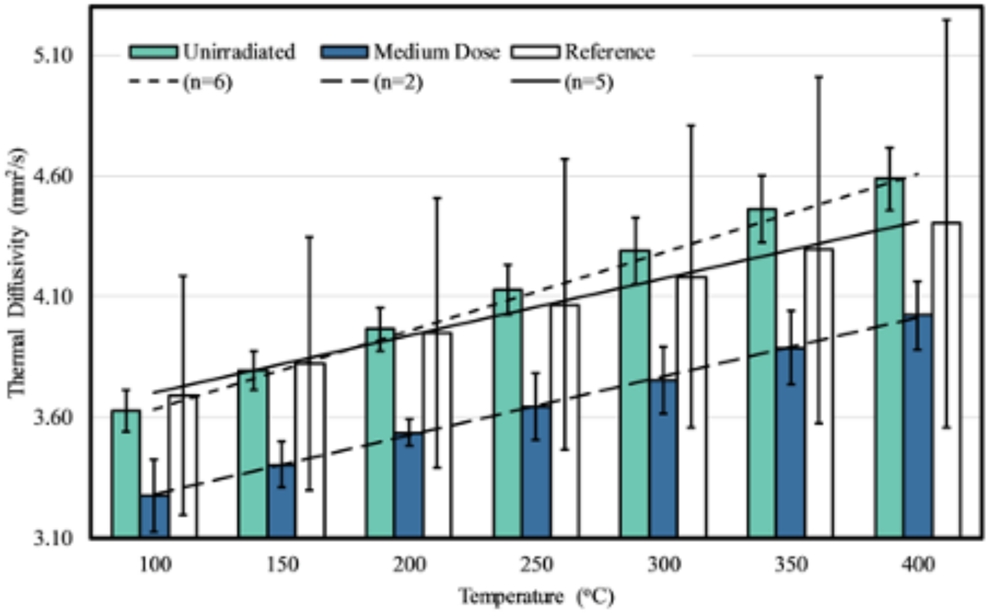
IN-P3 (625, LPBF-argon)

Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

Thermal Diffusivity Results (Inconel)

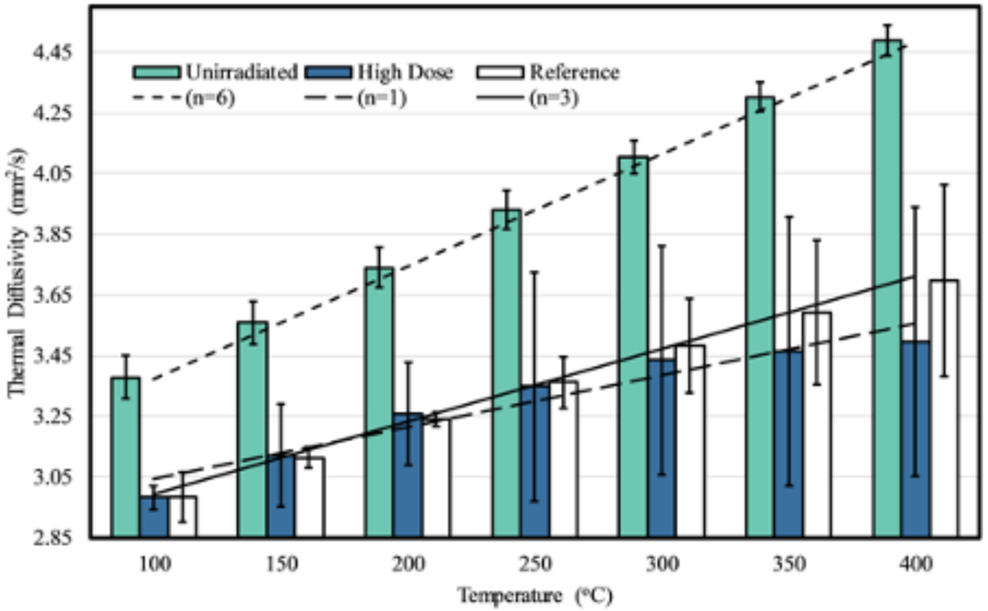


IN-P1 (718, LPBF-argon)



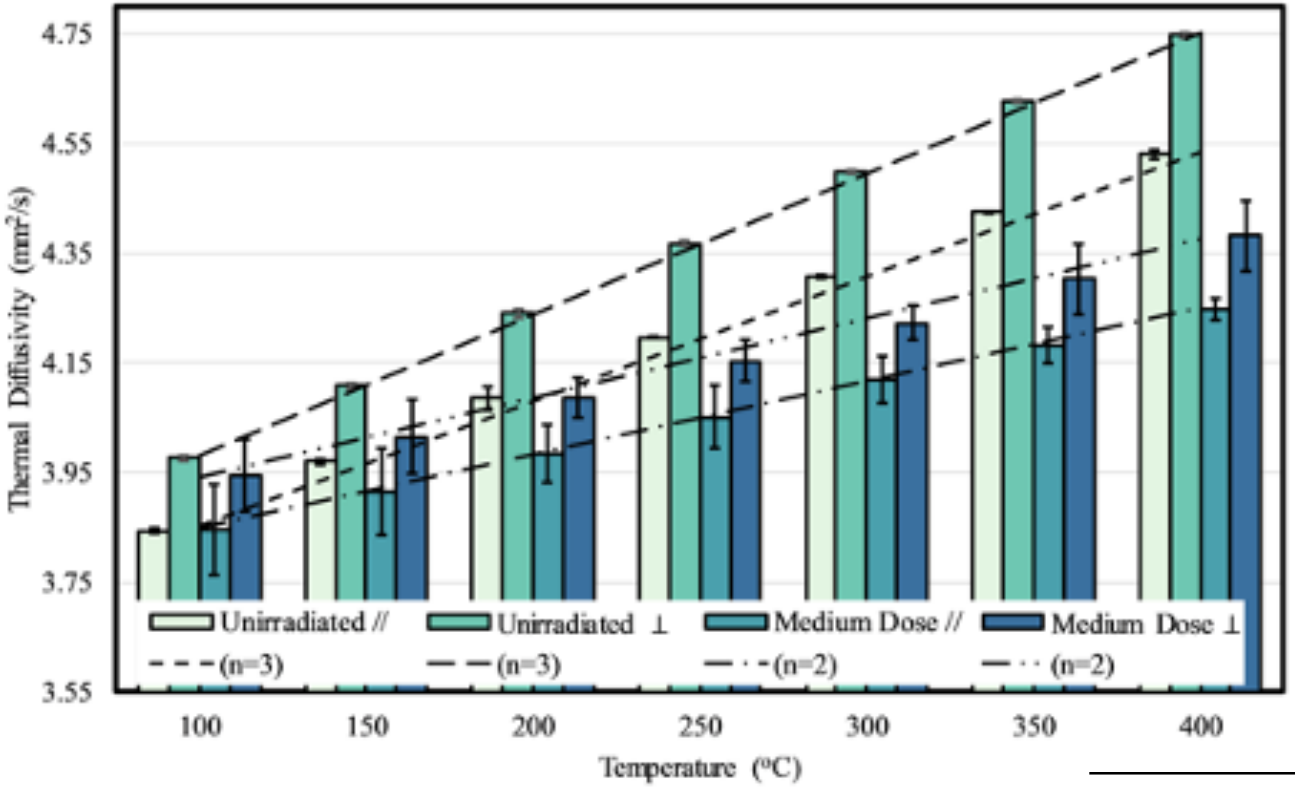
IN-P2 (718, LPBF-vacuum)

Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

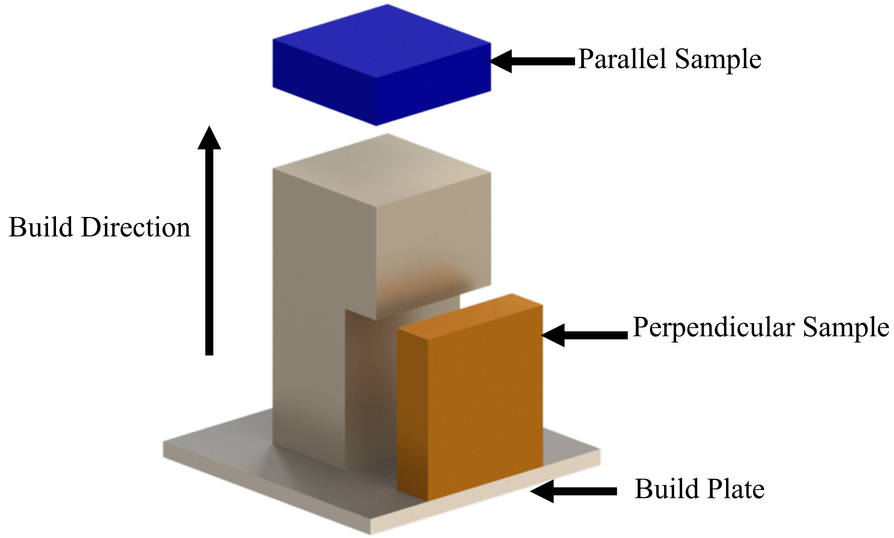


IN-P3 (625, LPBF-argon)

Anisotropic Thermal Diffusivity?



SS-P2 (LPBF-vacuum)



Low Dose -> 0.11-0.2 dpa
Medium Dose -> 0.47-0.67 dpa
High Dose -> 1.49-1.63 dpa

	Unirradiated SS-P1 (n=6)		Unirradiated SS-P2 (n=6)		Medium Dose SS-P2 (n=4)		Unirradiated SS-P3 (n=6)	
Temperature	p-value	t-value*	p-value	t-value*	p-value	t-value+	p-value	t-value*
100 °C	0.450	1.169	0.115	2.007	0.134	4.683	0.857	0.197
150 °C	0.453	1.161	0.115	2.009	0.029	5.754	0.323	1.126
200 °C	0.459	1.137	0.115	2.005	0.136	4.617	0.288	1.223
250 °C	0.455	1.152	0.078	2.359	0.042	4.733	0.108	2.065
300 °C	0.451	1.167	0.062	2.568	0.152	4.108	0.106	2.289
350 °C	0.453	1.162	0.061	2.581	0.016	7.776	0.087	2.508
400 °C	0.454	1.155	0.070	2.458	0.038	16.574	0.090	2.469

*T-critical=1.728 (DOF=2, α=0.159)
+T-critical=1.833 (DOF=1, α=0.159)