Technology Maturation – Conclusions and Future Work Ideas

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In summary

- Technology maturation is a vital part of the microreactor program to help numerous vendors achieve higher TRLs and successfully deploy microreactors.
- Work on 37 heat pipe test article and PIE of YH_x will yield valuable information for microreactors and are a focal point of FY22.
- Embedded sensors and other measurements at MAGNET are also important.
- More technology maturation is required for microreactor building and deployment though.
- Structural material, autonomous control, legacy fuel and other activities may be examined soon, but the list of needs does not end there.

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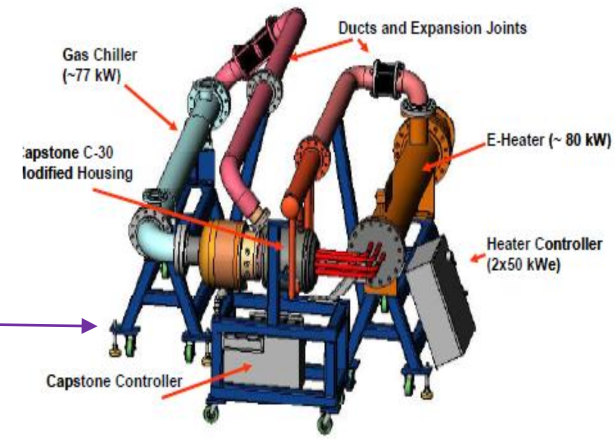
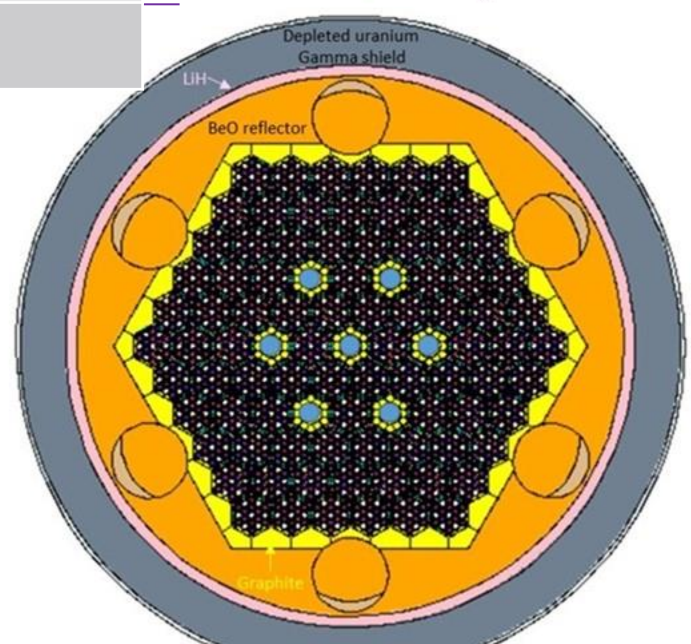
Needs

Feature	Commercial Reactors	Microreactors
Cooling	Water	Heat pipes, gas
Control	Soluble boron	Control drums
Electricity Generation	Steam Generator /Turbine	Heat Exchanger/ Power Conversion
Moderator	Water	Hydrides/Graphite?
Enrichment	<5% UO_2	<20% HALEU





- Shielding, reflectors, and control material such as drums or burnable poison need to be assessed along with safeguards and other topics in conjunction with other programs (i.e. NEAMS, MPACT, NEET).
- Power conversion unit (PCU) and other technology such as gas coolant are important in addition to enhanced measuring techniques at MAGNET.

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Additional Workscope Planned for FY22 (assuming $25M and end of CR)

High Temperature Moderator	- Encapsulation and containment of YH - Advanced Coatings
Instrumentation and Sensors	- Microreactor Autonomous Control System for graded response of critical systems
Fuel Qualification	Complete microreactor activities on legacy fuel qualification of metallic fuels.
Heat Transfer	- Support PCU integration - Fabricate gas-cooled test article
Instrumentation and Sensors	- Acoustic Sensors, Improve DIC
Structural Materials	Refractory metals: Perform initial investigations of advanced materials and manufacturing for microreactors such as TZM and gap analysis on code qualifying

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Potential Future Work Scope

- Fabricate graphite/based heat pipe test article
- Integrate power conversion unit with test articles/heat exchanger for thermal energy conversion
- Complete PIE and other analyses of YH_x samples irradiated in ATR
- Fabricate and test encapsulated sample of YH_x for hydrogen permeation for long lifetime operation
- Examine other types of moderator material (Be, graphite, ZrD_2)
- Complete evaluation of burnable poisons, reflectors, control drums, and/or shielding material options for microreactors
- Evaluate results of instrumentation and sensor measurements of test articles at MAGNET
- Develop acoustic or other structural health monitoring techniques for microreactors (embedded fiber optic sensors, piezoelectric sensors, traditional bonded strain gauges, DC potential drop, or non-contact techniques)
- Extend distributed temperature and strain sensing capabilities from SPHERE to MAGNET test articles
- Fabricate metal refractory test articles to examine structural material integrity
- Test safeguards instrumentation at MAGNET or MARVEL

MRP Microreactor Program

Determining the Effects of Neutron Irradiation on the Structural Integrity of Additively Manufactured Heat Exchangers for Very Small Modular Reactor Applications

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MICROREACTOR PROGRAM REVIEW, MARCH 2022

overview

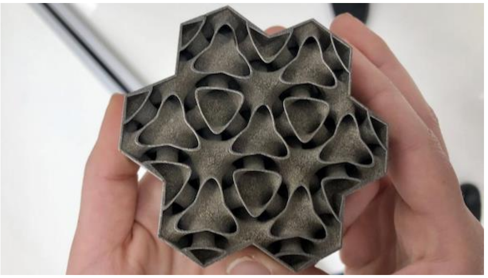
- Nuclear applications
- Project Objectives
- Materials and Production Method
- Radiation Experiments
- Experimental Results
- Summary, Conclusions, and Continuing Work

Additive manufacturing – complex hExs

- Additive Manufacturing enables novel geometries and performance
  - part/joint consolidation
  - non-uniform cross-sectioned channels,
  - asymmetric core architecture,
  - fully-circular channels

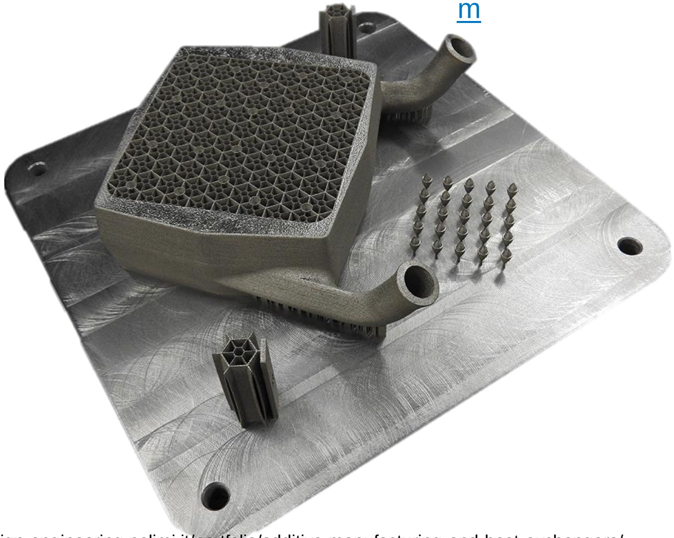
- Effects of neutron irradiation on AM not well studied yet
  - Nuclear Attenuation
  - AM Processing Characteristics
  - Microstructure / mechanical / corrosion properties

- AM Microstructures differ from wrought microstructures
  - AM microstructures are anisotropic
  - Limited to no thermal-mechanical processing



https://www.metal-am.com/

www.renishaw.com



https://design-engineering.polimi.it/portfolio/additive-manufacturing-and-heat-exchangers/

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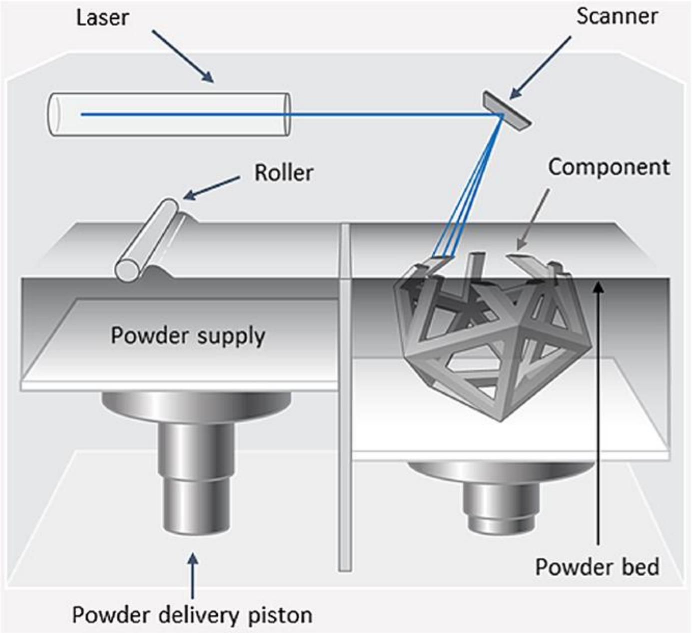
Project Objectives

Determine effects of thermal and fast neutron irradiation on additively manufactured (AM) 625 and 718 nickel-based super alloys

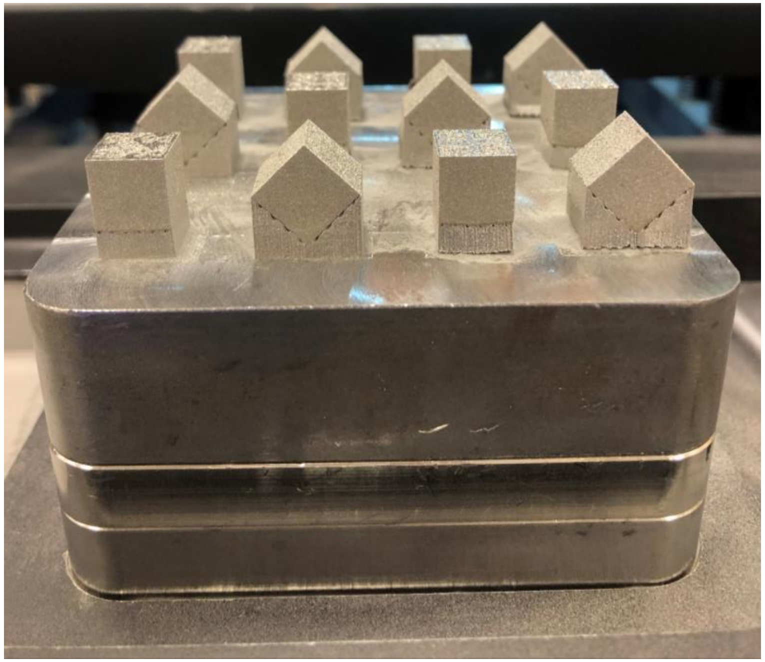
- **Neutron Irradiation Effects**
  - Swelling
  - Voids
  - Frenkel pairs
  - Dislocations
  - Hardening & Embrittlement
  - Impurity formation (hydrogen, helium)

- **Microstructure/mechanical properties**
  - Micro/nano hardness
  - As-printed microstructure
  - Heat-treatment effects
  - AM built angle effects

Laser Powder bed fusion (L-PBF)



O'Brien, Optical Engineering ***58****(1), 010801 (2019)*



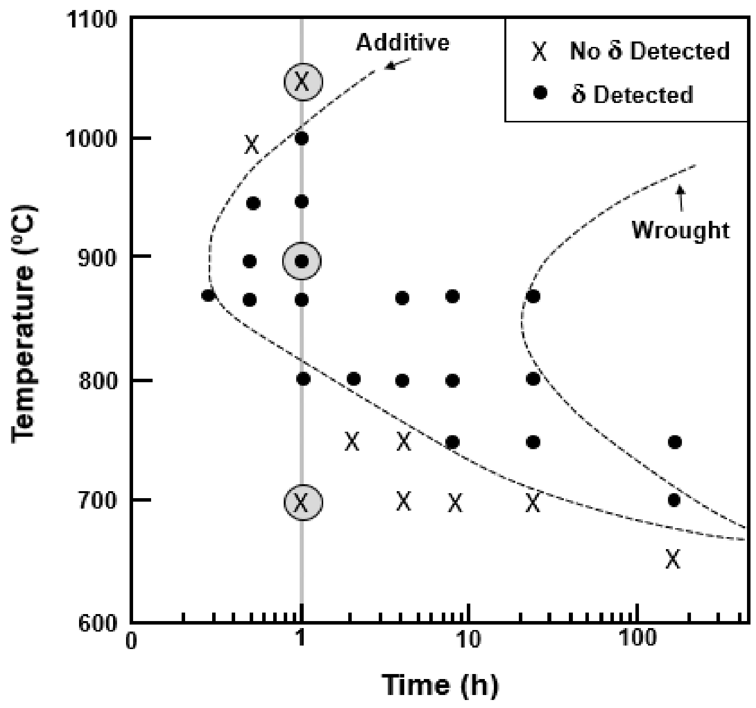
Heat-treatment schedules

Heat treatment schedules for this study

- As-built (no heat treatment)
- 700 ℃ - 1 hour
- 900 ℃ - 1 hour
- 1050 ℃ - 1 hour

Precipitates formed

- γ“- contributes to hardening effect in microstructure
- δ- Needle and plate shaped precipitate (deleterious)- makes part brittle
- Both precipitates are rich in Niobium
- 1050 ℃ -1h was carried out to dissolve all precipitates back in Ni-Cr matrix.
- Final microstructure resembled wrought IN625 microstructure.



https://doi.org/10.1007/s11661-018-4643-y

Heat treatments were performed on samples of both build orientations

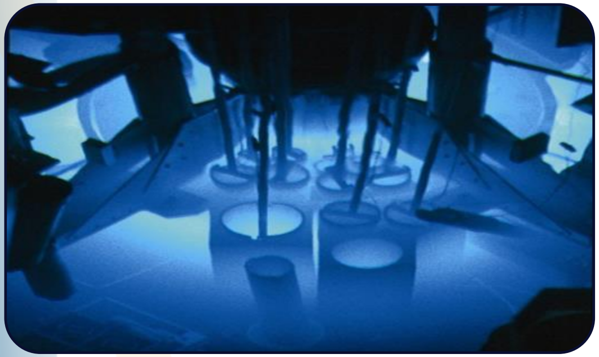
Radiation Experiments

MURR

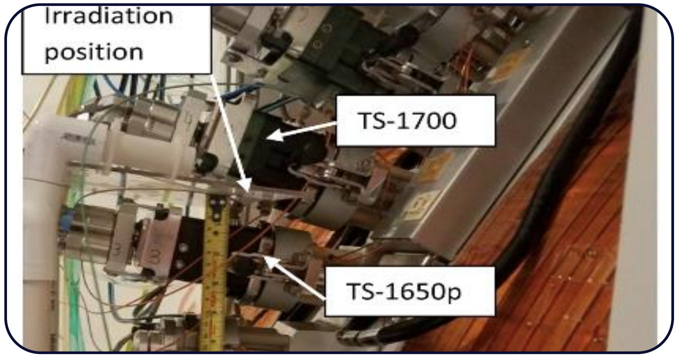
16 MeV Cyclotron

Full-Spectrum Neutron	(Fast) Neutron	Proton

- 10 MW reactor at MURR
- 310 hours
- Neutron flux = 6.61 x 10^{13} neutrons/cm^2/s
- Neutron fluence = 7.37 x 10^{19} neutrons/cm^2



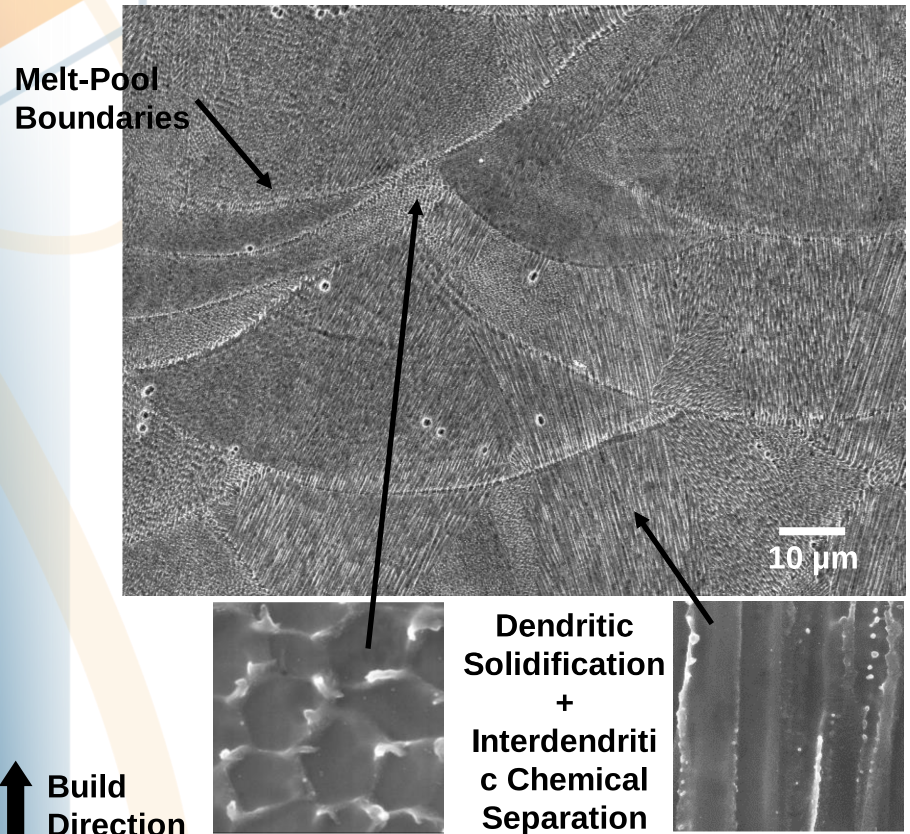
- Neutrons from PET isotope production $^{18}O(p, n)^{18}F$ reaction
- 25-week experiment
- Neutron fluence = 9.08 x 10^{15} neutrons/cm^2
- Low fluence, but low activity



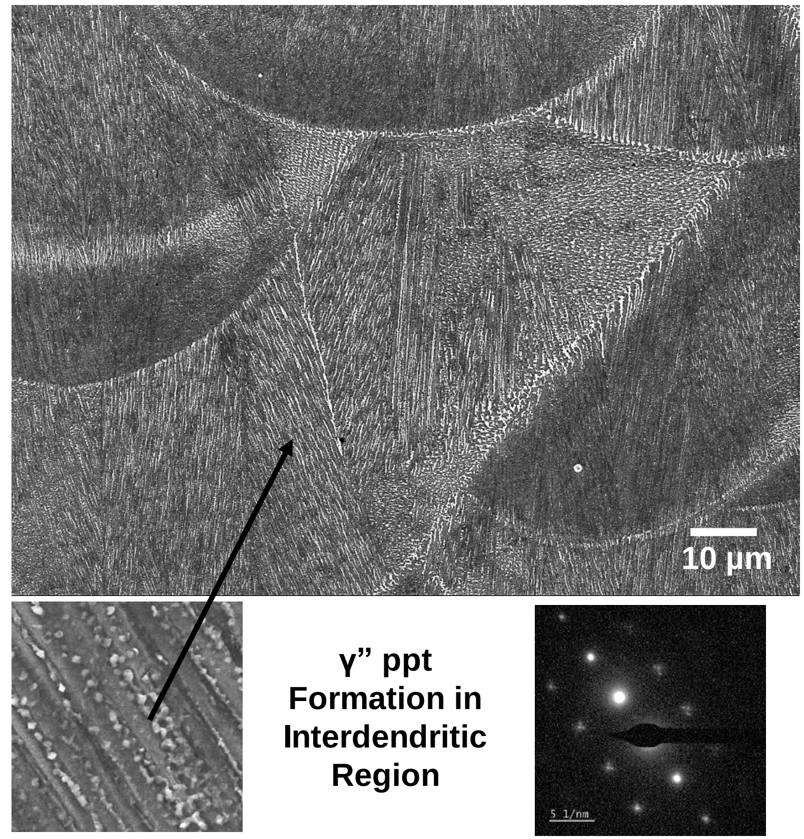
- 80 μA BEAM
- Currently investigating the methodology

MICROSTRUCTURE

As-Built Microstructure

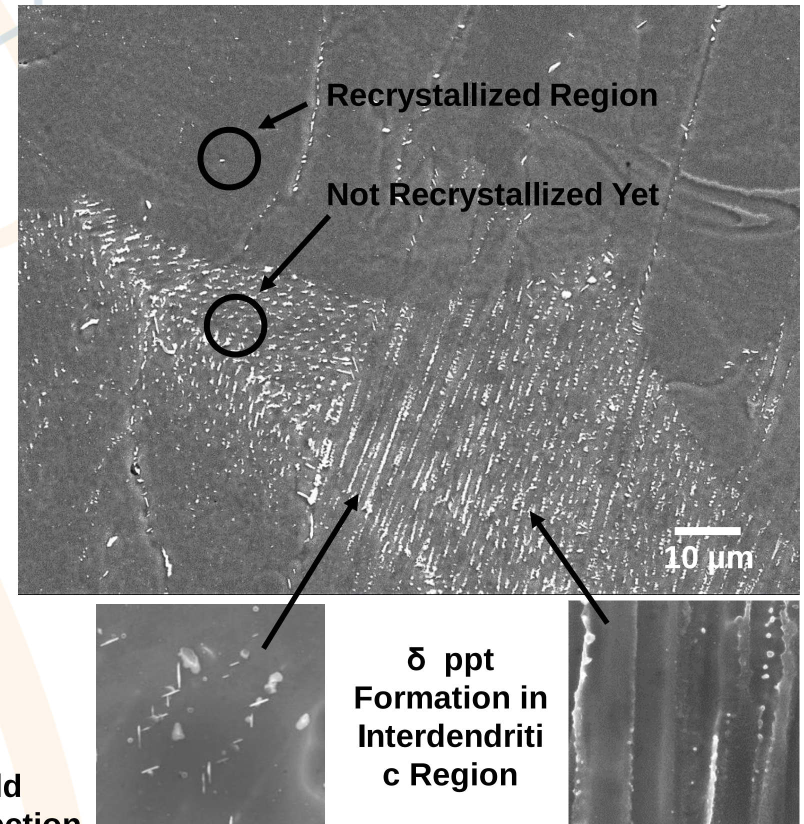


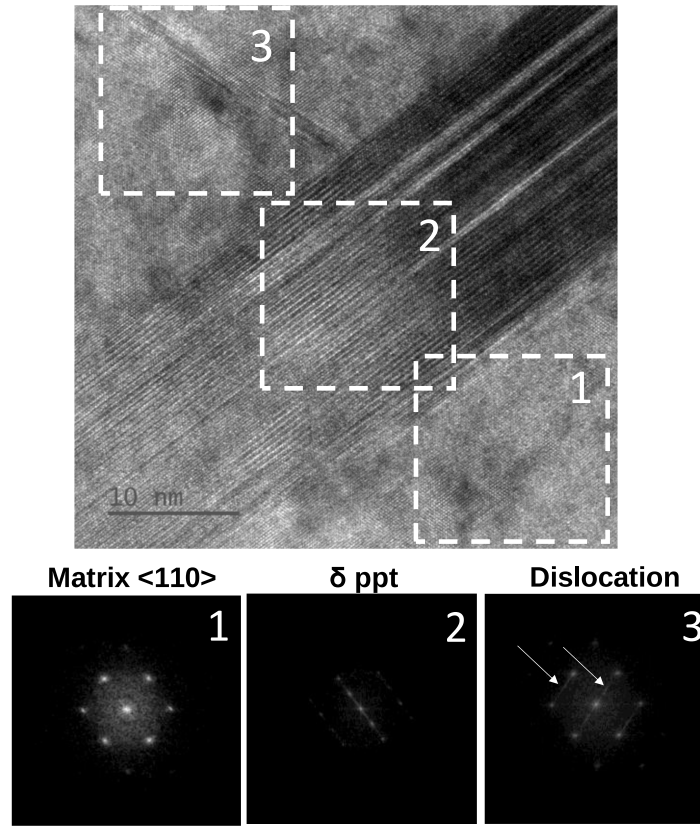
700°C Microstructure



MICROSTRUCTURE

900°C Microstructure

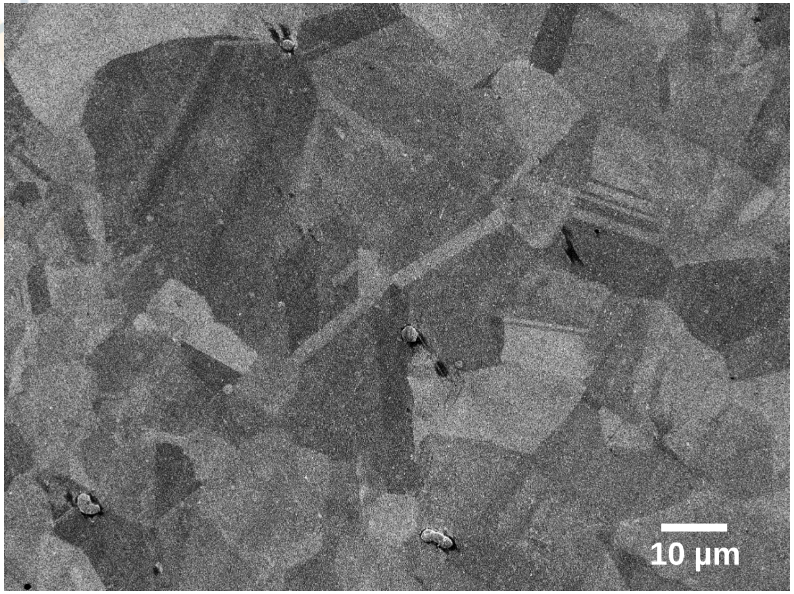




Build Direction

MICROSTRUCTURE

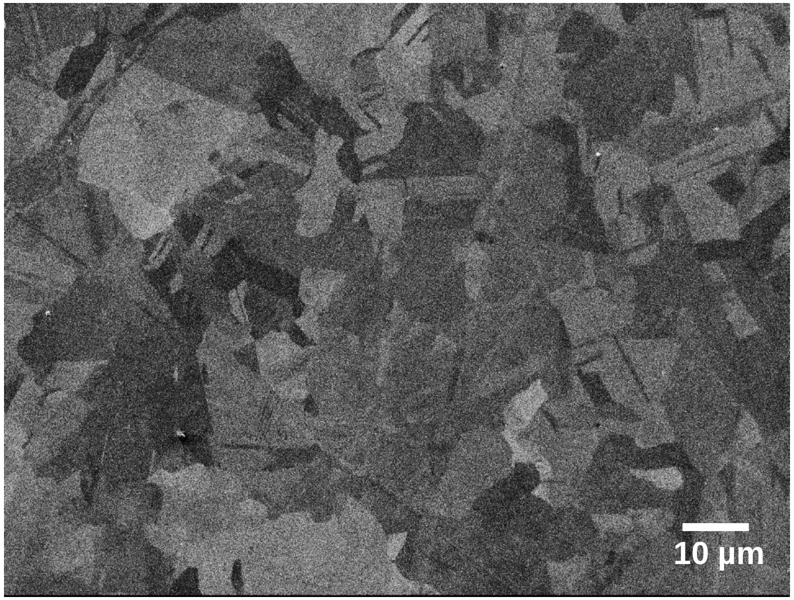
As-Built Microstructure



Completely Recrystallized

ppts Dissolved

700°C Microstructure

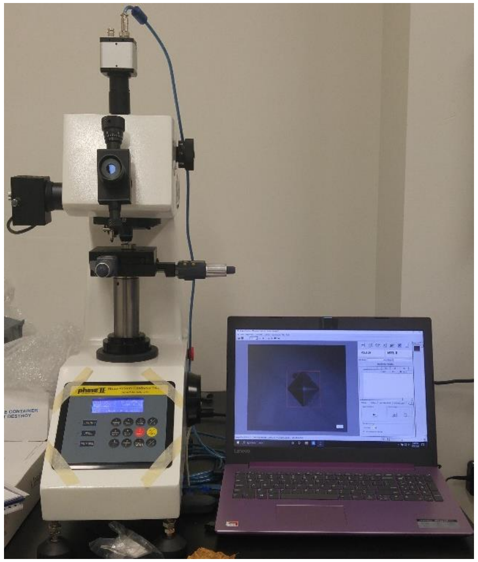


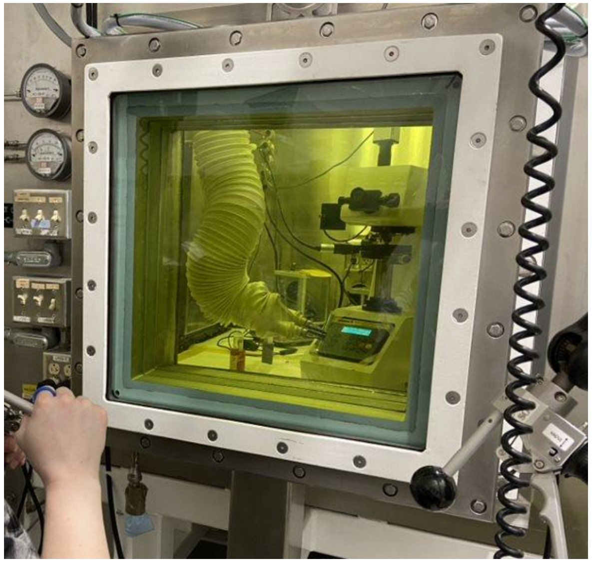
Build Direction

Microhardness measurements

Vickers Microhardness

- Phase II 900-391D
- Load = 1 kgf (9.8 N)
- Dwell time = 15 secs
- Hot cell and manipulator arms for radioactive samples
- Hardness measurements pre- and post- irradiation to track radiation-induced changes





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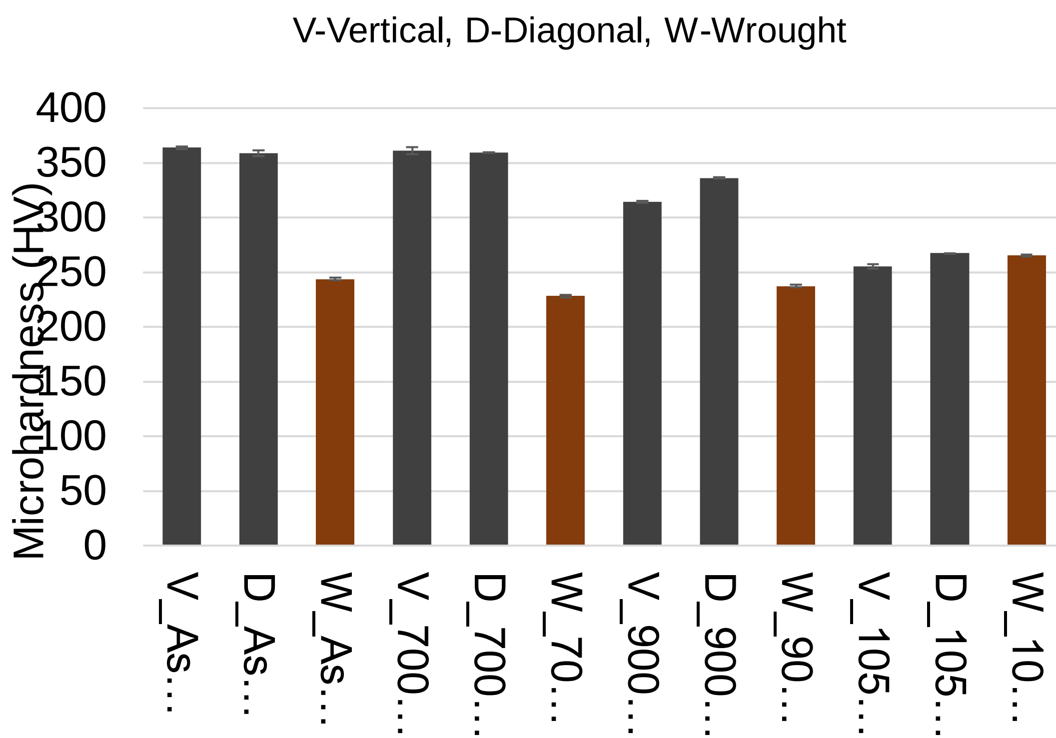
Microhardness of L-PBF and wrought in625

- As-built Vert and Diag showed minimal variation in microhardness.
  - This shows built directional independence.
- Microhardness decreased as heat treatment temperature increased
- 1050 °C AM samples display similar microhardness to wrought Inconel 625
  - This indicates the microstructures are similar



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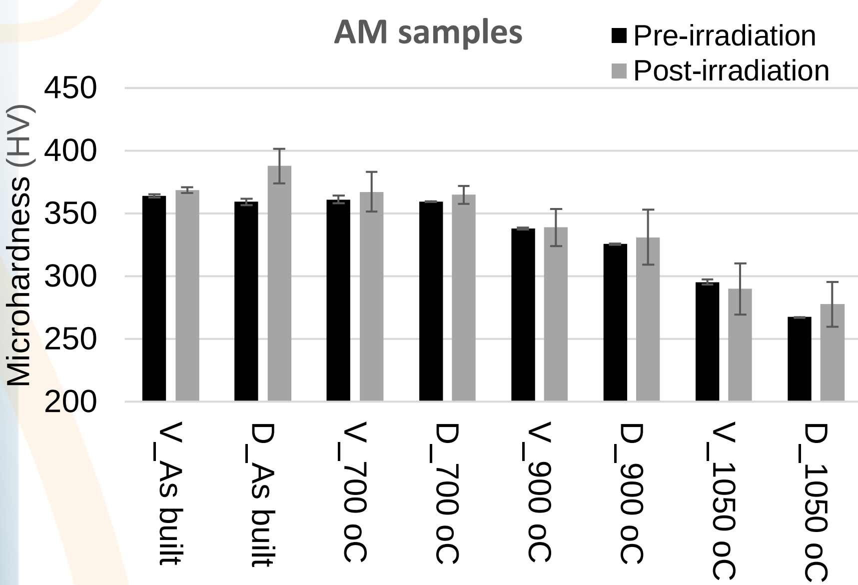
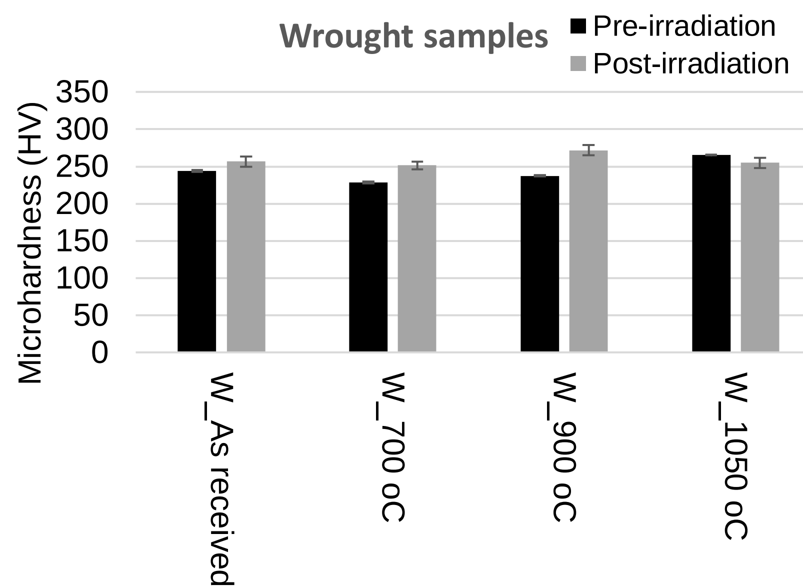
Full-spectrum neutron irradiation

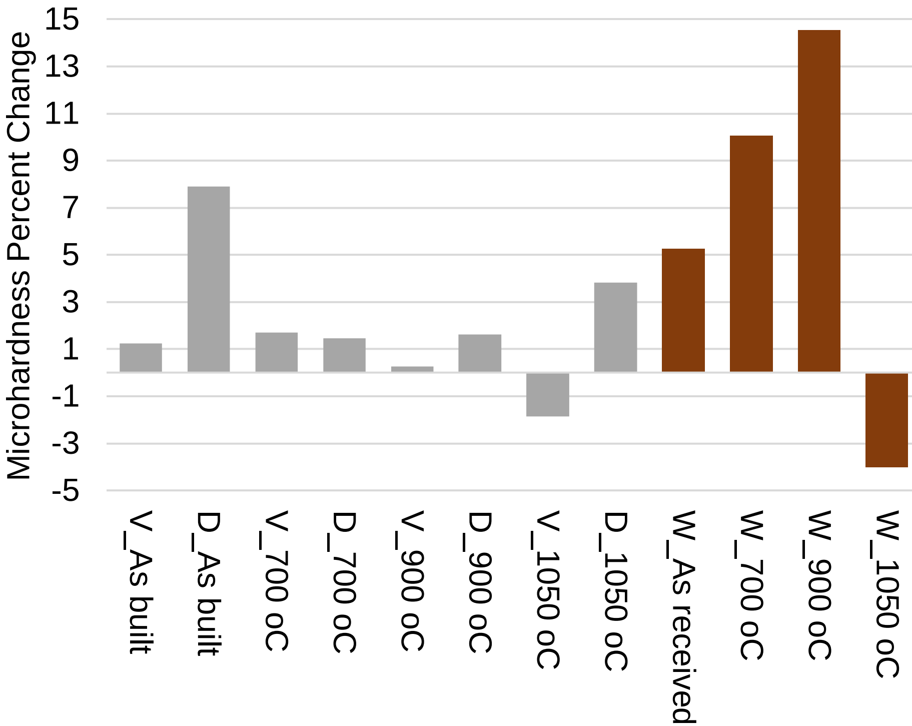
- Thermal neutron irradiation induced embrittlement/hardening in AM and wrought IN625
- 1050 °C AM vertical and wrought showed slight radiation softening phenomenon
- Preliminary results show AM IN625 to be more resistant to radiation hardening than wrought IN625



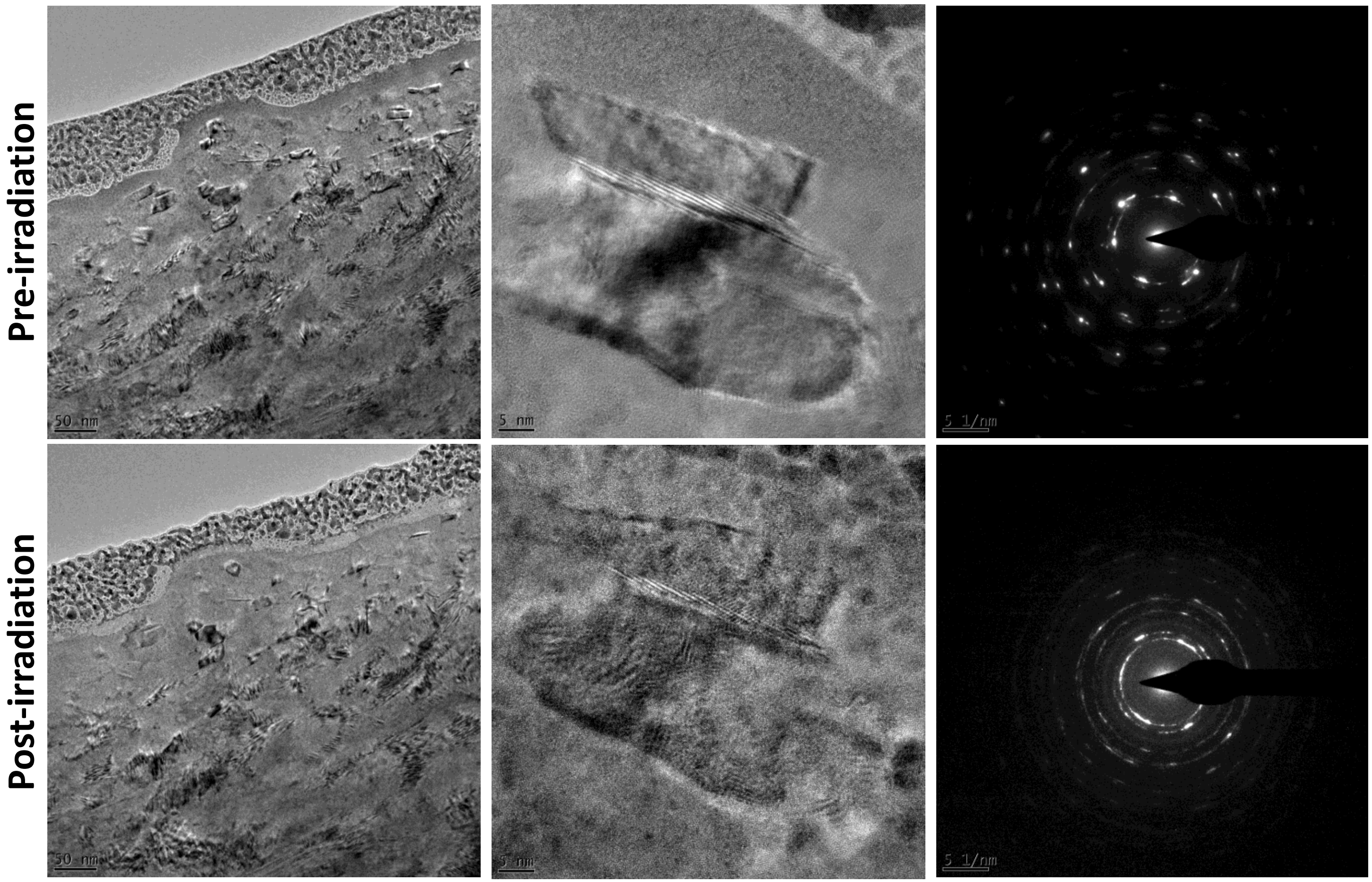


Full spectrum neutron irradiation

- Vertically printed AM samples hardened 0.4% on average
- Diagonally printed AM samples hardened 3.8% on average
- Conventionally wrought samples hardened 6.1% on average



FAST NEUTRON IRRADIATION – LAMELLA TECHNIQUE



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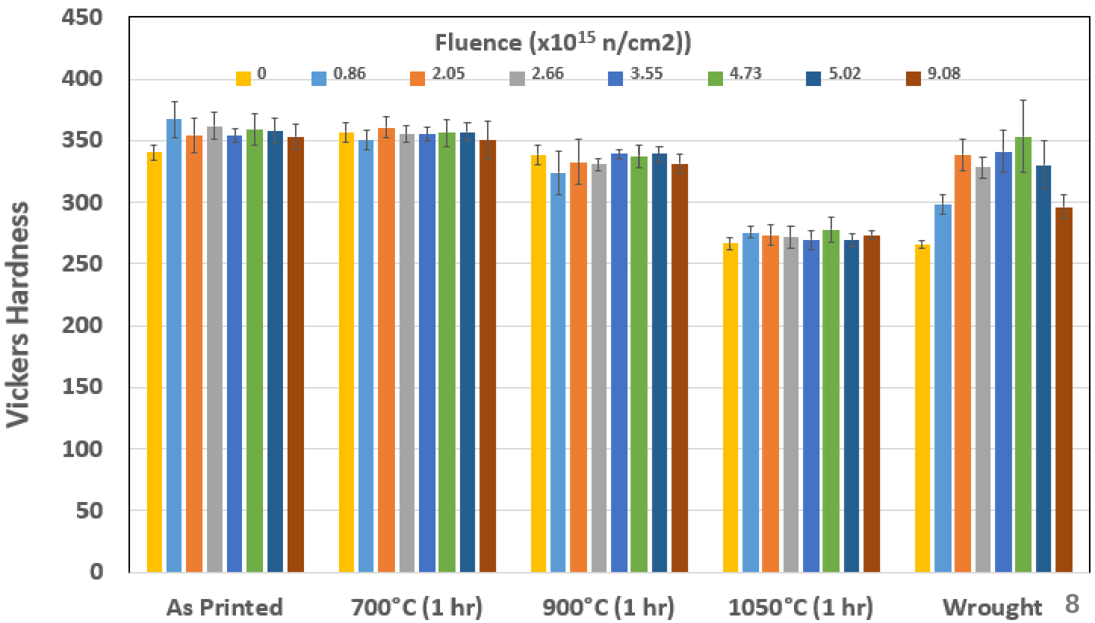
FAST NEUTRON IRRADIATION

- Microhardness was measured at different neutron fluences
- Less variation seen in the microhardness values of AM Inconel 625 compared to wrought Inconel 625

  - Lower overall fluence compared to thermal neutron irradiation meaning lower DPA
  - No thermal neutrons meaning lower activity



SUMMARY AND CONCLUSIONS

- Several L-PBF AM IN625 and wrought IN625 samples were irradiated using thermal and fast neutrons.
  - Results showed that L-PBF IN625 samples were more resistant to radiation hardening compared to wrought IN625.
  - Wrought IN625 samples were most prone to radiation hardening with average of 6.1%.
  - Diagonal AM IN625 samples experienced slightly more radiation hardening than vertical AM samples

- L-PBF AM IN625 and wrought IN625 samples were irradiated using fast neutrons
  - Results showed that wrought IN625 hardness values had more variation over the course of the experiment than the AM IN625 samples

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CONTINUING WORK

- Detailed microstructure investigation to thoroughly understand the radiation damage mechanism in L-PBF AM and wrought samples
  - SEM and TEM imaging
  - Investigation of phase contributions, build orientation effects
- L-PBF AM Inconel 718 samples currently undergoing irradiation trials.
- Proton beam experiments are being conducted to supplement full-spectrum neutron irradiation experiments.

THANKS

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