Final Presentation

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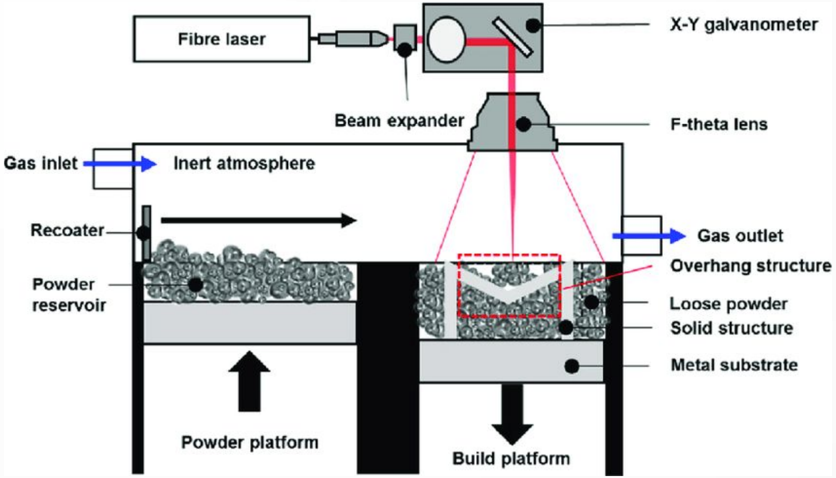
Selective Laser Melting of Ti64 with HIP Post-Processing

Brief Introduction

What is LB-PBF (LPBF)?

- Laser beam (LB)
- Powder bed fusion (PBF)
    - an additive manufacturing process
    - thermal energy selectively fuses regions of a powder bed



Typical LPBF machine

https://www.researchgate.net/figure/Schematic-of-a-typical-LPBF-machine-The-build-chamber-is-purged-with-a-flowing-inert_fig1_327179759

(ASTM E52900, 2021)

Brief Introduction

This work

- Ti-6Al-4V (Ti64) samples
  - α + □ Ti alloy
  - Prepared using SLM printer
- Post-processing step
  - Hot isostatic pressing (HIP)
  - Close pores (apply heat and pressure at the same time)

Selective laser melting printer (SLM Lasertec 30 DMG Mori)

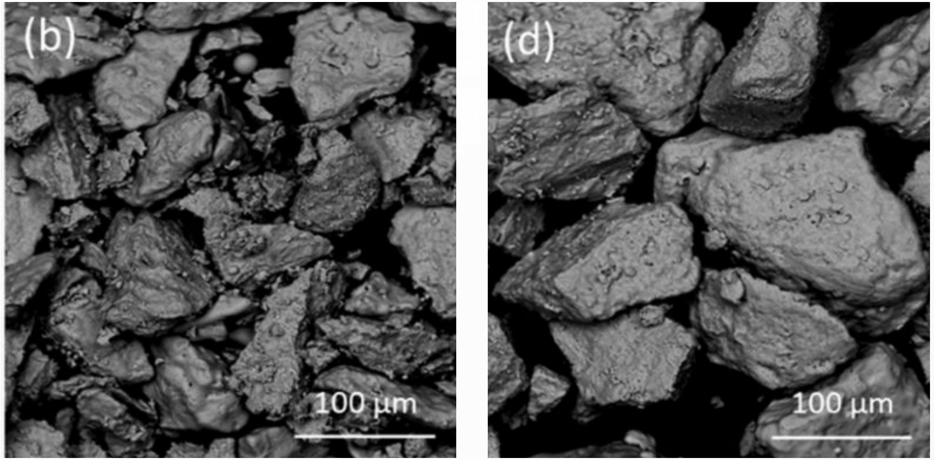
https://www.dmgmori.co.jp/en/products/machine/id=3823

(Asherloo, 2022)

Brief Introduction

This work

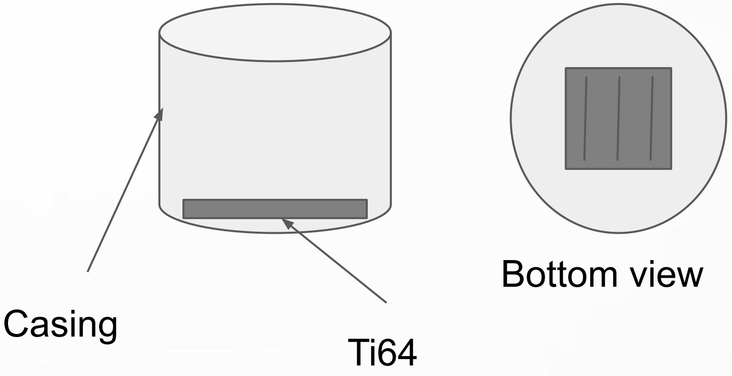
- Hydride-dehydride (HDH) powder manufacturing process
  - Cheaper than conventional method (gas atomization)
  - Non-spherical powders
    - 50–120 µm fine
    - 75–175 µm coarse



(b) Fine powder, (d) Coarse powder

(Asherloo, 2022)

Sample Preparation - Grinding & Polishing



Goal

- Remove surface topography to have flat surface for characterization (e.g., optical microscopy)

Method (Grinding)

- Water constantly flowing onto sandpaper
  - Rotating wheel or stationary
- Rotate sample 90° with each paper to remove lines
  - Grits: 240, 400, 600, 800, 1200

Ti64 sample in polymer mold (after grinding with 240 grit)

Sample Preparation - Grinding & Polishing

Method (Polishing)

- Optical microscopy
  - Polishing cloth on rotating wheel
    - 3 µm Al_2O_3 slurry (~10 min)
    - 1 µm Al_2O_3 slurry (~7 min)
  - Vibrating polisher
    - 0.05 µm Al_2O_3 slurry (~30 min)

Polished sample, surface is mirror-like

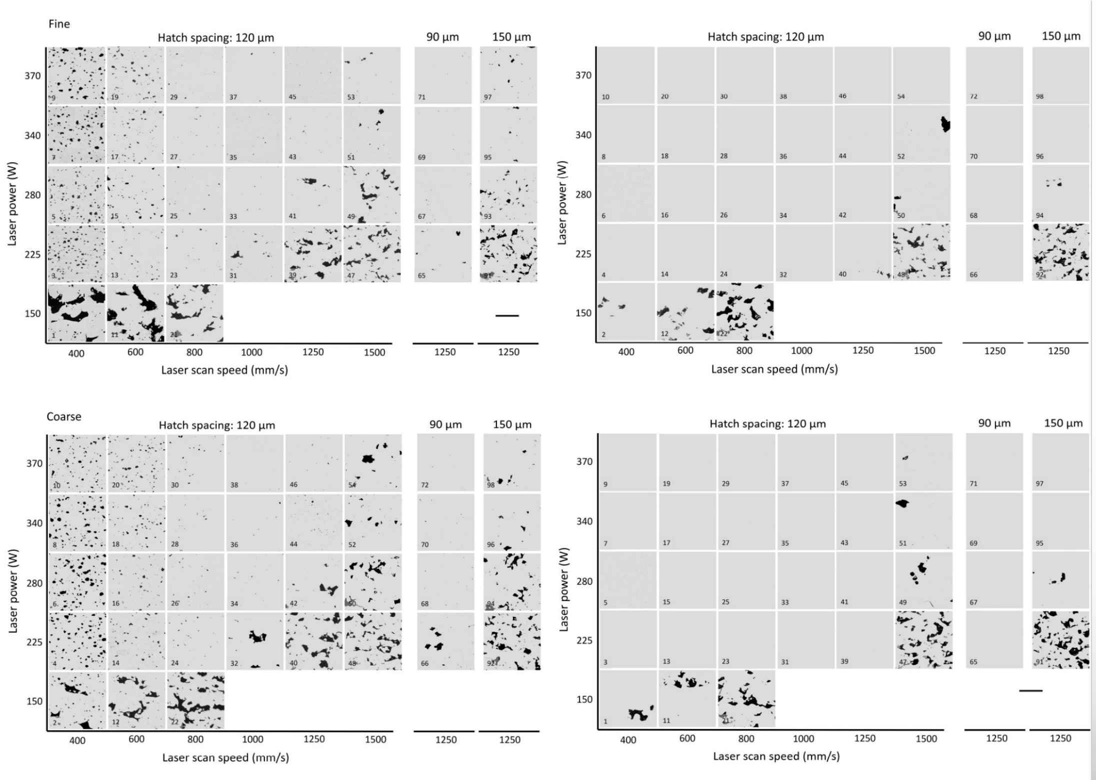
Sample Preparation - Grinding & Polishing

Method (Polishing)

- EBSD
  - Add P4000 grinding paper
  - Polishing cloth on rotating wheel
    - 1 μm Al_2O_3 slurry (~7 min)
  - Vibrating polisher
    - 0.05 μm Al_2O_3 slurry (1 h 15 min)
  - Colloidal silica polisher
    - 0.04 μm colloidal SiO_2 (1 h 39 min)

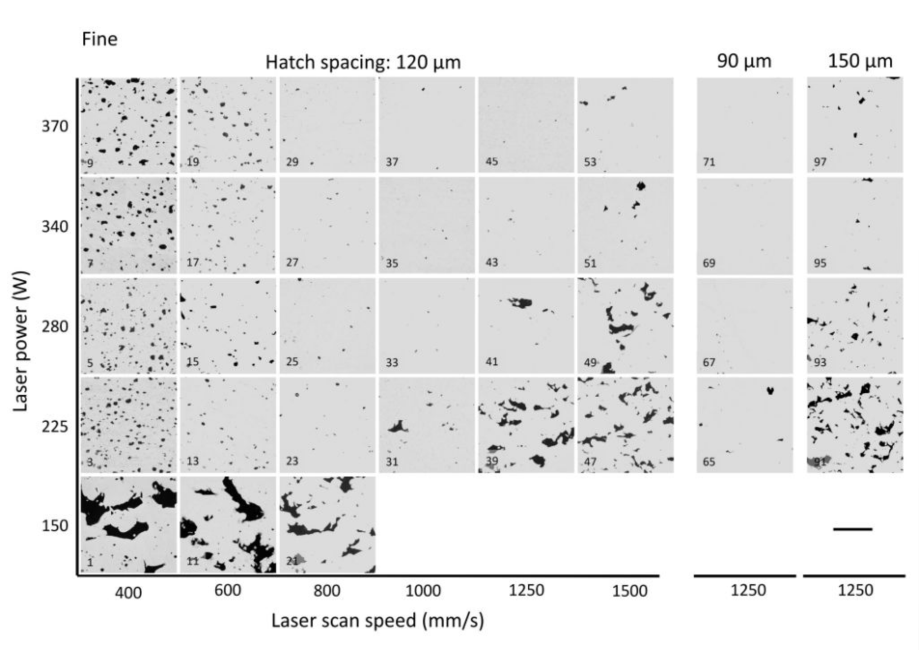
Machine for polishing with colloidal silica

Ti64 Processing Map (Before and After HIP)

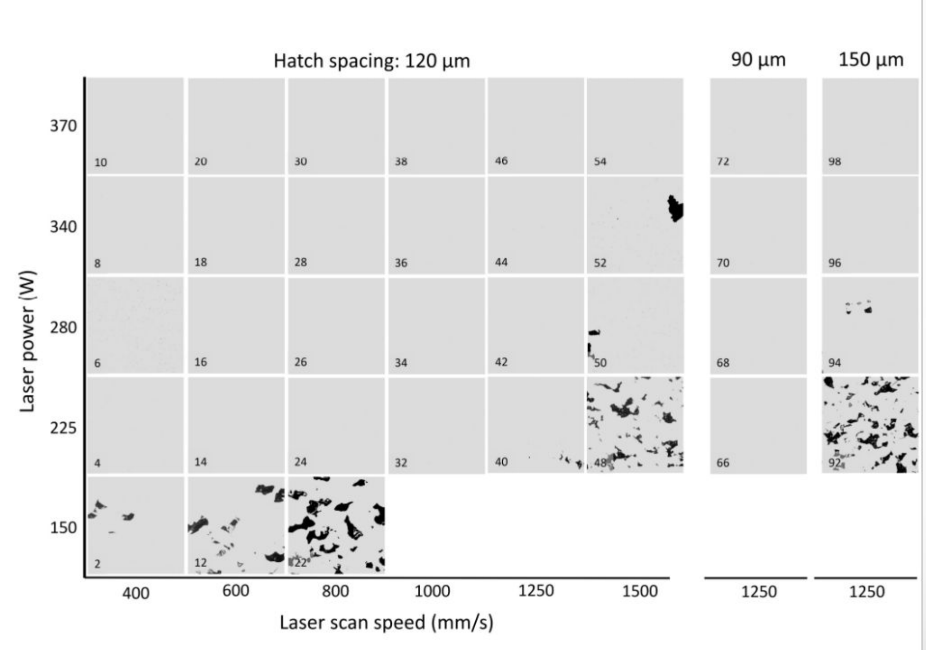


Processing parameter map. The left side is before HIP treatment, and the right side is after.

Ti64 Processing Map



Fine powder samples before HIP



Fine powder samples after HIP. Smaller and less frequent pores

Hardness Test (Theory)

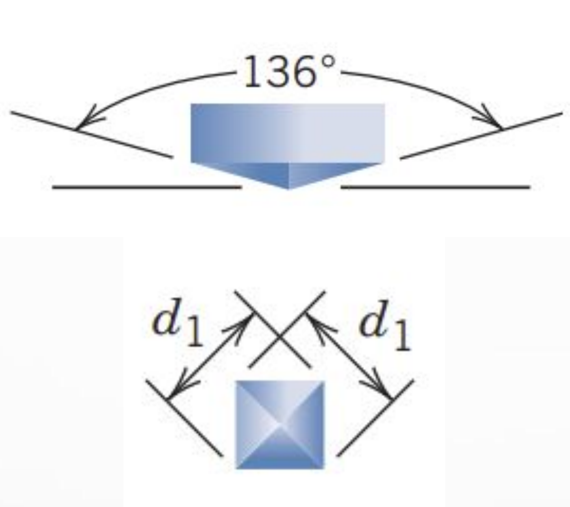


Illustration of Vickers hardness indent

$$HV = 1.854P/d_1^2$$

Vickers Hardness Equation

- P: applied load (kg)
- d_1: diagonal (mm)

(Callister, 2018)

Hardness Test

Goal

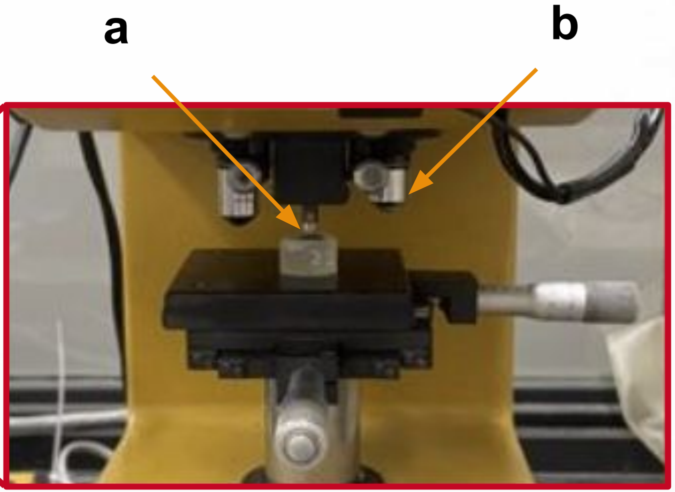
- Measure hardness (resistance to permanent deformation) of Ti64 samples
  - Fine powder, 120 µm hatch spacing

Method

- Indent sample 12 times
  - 3 rows of 4
  - Avoid pores, other indents, and epoxy
- Measure diagonals using optical microscope
  - Not necessarily equal
- Vickers Hardness test
  - Can be converted into Pa

Hardness Indentation

Digital Micro Hardness Tester



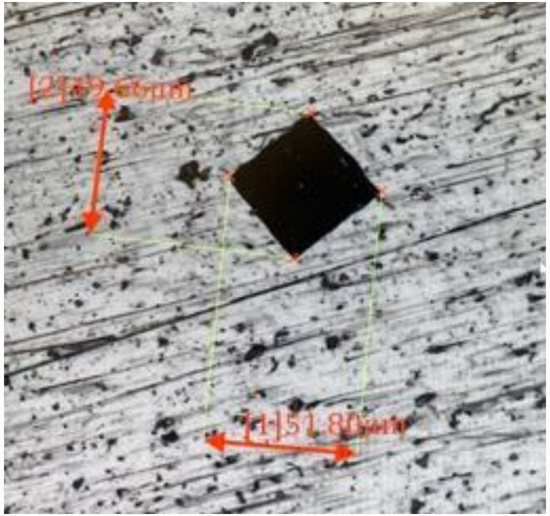
(a) Diamond tip indenter, (b) Lens

Test Parameters

- 15 s load time
- 500 g load

Hardness Measurements

Optical microscope



Measure diagonals (computer accounts for magnification)

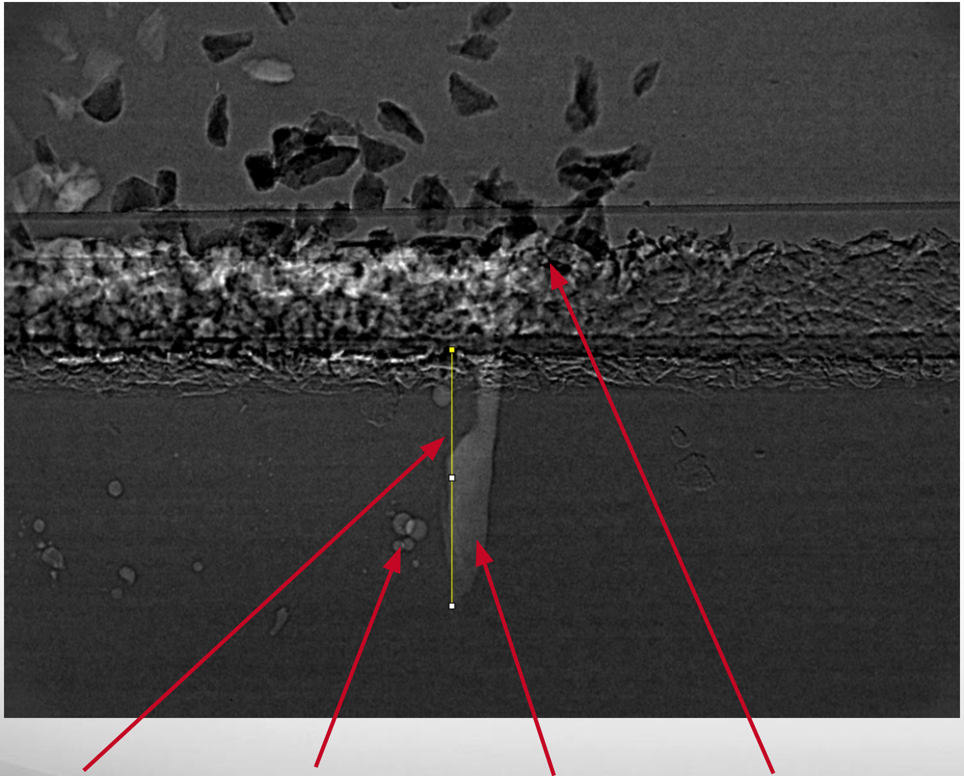
Total Average (across all samples)

358.83 $HV_{0.5}$

- Similar value to LPBF Ti64 w/o HIP
- Reference for Vickers:
  - WC ~2500
  - Epoxy ~45
  - LPBF 316L SS ~240

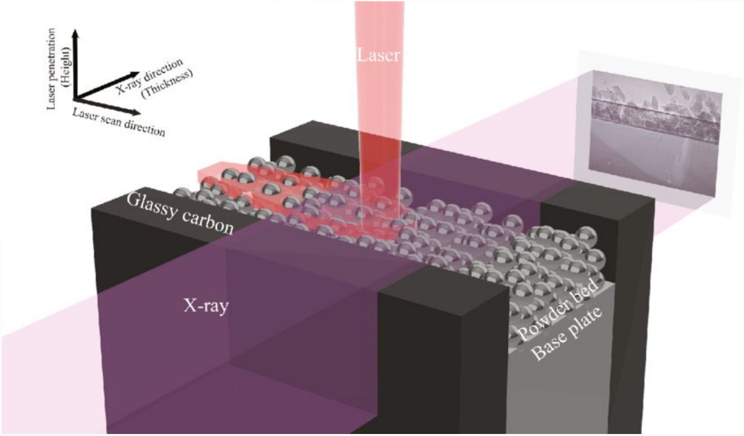
https://www.tf.uni-kiel.de/matwis/amat/mw1_ge/kap_8/advanced/t8_4_2.html
(Mokhtari, 2021)

Dynamic X-ray Radiography Measurements



1 2 3 4

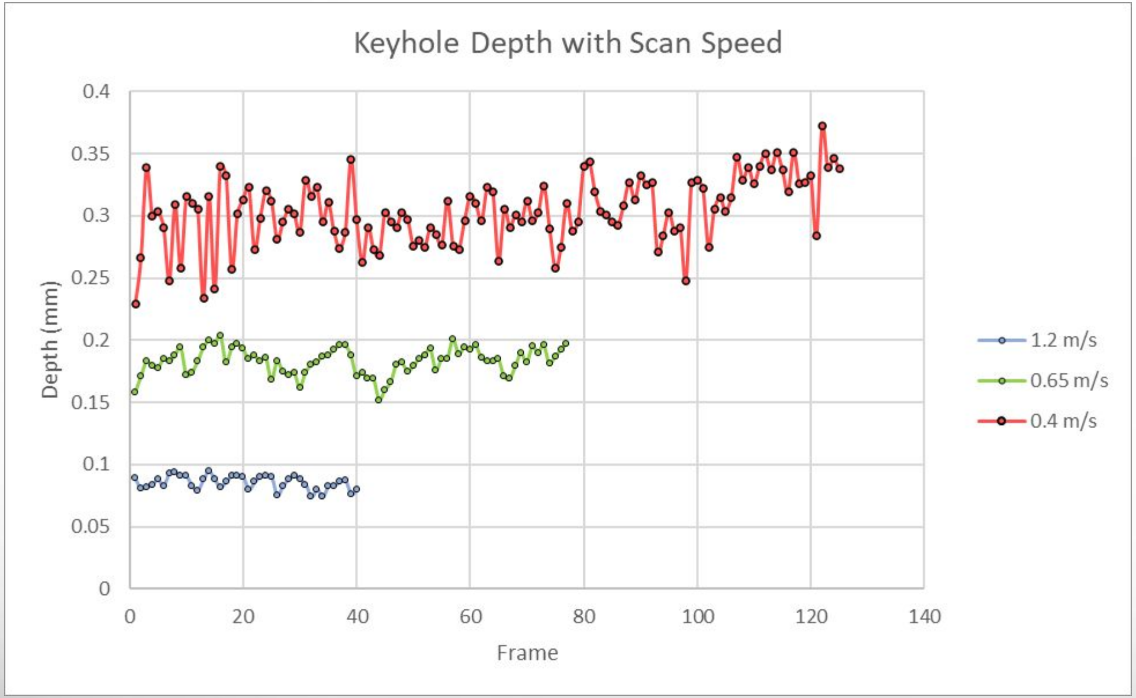
(Wu, 2021)



Schematic of setup at APS

1) Measuring tool
2) Keyhole pores
3) Keyhole
4) Powder layer and spattering

Dynamic X-ray Radiography Results



Speed (m/s)	Avg Depth (mm)	Stdev (mm)
0.4	0.3037	0.02677
0.65	0.1831	0.01060
1.2	0.0855	0.00545

Accomplishments

Measured

- Surface roughness
- Hardness
- Fatigue life
- Keyhole porosity depth from dynamic x-ray radiography images

Collected

- Optical microscopy images
  - Polished surface
  - Surface roughness “heat” map
- Porosity data from CT scan

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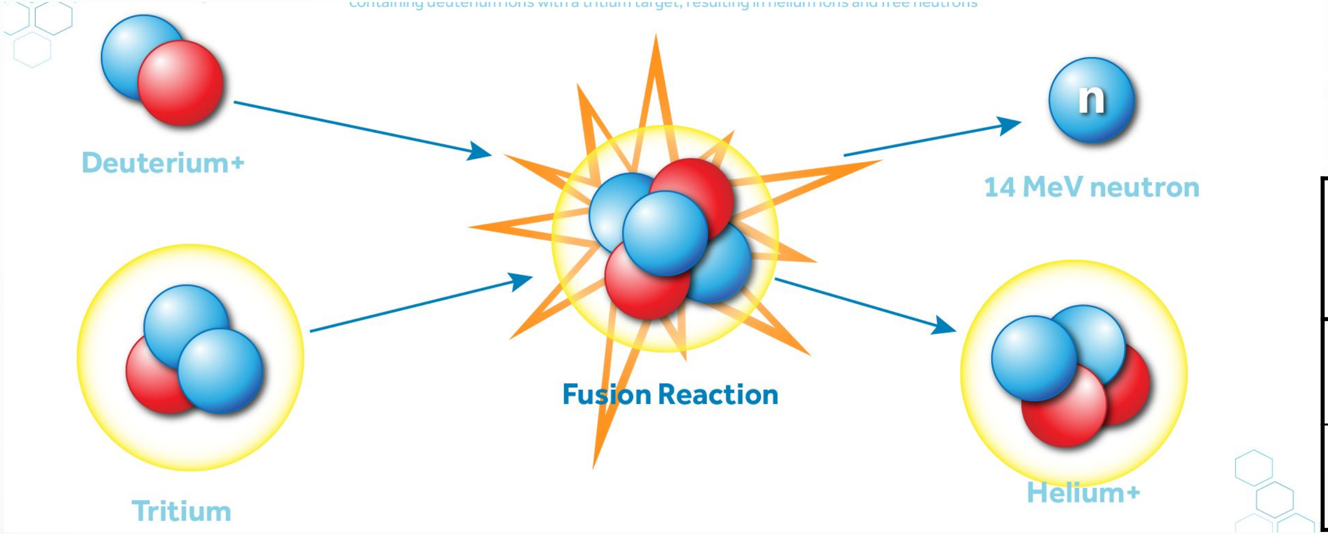
Combined Neutron and X-ray Imaging Literature Review and Potential Commercial Application

Brief History

1932	James Chadwick discovered the neutron
1935-44	First reported use of neutron activation analysis (NAA)
	- Neutrons hit object, radioactive isotopes form in object, gamma rays emitted are measured using film (now digital)
1943	First usable nuclear reactor (at Oak Ridge) was built
1950s	Availability of small accelerator-based neutron generators (increased use of neutrons in laboratories)
Late 1950s	Geologists and petroleum engineers used portable neutron generators (for fast NAA (FNAA))
70s - Present	Facilities built and new techniques developed

(James, 2000); ("Neutron Imaging", 2012); (Brenizer, 2013)

Neutron Generation



https://www.shinefusion.com/neutron-generators/

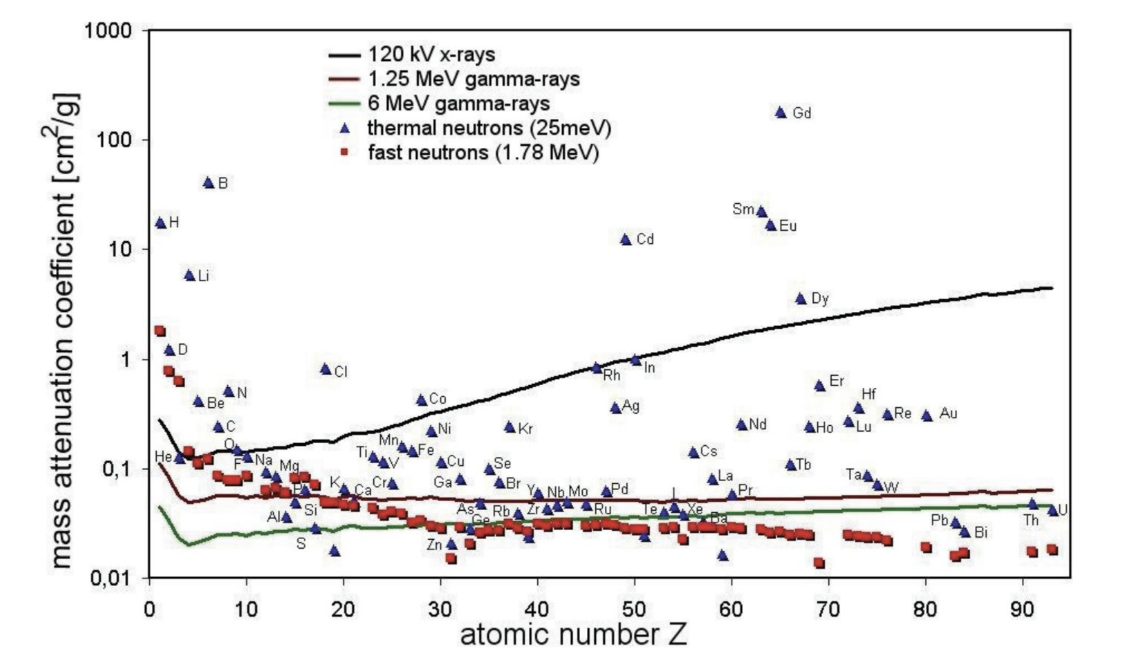
D = Deuterium
T = Tritium

Imaging (Most systems)	
Cold	Thermal
< 25 meV	25 meV

- DT fusion
  - Deuterium ion beam strikes target loaded with tritium
  - Produces 14.1 MeV neutron
- Also DD fusion
  - Produces 2.45 MeV neutron

http://adelphitech.com/

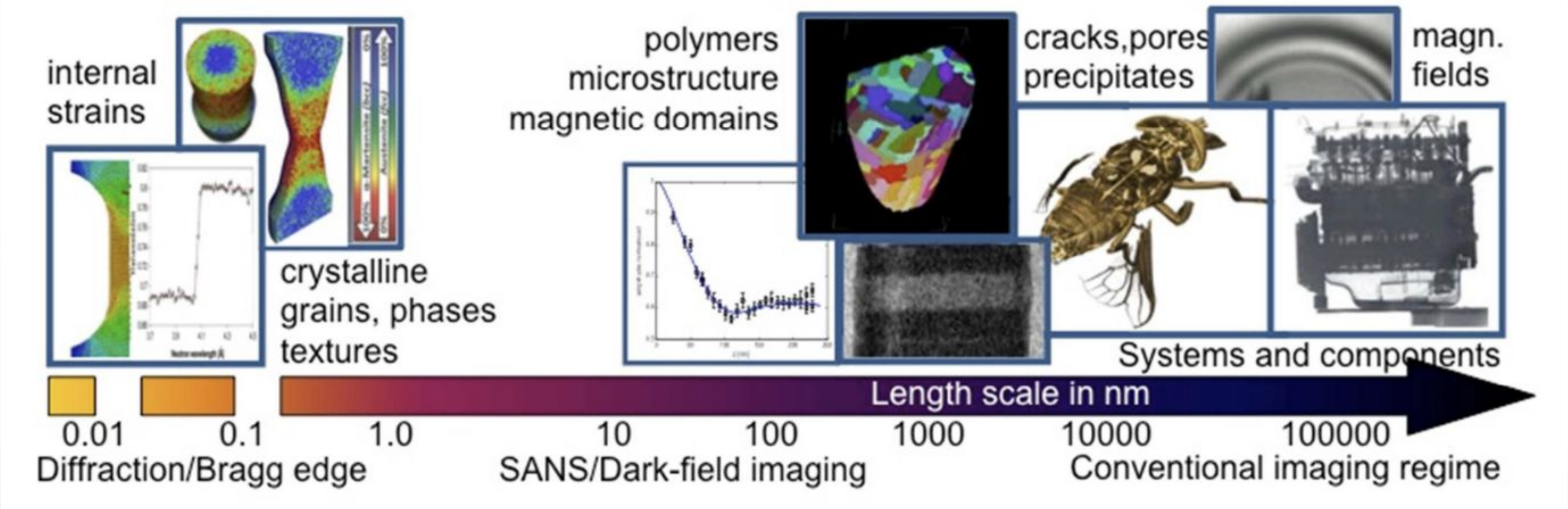
Attenuation vs. Z



- X-ray attenuation increases with Z
- Thermal neutrons show no simple relationship, while fast neutrons decrease with Z
- Note that cold neutrons are < 25 meV

(Kruhl, 2010); (Lehmann, 2021)

Modern Neutron Imaging Capabilities



Map of neutron imaging capabilities, from material data to images of large components

Strobl, 2015

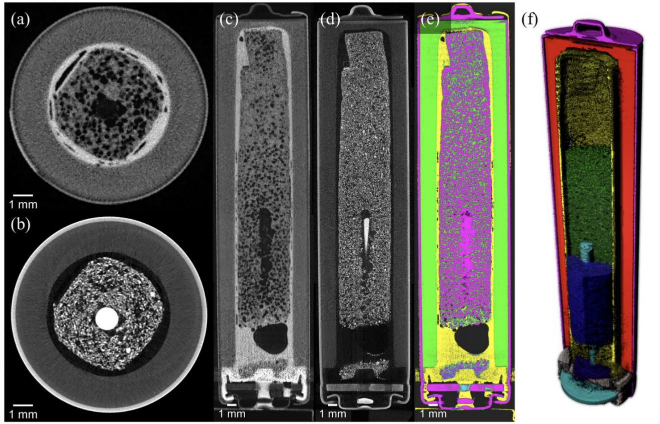
Neutron and X-ray Imaging (Lab)

- Simultaneous neutron and x-ray imaging
  - ICON at PSI, Switzerland
  - NeXT at ILL Grenoble, France
  - NeXT at NIST, USA
  - ODIN at ESS, Sweden
  - VENUS at ORNL, USA
- Neutron and x-ray imaging, not simultaneous
  - NEUTRA at PSI, Switzerland
    - Plans to upgrade XTRA option at NEUTRA to enable simultaneous bi-modal neutron and x-ray imaging

Combined Neutron and X-ray Imaging

Published

- Imaging composite materials
  - Volume segmentation of batteries and cement
  - Soil, electronic components, corroded nails, artifacts (e.g., sword), etc.

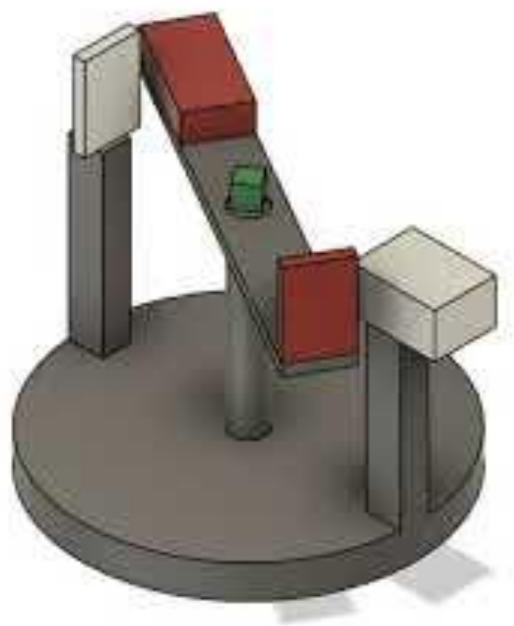


Neutrons pick up polymer separator, while x-rays show current collector

Not Published (as far as I know, possibly by 2023)

- Additive manufacturing
  - Some papers using neutron tomography

(LaManna, 2020); (Lehmann, 2021)



Simultaneous Neutron/X-ray Scan

N source/detector

- rotate 60°
- wait 90°
- rotate 60°

Sample

- rotate 360°

X-ray source/detector

- stationary

Future Work

- Continue researching sources
- Figure out what needs to be done commercially, and why?
- Answer: Do we have n sources for tomography? If not, for imaging? If not, n source/detector move with the sample.
- Figure out energy/exposure required for neutron images
  - For 4×10^7 n/s output, image took 4 hours (first radiography, 1935)
  - 1946: Neutron radiograph took a few minutes
  - What are the times nowadays?

1998, Berger

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