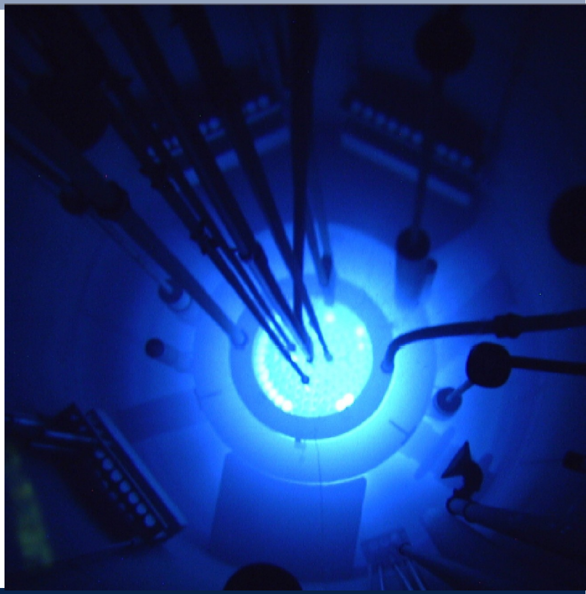
Irradiation Performance Testing of Specimens Produced by Commercially Available Additive Manufacturing Techniques

Dr. Jeffrey C. King[1], Dr. Douglas Van Bossuyt[2]
Nuclear Science and Engineering Program
[1]Metallurgical and Materials Engineering Department
[2]Mechanical Engineering Department

NEET-AMM Workshop

October 17-18



COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Motivation

- Additive manufacturing offers several potential benefits to the nuclear energy enterprise...
  - Unique shapes
  - Custom parts
  - Just in time manufacturing
- ...but, several issues remain
  - Understanding process variables
  - Reproducibility
  - Qualification
  - Irradiation performance data

Project

- Test current commercial AM technologies
  - Pre-irradiation characterization
  - Thermal aging
  - Irradiation (0.05-0.8 DPA)
  - Post-irradiation testing and examination
- Compare impact of neutron irradiation as a function of alloy and manufacturing technique
- Provide data for future inquiries/experiments

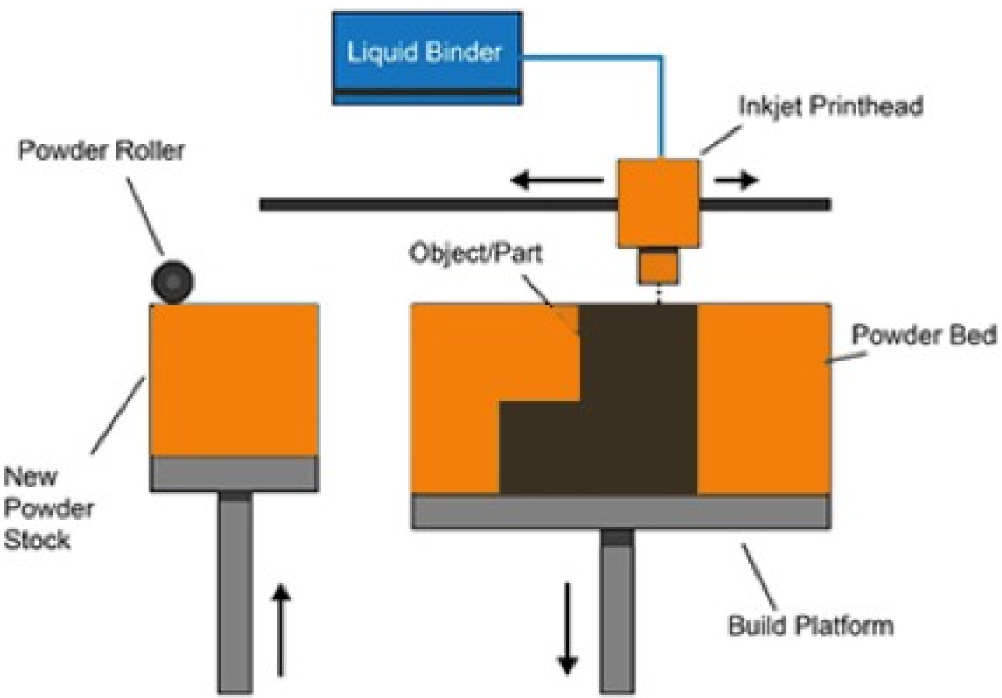
Test Matrix

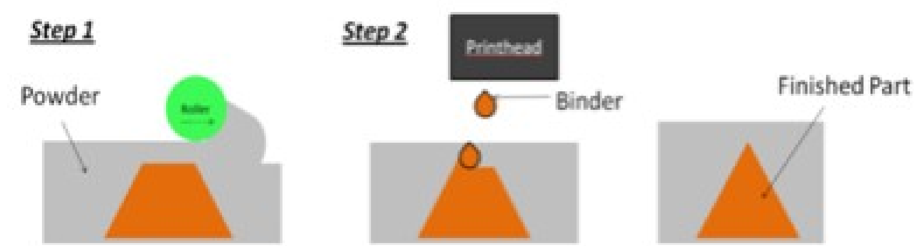
- Four production methods
  - Powder Bed Binder Jet (PBBJ)
  - Powder Bed Laser Sintering (PBLS)
  - Laser Powder Fabrication (LPF)
  - Electron Beam Free Form Fabrication (EB3F)
- Two alloys
  - SS-316L
    - Common stainless steel
  - Inconel-718
    - Representative of nickel-based alloys

Powder Bed Binder Jetting

- A liquid bonding agent is supplied by a print head onto a layer of raw material powder
- A counter-rotating roller then spreads a new layer of powder and the print head binds the next layer of material
- This process is repeated layer by layer along the 2-D cross sectional shape of the desired 3-D object
- Green part is then sintered to yield final shape and density

Powder Bed Binder Jetting



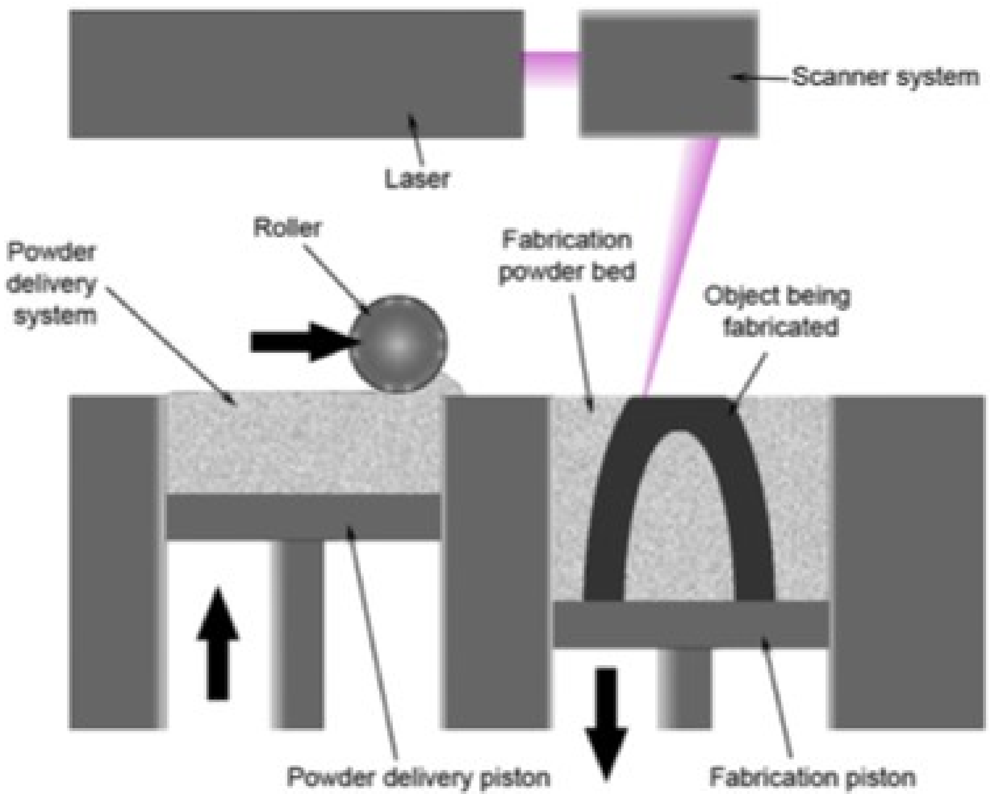


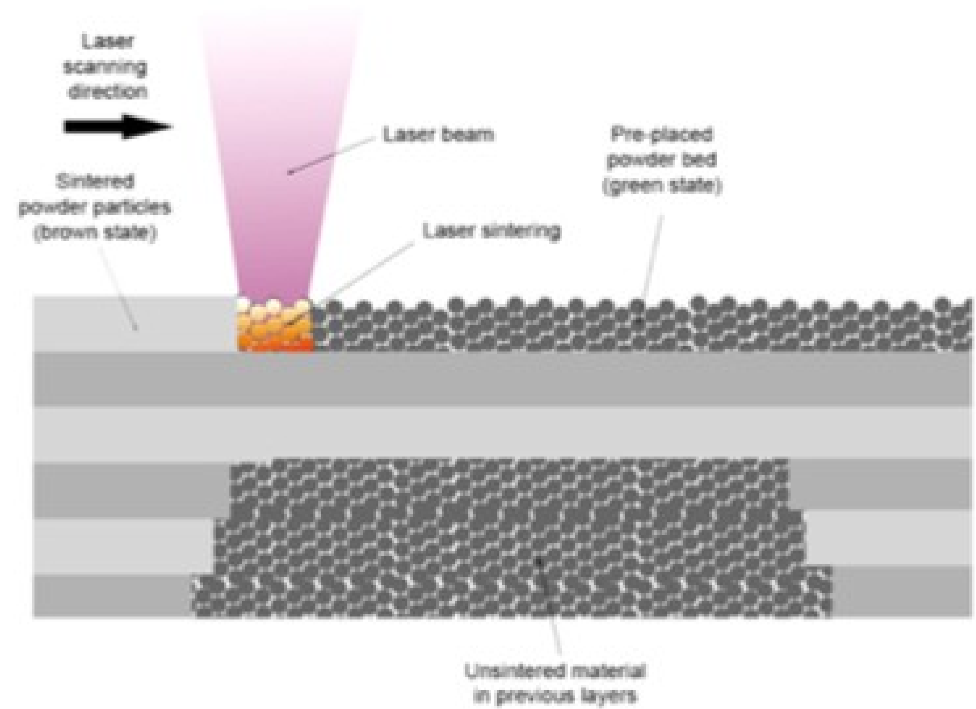
https://www.rapidsol.org/blogitem.aspx?id=10
http://www.me.vt.edu/dreams/binder-jetting/

Powder Bed Laser Sintering

- A laser is directed onto a bed of raw material powder, which sinters the material into a solid form
- A roller then spreads a new layer of powder and the laser binds the next layer of material
- This process is repeated layer by layer along the 2-D cross sectional shape of the desired 3-D object

Powder Bed Laser Sintering



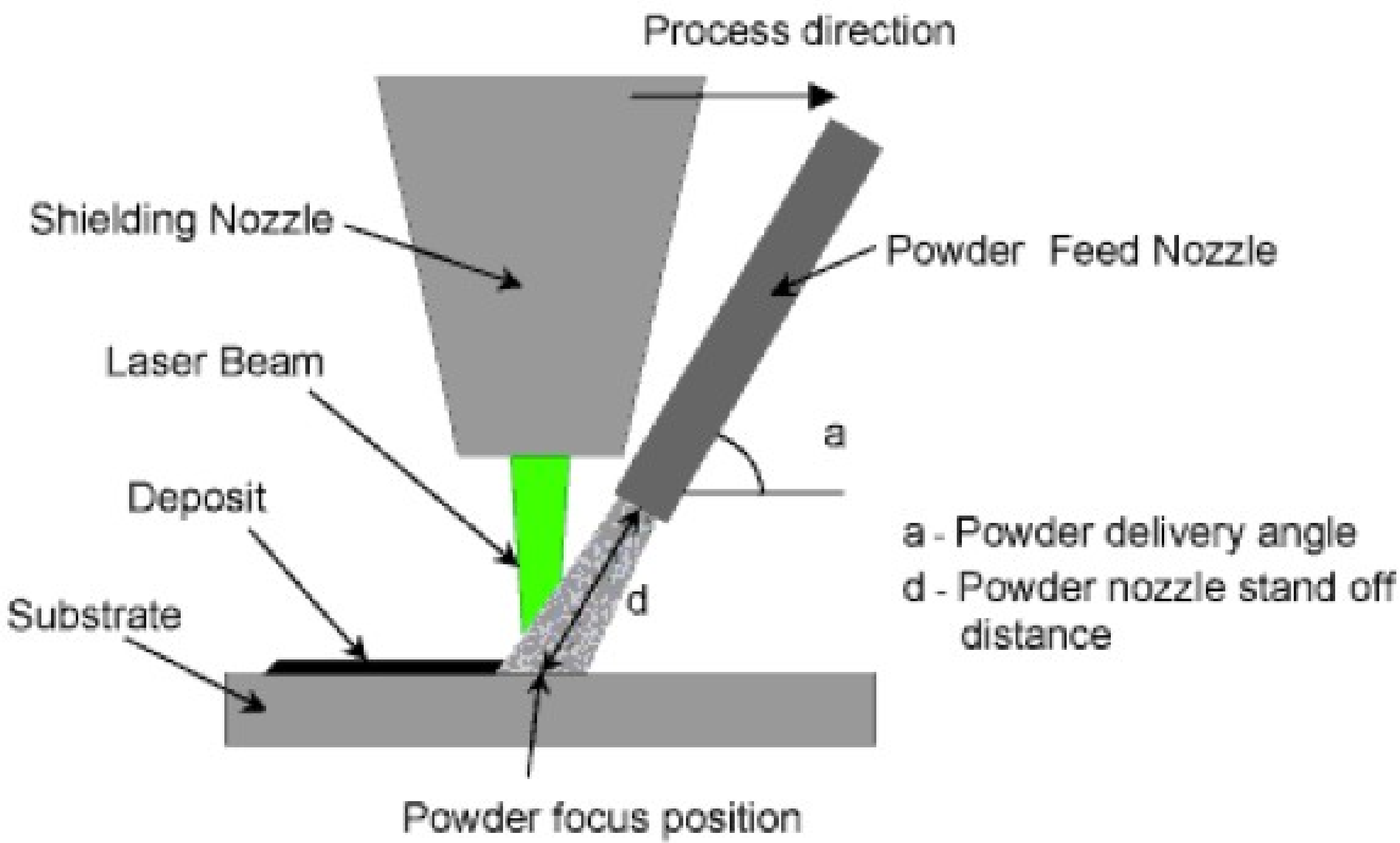


https://en.wikipedia.org/wiki/Selective_laser_sintering

Laser Powder Fabrication

- A printer head deposits raw material powder and uses a laser to bind it simultaneously
- The printer head builds a part by depositing and binding layers of material in the 2-D cross sectional shape of the desired 3-D object

Laser Powder Fabrication

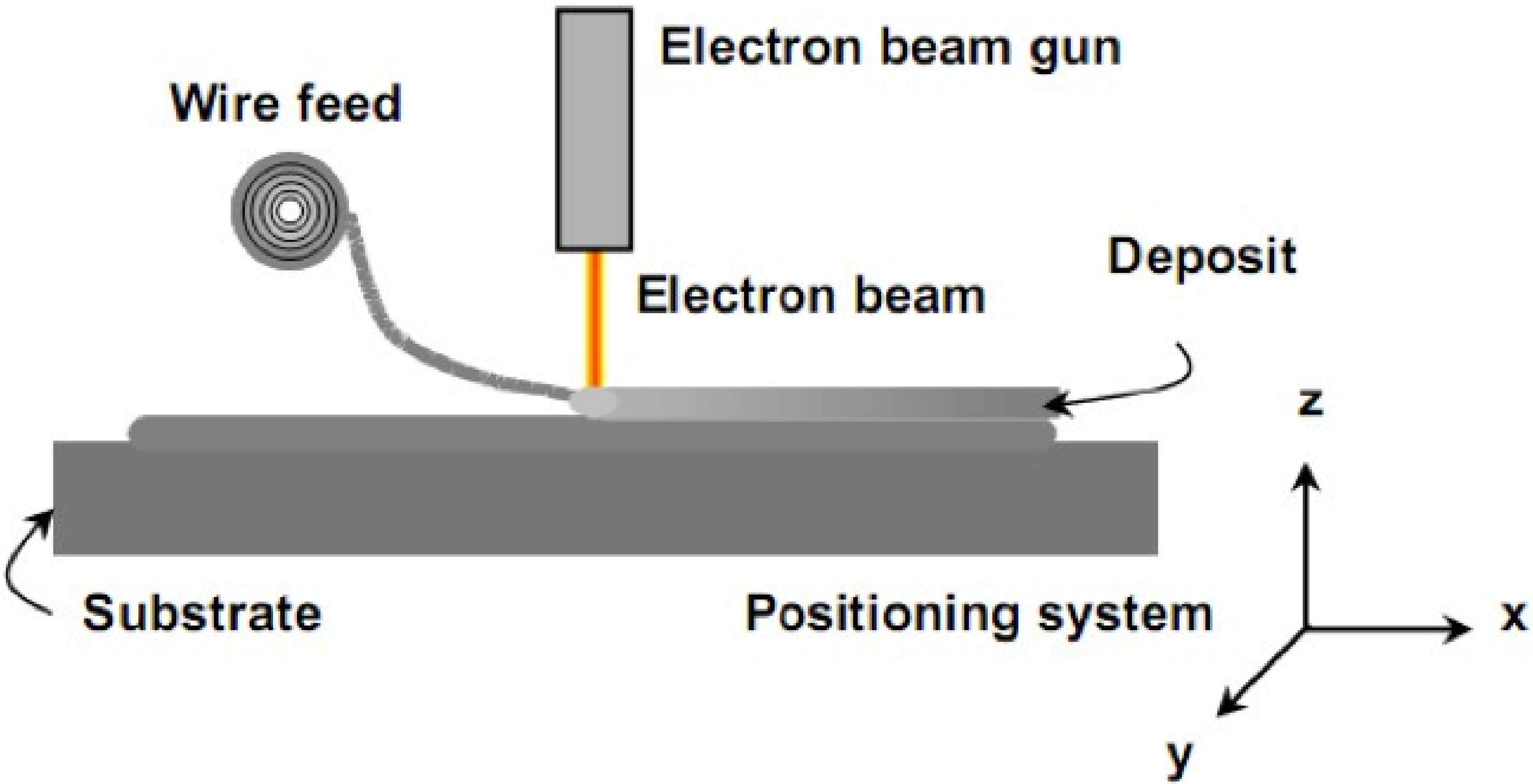


http://www.twi-global.com/technical-knowledge/published-papers/manufacturing-with-lasers-developments-and-opportunities-july-2004/

Electron Beam Free Form Fabrication

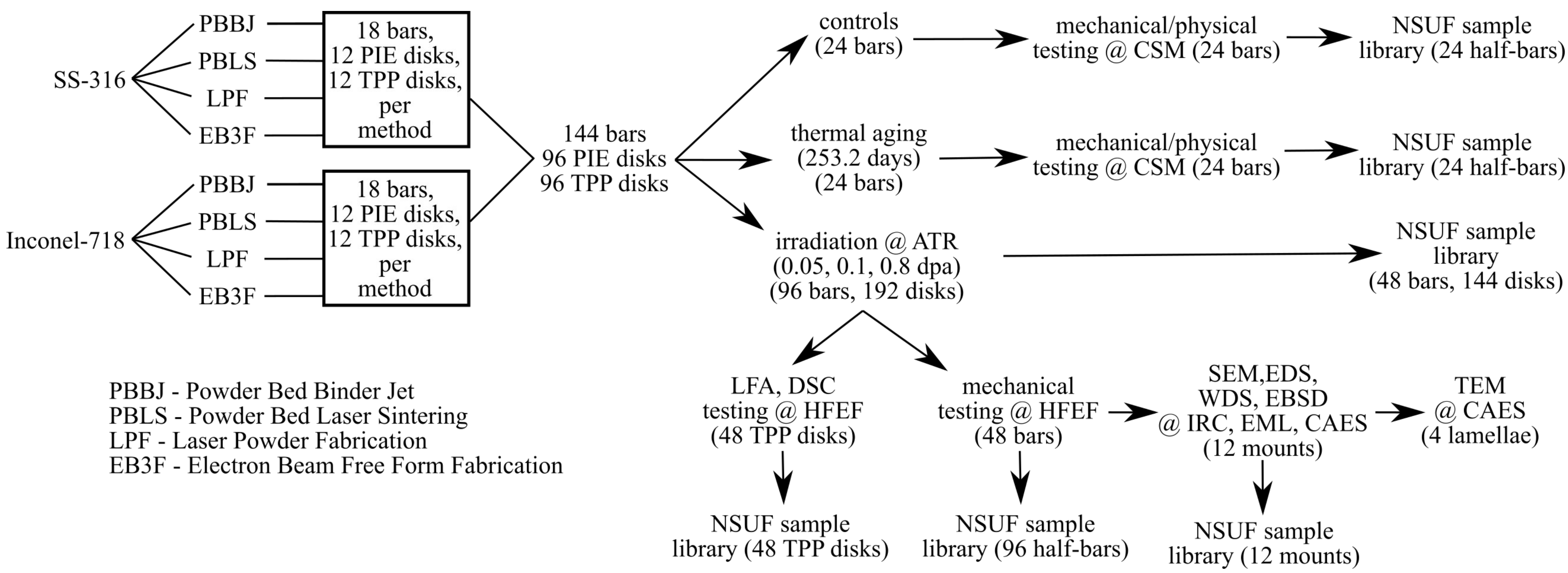
- A focused electron beam in a vacuum environment creates a molten pool on a metallic substrate
- Metal wire is fed into the molten pool and binds with the substrate as soon as the electron beam passes
- This process is repeated layer by layer along the 2-D cross sectional shape of the desired 3-D object

Electron Beam Free Form Fabrication



https://www.whiteclouds.com/3dpedia-index/electron-beam-freeform-fabrication-ebf

Test Plan

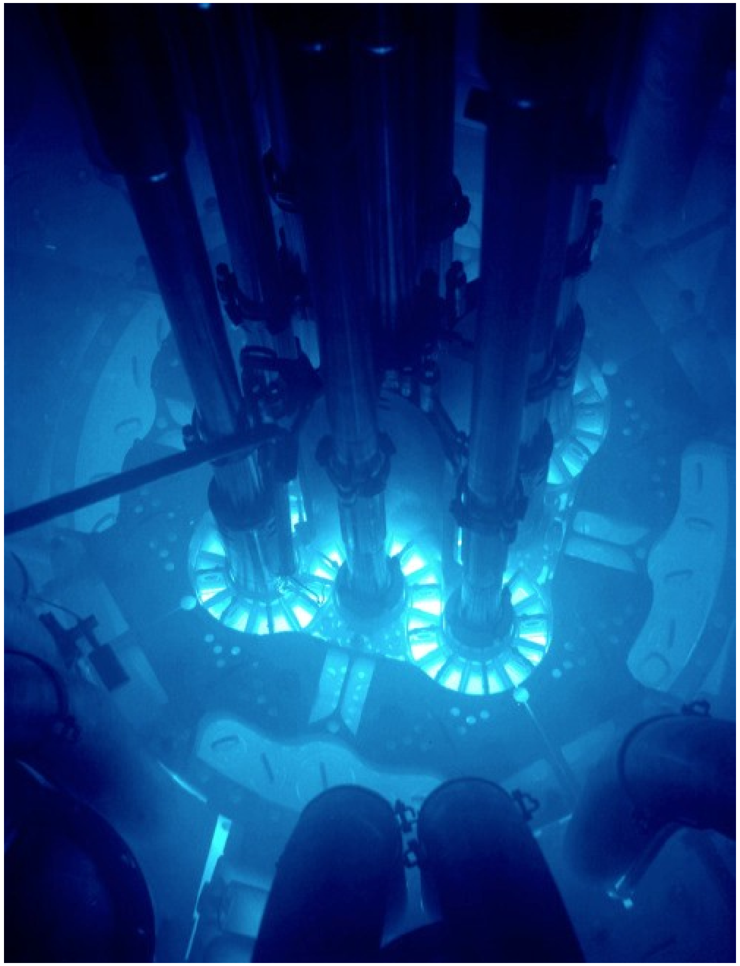

SS-316
PBBJ
PBLS
LPF
EB3F
18 bars, 12 PIE disks, 12 TPP disks, per method
Inconel-718
PBBJ
PBLS
LPF
EB3F
18 bars, 12 PIE disks, 12 TPP disks, per method
144 bars
96 PIE disks
96 TPP disks
controls
(24 bars)
mechanical/physical testing @ CSM (24 bars)
NSUF sample library (24 half-bars)
thermal aging
(253.2 days)
(24 bars)
mechanical/physical testing @ CSM (24 bars)
NSUF sample library (24 half-bars)
irradiation @ ATR
(0.05, 0.1, 0.8 dpa)
(96 bars, 192 disks)
NSUF sample library
(48 bars, 144 disks)
LFA, DSC testing @ HFEF
(48 TPP disks)
NSUF sample library (48 TPP disks)
mechanical testing @ HFEF
(48 bars)
NSUF sample library (96 half-bars)
SEM,EDS, WDS, EBSD
@ IRC, EML, CAES
(12 mounts)
NSUF sample library (12 mounts)
TEM
@ CAES
(4 lamellae)
PBBJ - Powder Bed Binder Jet
PBLS - Powder Bed Laser Sintering
LPF - Laser Powder Fabrication
EB3F - Electron Beam Free Form Fabrication

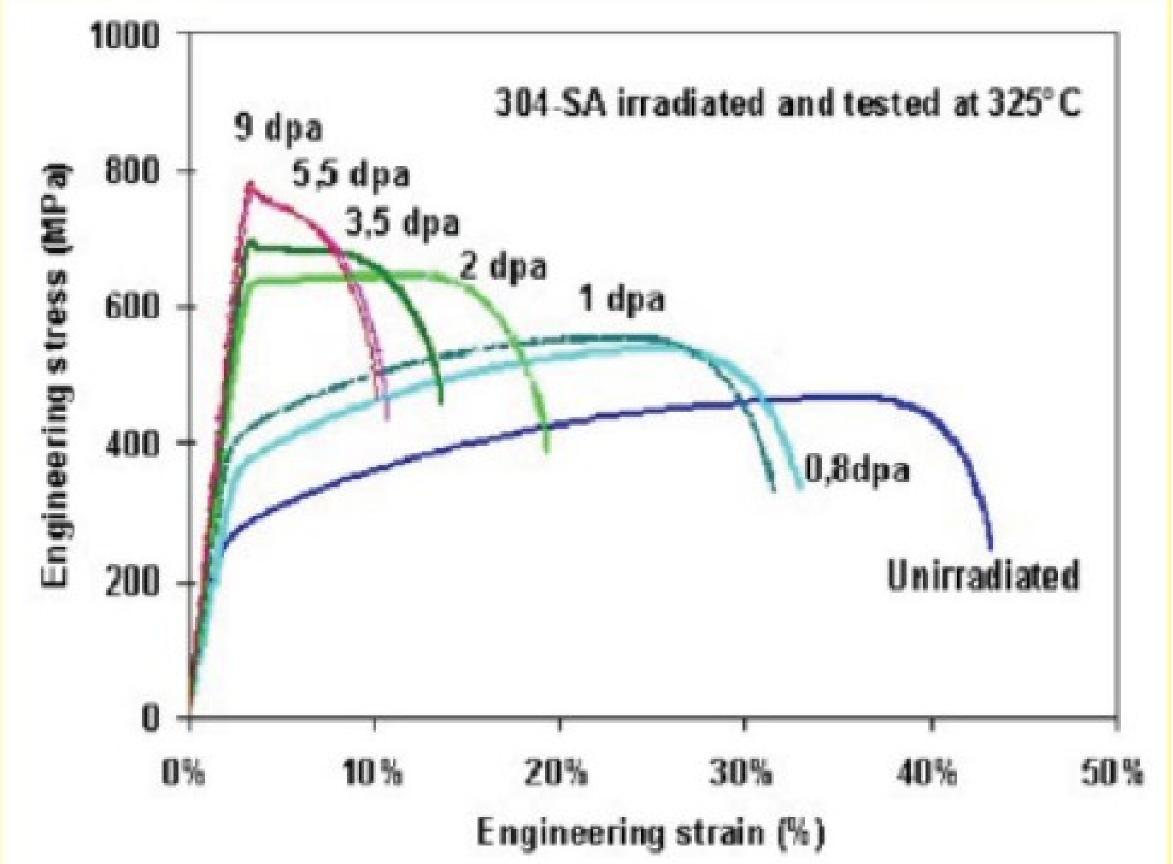
Test Specimens

- Controls
  - Baseline as-manufactured properties
- Thermal aging
  - Time and temperature equal to one irradiation cycle (325±50 ^{o}C)
  - Property changes due to thermal effects
- Neutron irradiation
  - 0.05, 0.1, 0.8 dpa @ 325±50 ^{o}C
  - Onset of irradiation hardening

Irradiation Plan

One cycle in the Advanced Test Reactor (0.05, 0.1 and 0.8 dpa)





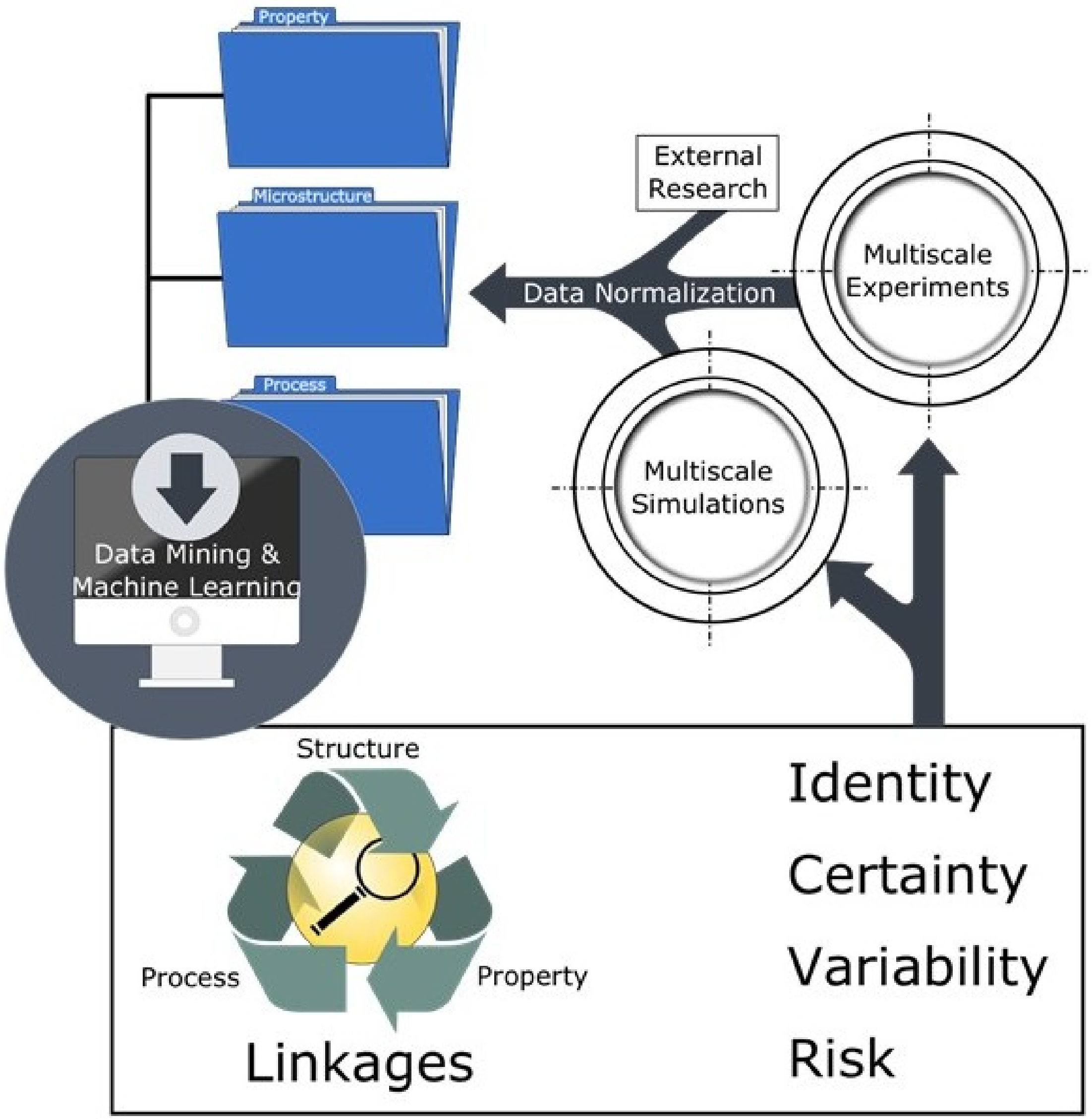
Was, G.S., "Fundamentals of Irradiation Damage", ATR NSUF Summer School, June 8, 2010.

Sample Characterization

- Mechanical (tensile testing)
  - Yield stress, ultimate tensile stress, elongation at fracture
- Thermophysical (laser flash/differential scanning calorimetry)
  - Thermal diffusivity
  - Heat capacity
- Microstructure
  - Scanning electron microscopy
    - Electron dispersive spectrometry
    - Wavelength dispersive spectrometry
  - Focused ion beam microscopy
    - Electron backscatter diffraction
  - Transmission electron microscopy

Long Range Goal

- Provide information for the qualification of additive manufacturing processes for nuclear applications



Questions/Comments?