Fine-tuning hierarchy: targeted in-situ annealing of additively manufactured titanium lattices

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Lawrence Livermore National Laboratory

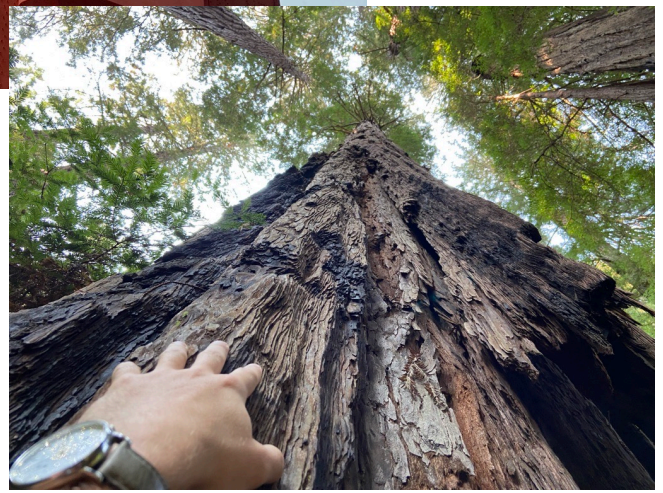
My background:

Honorable Mention

The Present:

Lawrence Livermore National Laboratory

Materials SCIENCE



~7400 employees.

Safety, security, and reliability of the nation's nuclear deterrent.

Energy and environment, scientific research/outreach, and the nation's economic competitiveness.

Back to fine-tuning hierarchy: Why build titanium lattices?

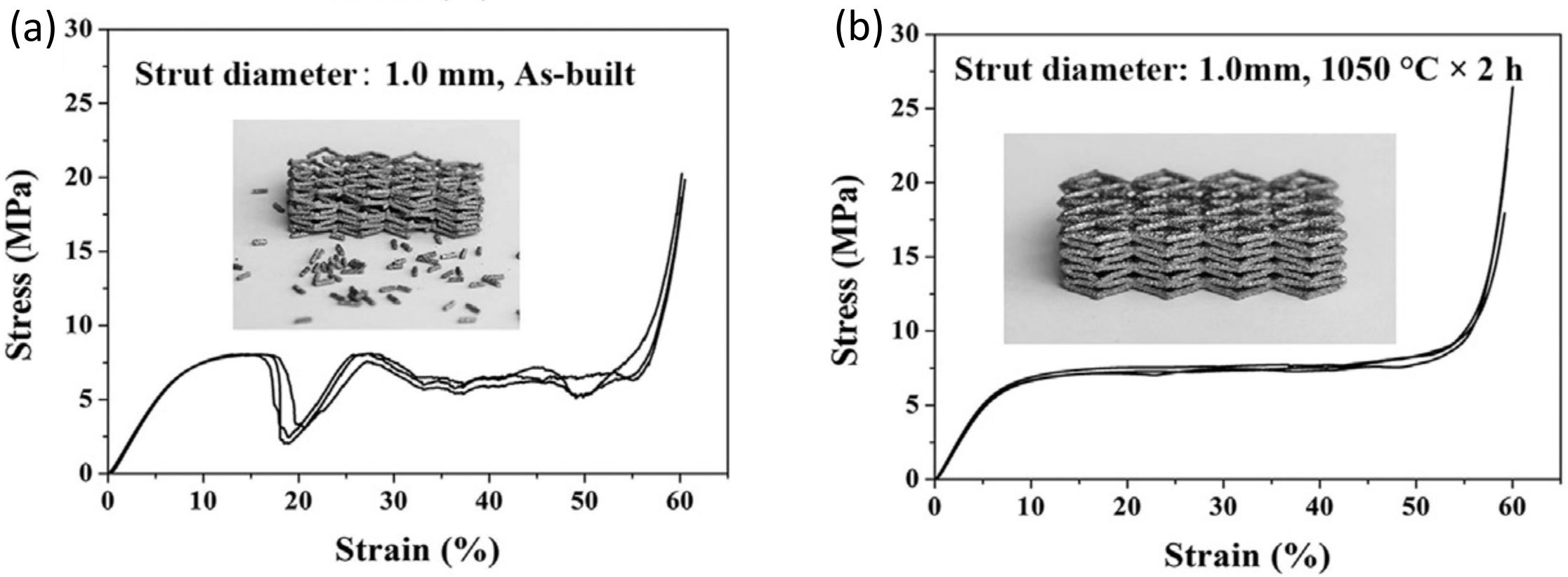
Aerospace applications: Strength to density ratio

Biomedical applications: Biocompatibility + stress shielding avoidance

[1] Leary, M. (2018). Design of titanium implants for additive manufacturing. Titanium in Medical and Dental Applications**:** 203-224.

Background: A problem with lattices as-printed

[2]



Any Downsides to (b)?

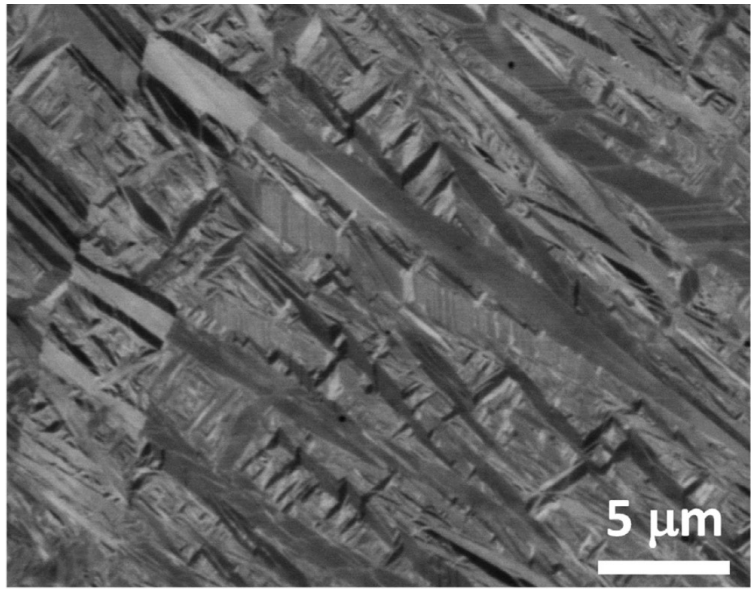
Decreased Specific Strength

[2] Yang, K., et al. (2019). "Additive manufacturing of Ti-6Al-4V lattice structures with high structural integrity under large compressive deformation." Journal of Materials Science & Technology **35**(2): 303-308.

Background: Developing a favorable microstructure in AM Ti

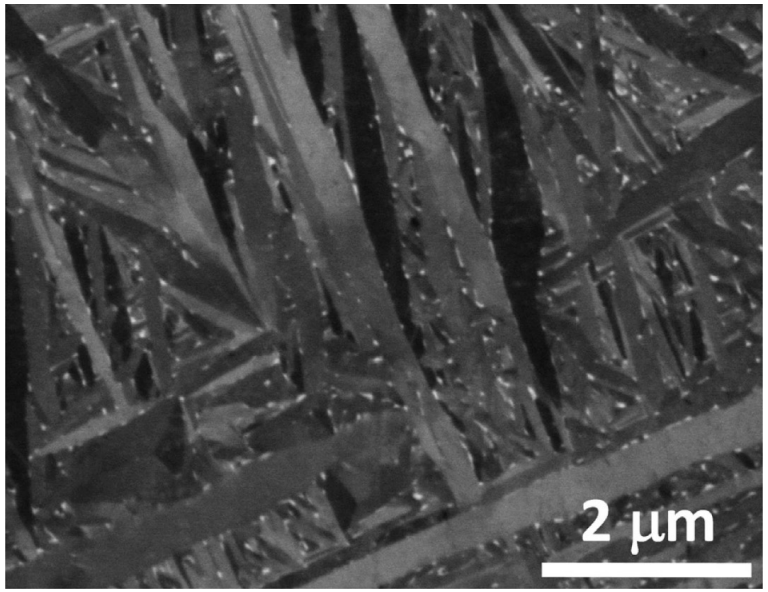
[3]

As-printed



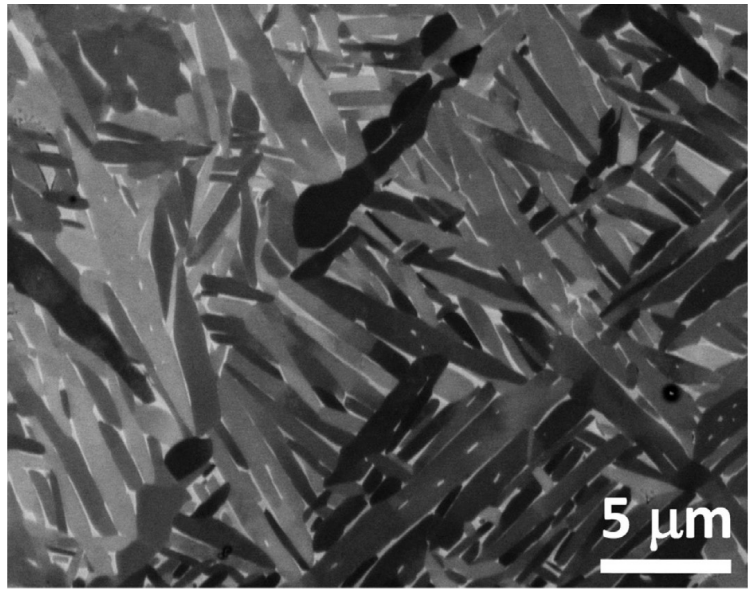
Acicular α'

120 min 540˚C



Nucleation of β

120 min 800˚C



Formation of $\alpha + \beta$ lemellae

Increasing Ductility / Decreasing Strength

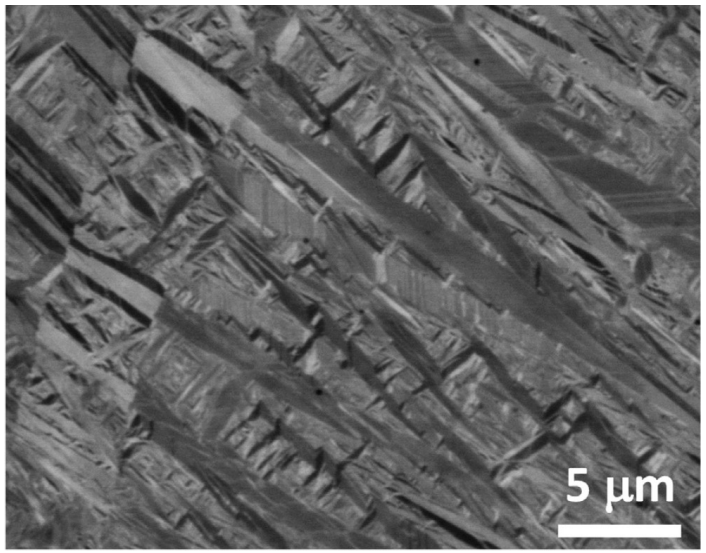
[3] Xu, W., et al. (2015). "Additive manufacturing of strong and ductile Ti–6Al–4V by selective laser melting via in situ martensite decomposition." Acta Materialia **85**: 74-84.

Combining the best of both microstructures

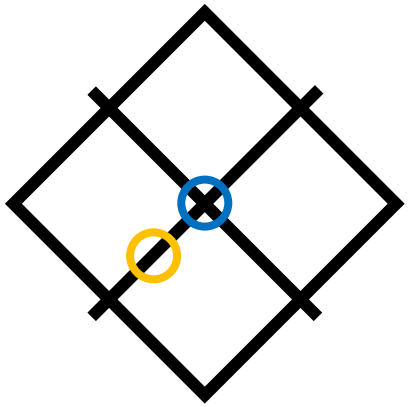
[3]

Microstructure	$\sigma_{0.2}$ (MPA)	% Elongation
Acicular α'	1125	6
Lamellar $\alpha + \beta$	830	13.1

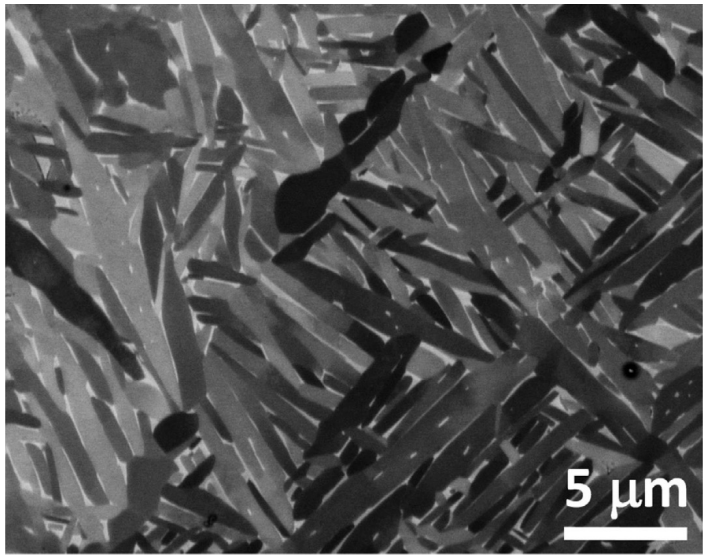
Acicular α'



Strut: Strength



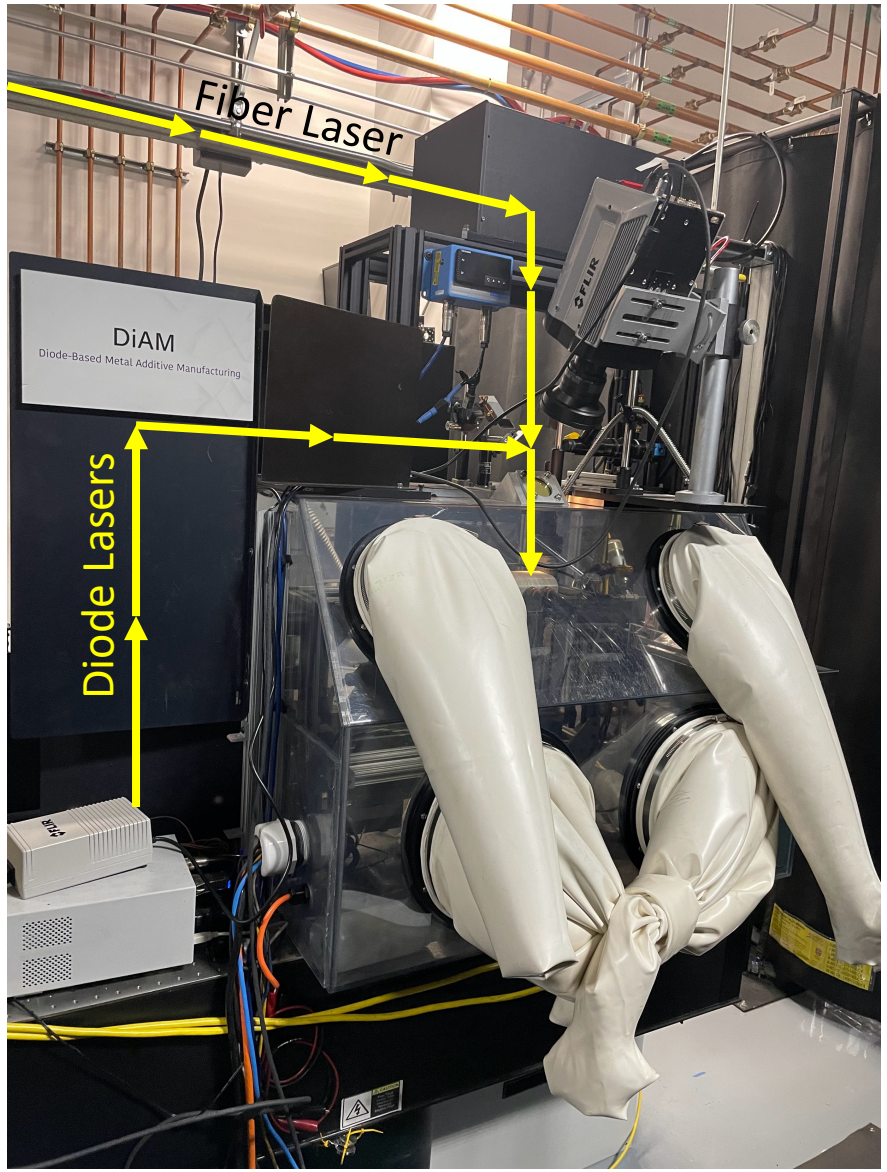
Lamellar $\alpha + \beta$

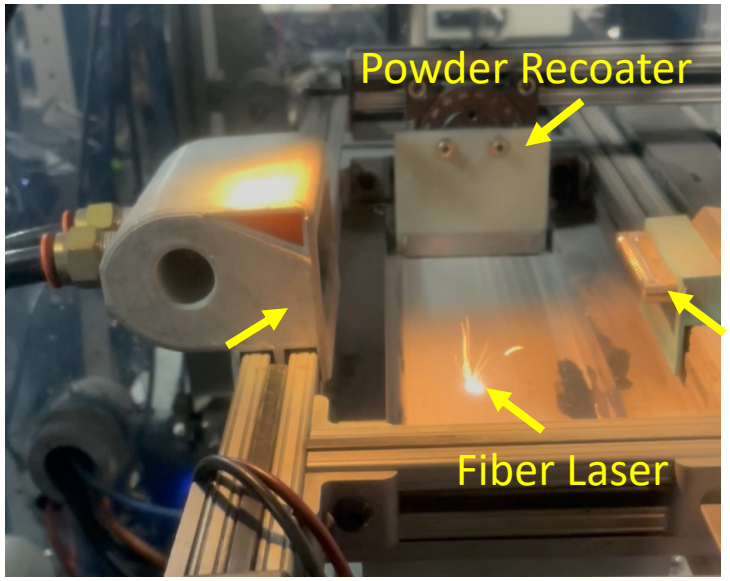


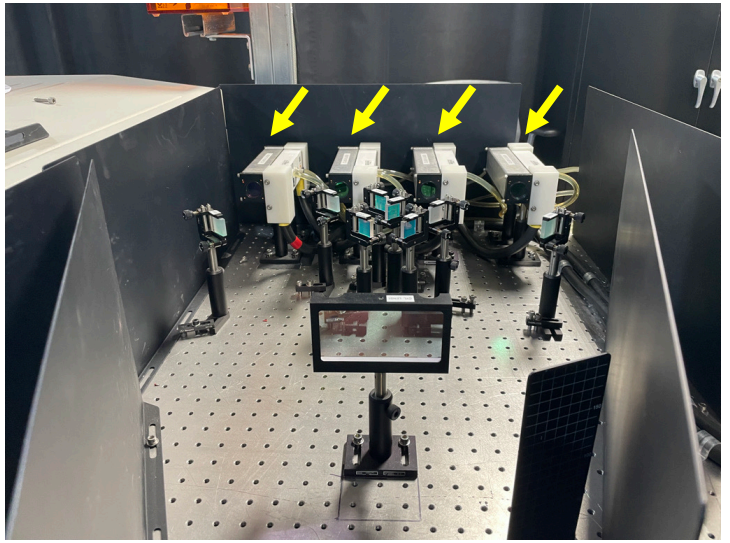
Node: Ductility

[3] Xu, W., et al. (2015). "Additive manufacturing of strong and ductile Ti–6Al–4V by selective laser melting via in situ martensite decomposition." Acta Materialia **85**: 74-84.

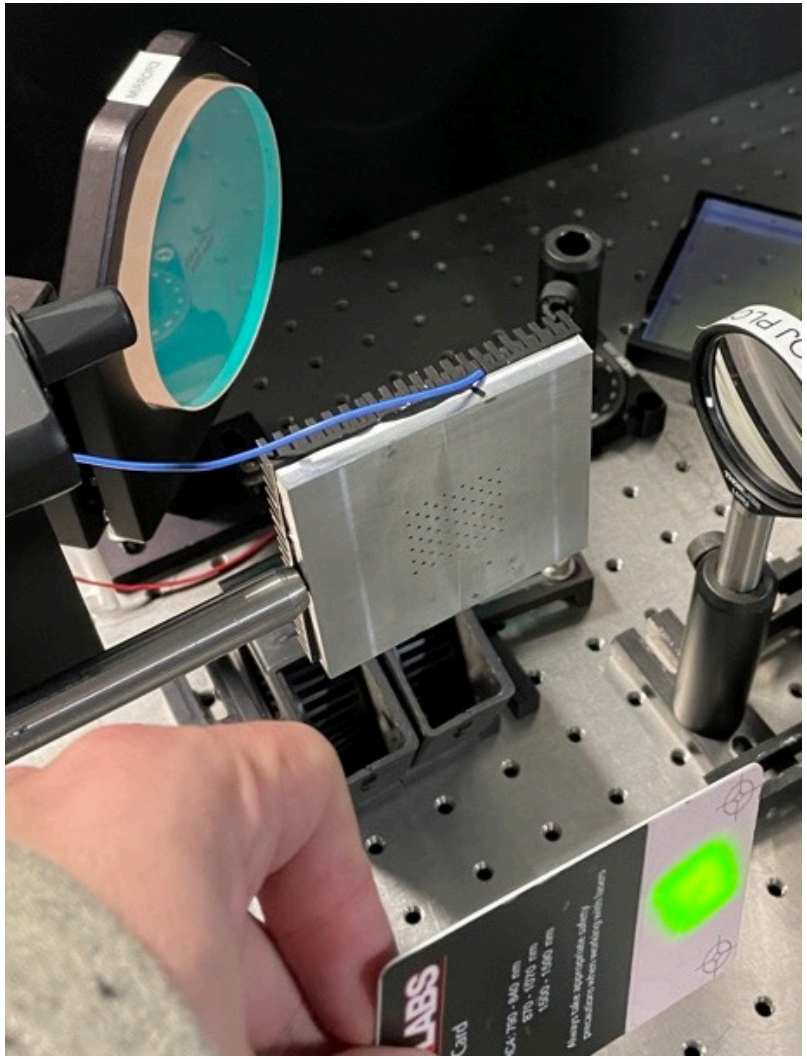
Intro to the DiAM system (**Di**ode-Based Metal **A**dditive **M**anufacturing)

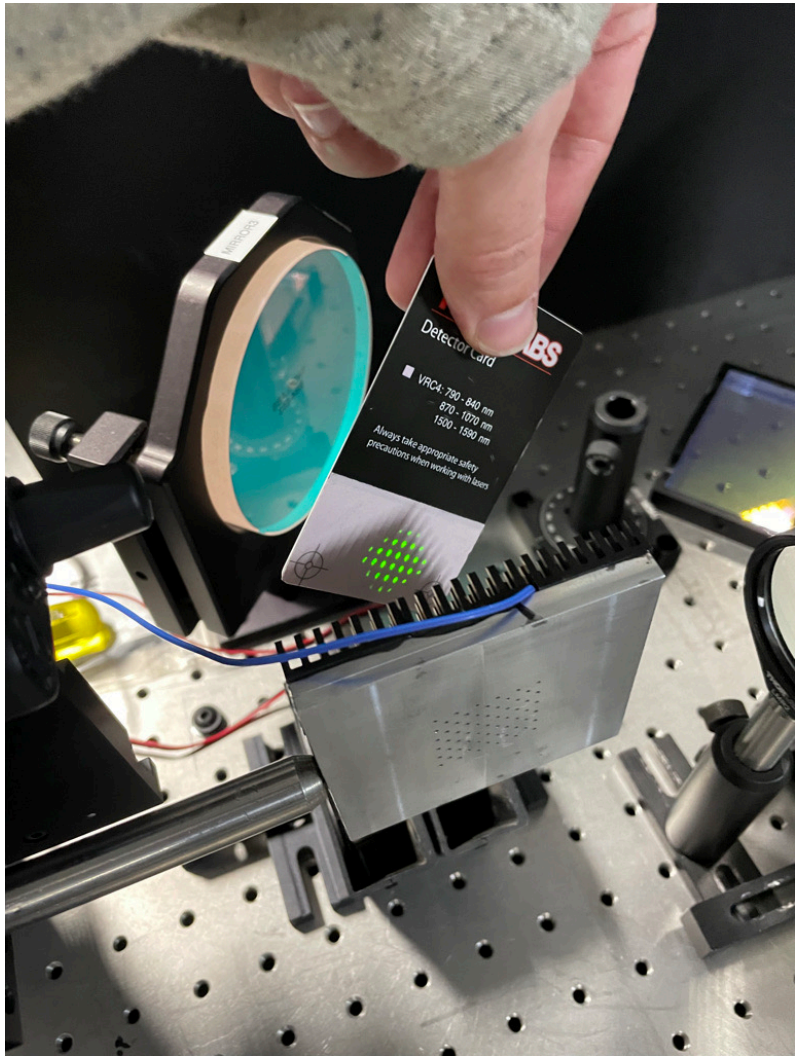


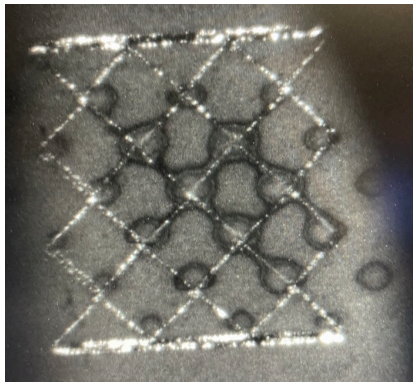




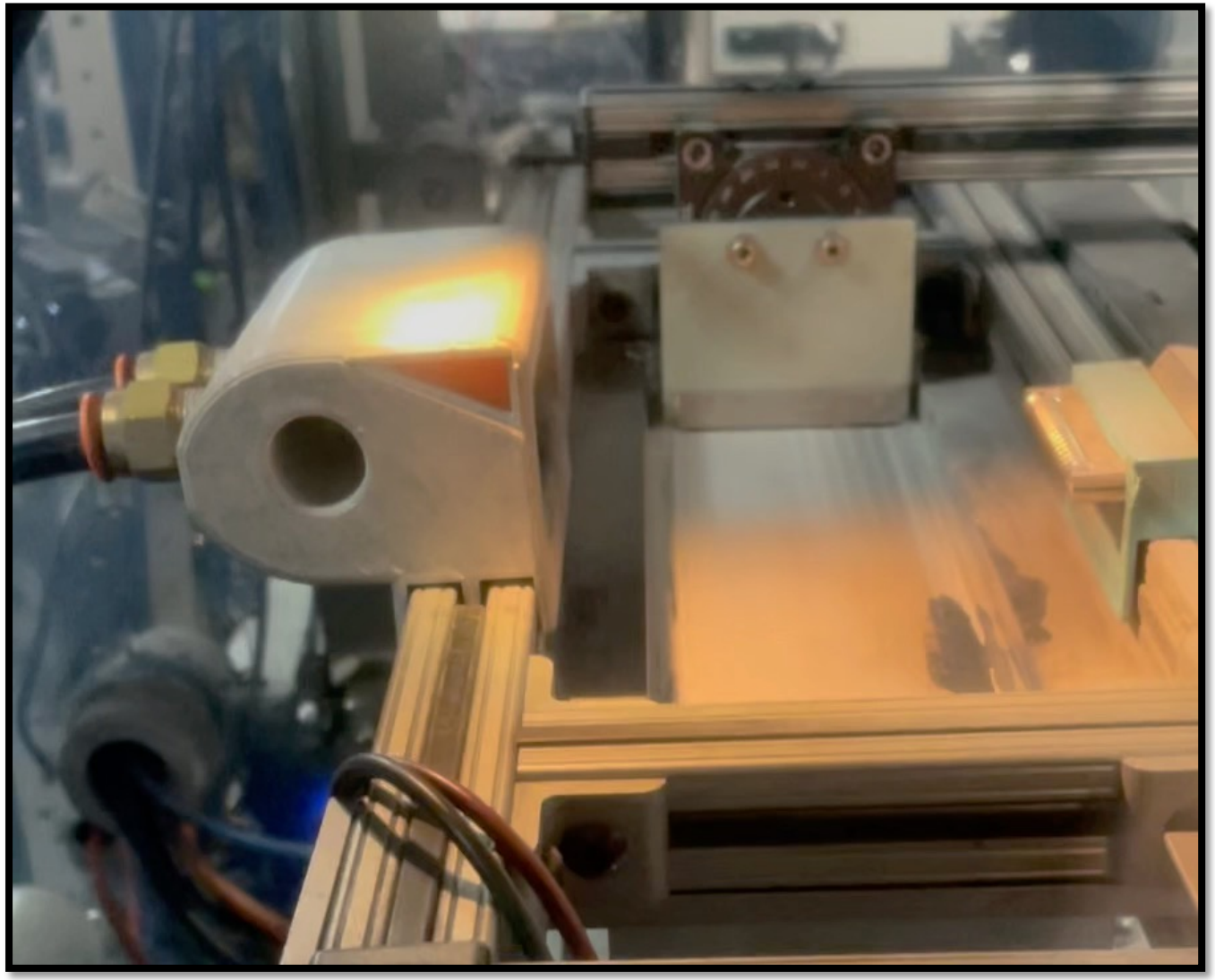
Masking the diode lasers to hit only the lattice nodes

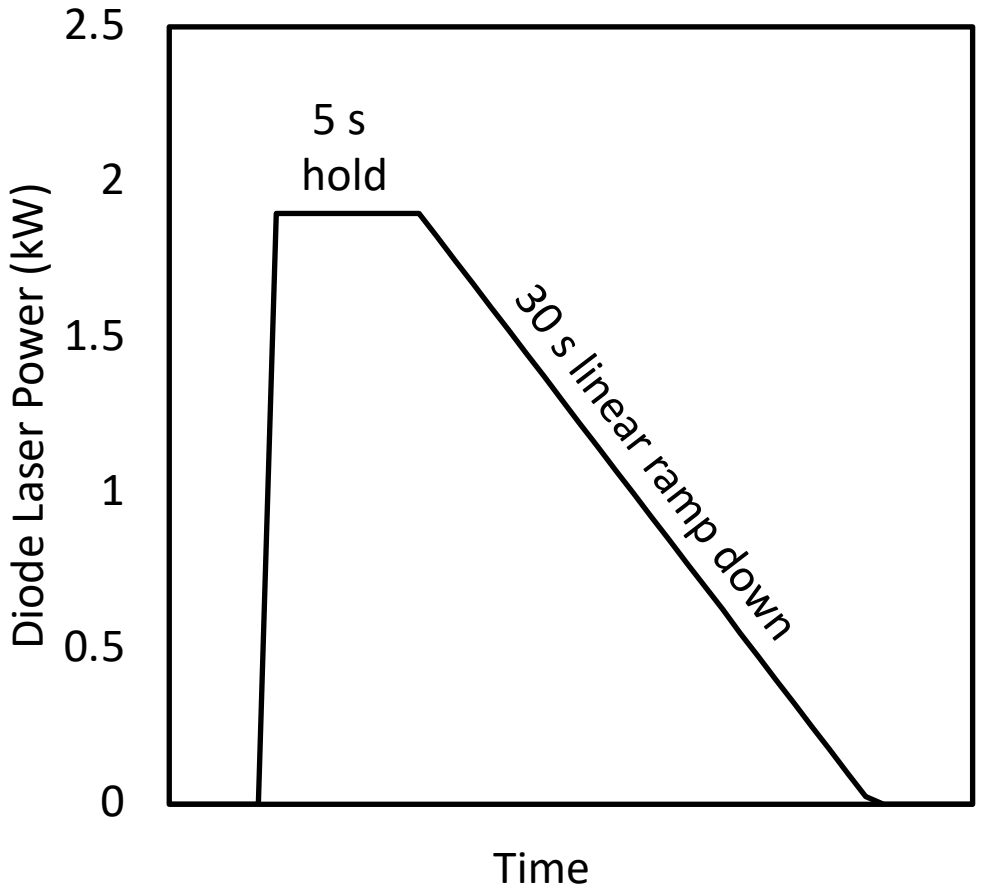




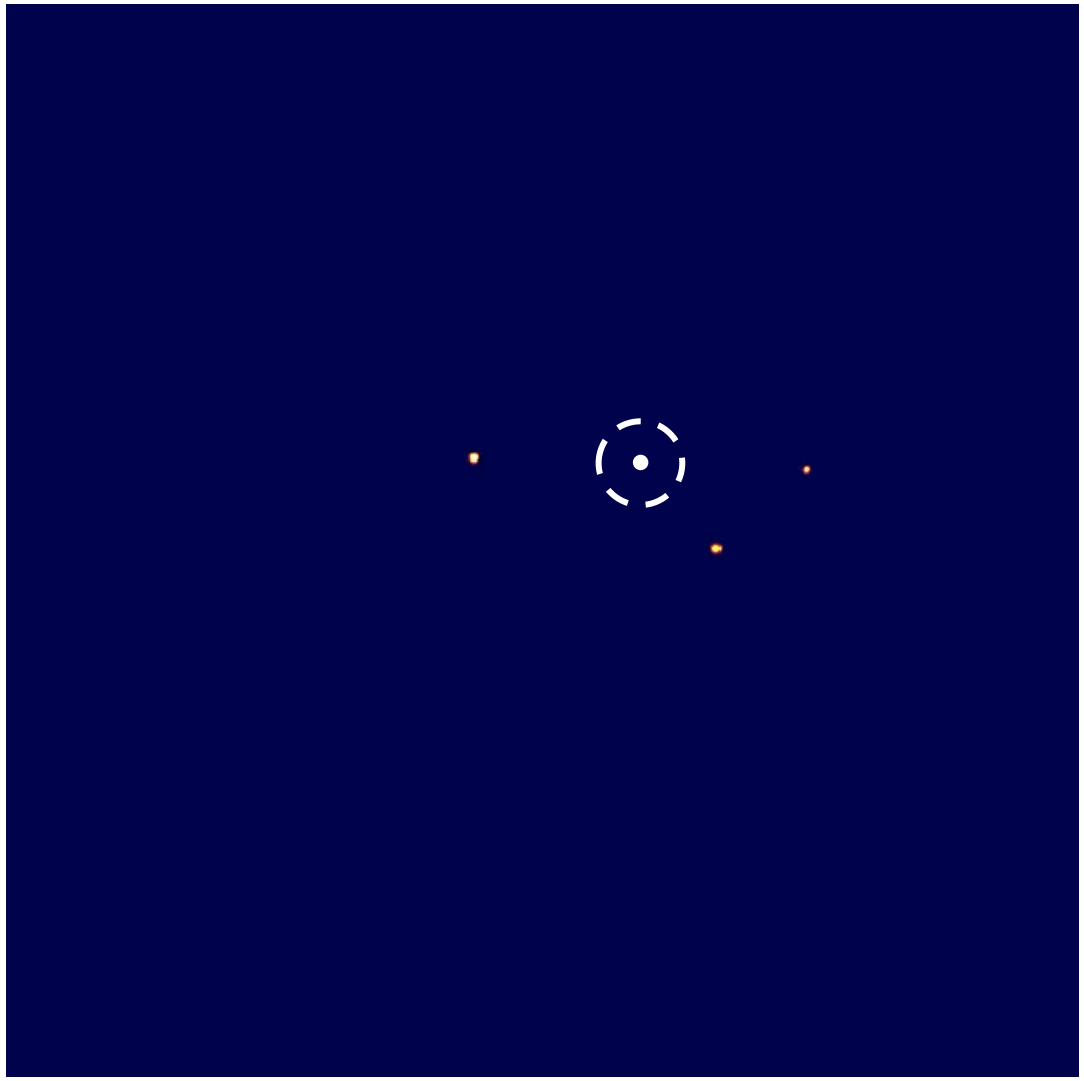


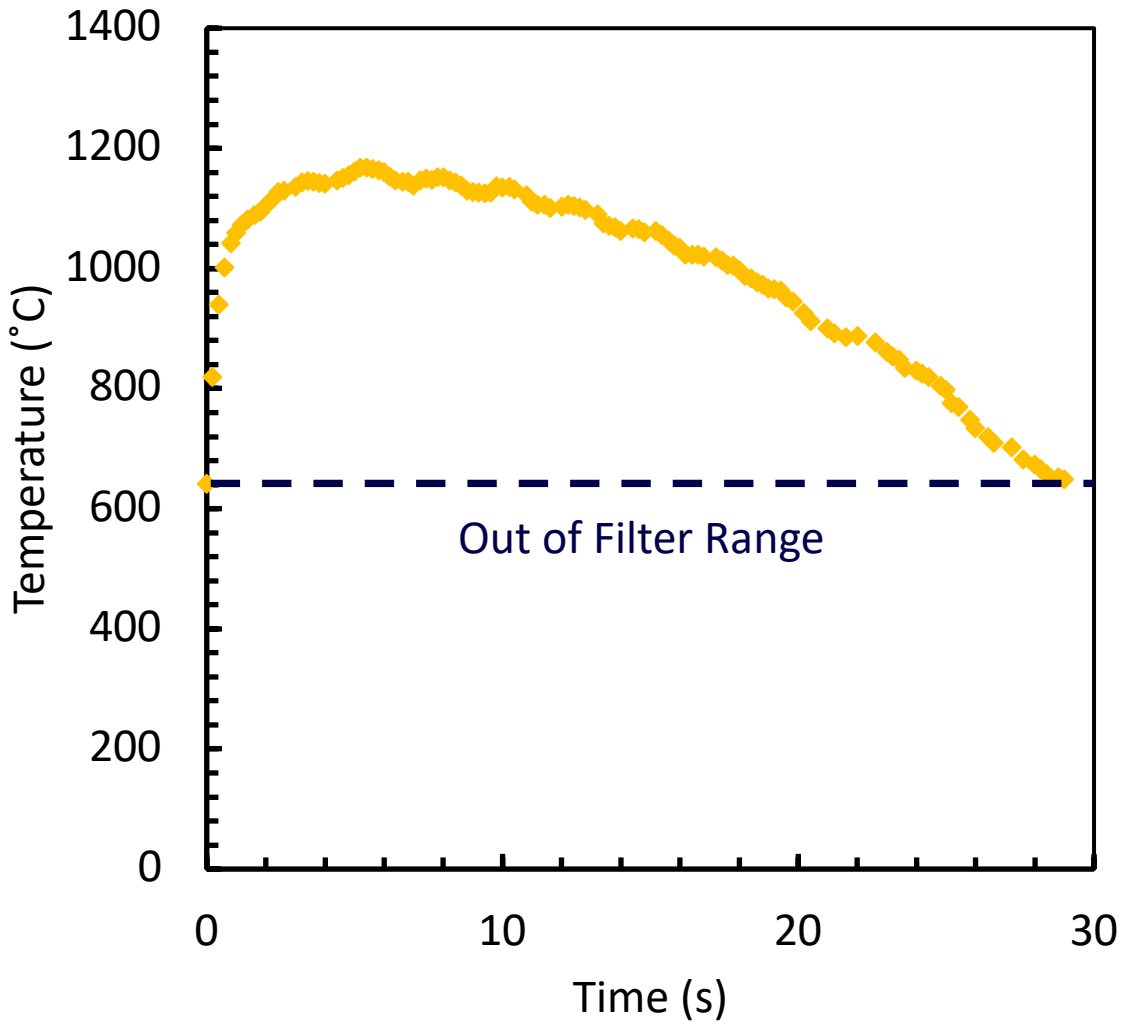
Example of a build layer and node anneal





Node temperatures during laser hit



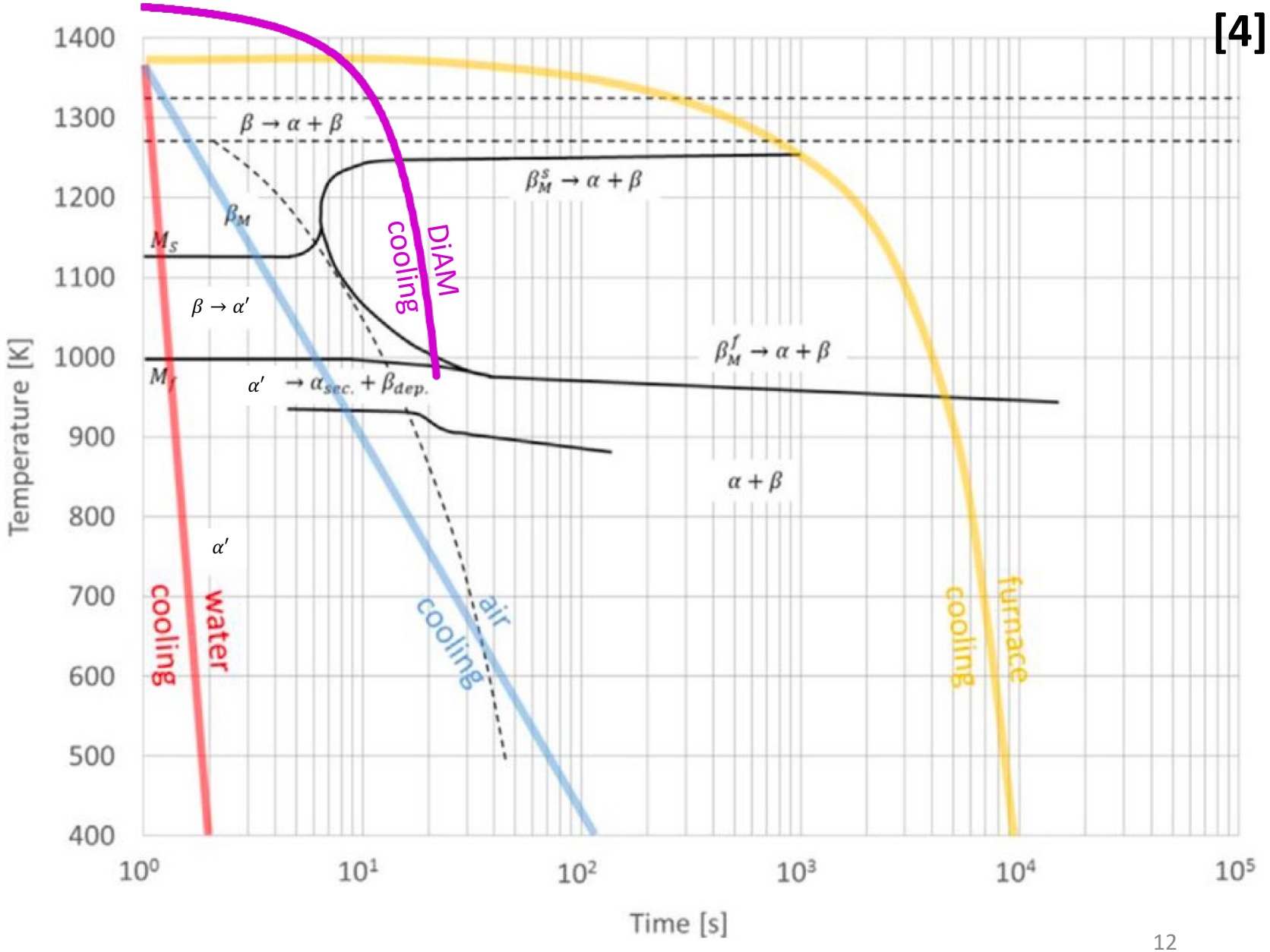


Based on temperature profile what phases should we expect?

CCT Diagram
Continuous
Cooling
Transformation

Formation of
$\alpha + \beta$

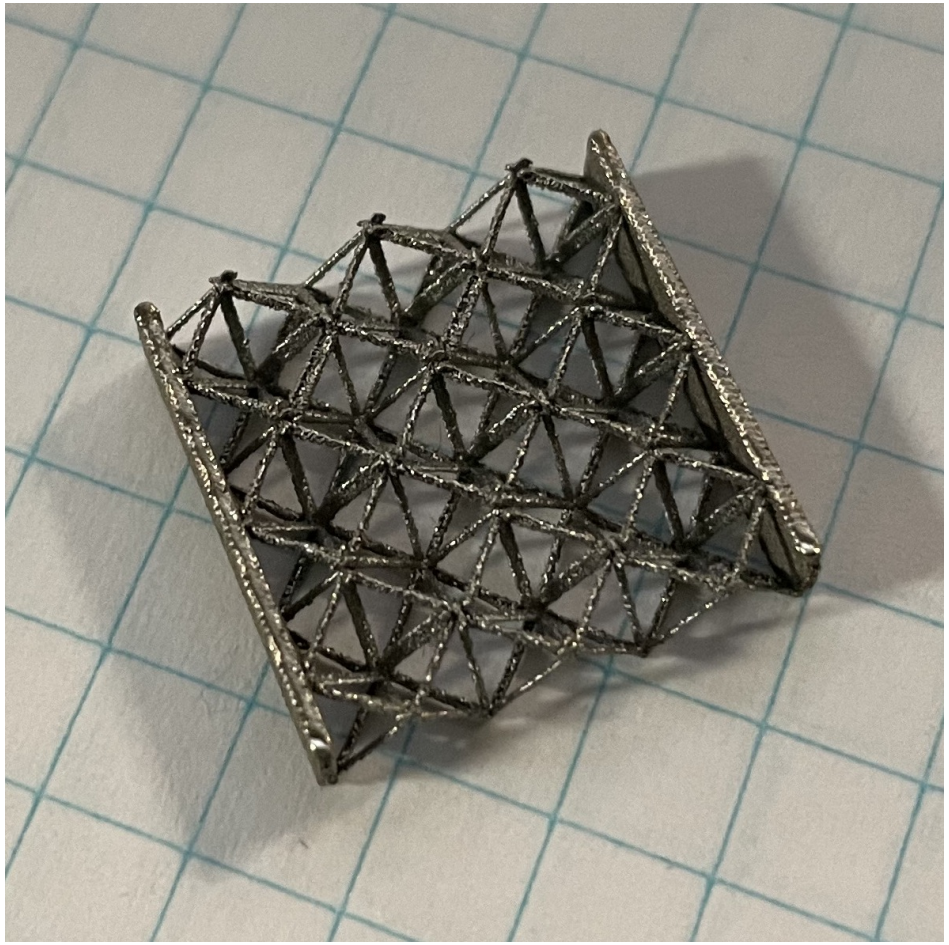
[4]

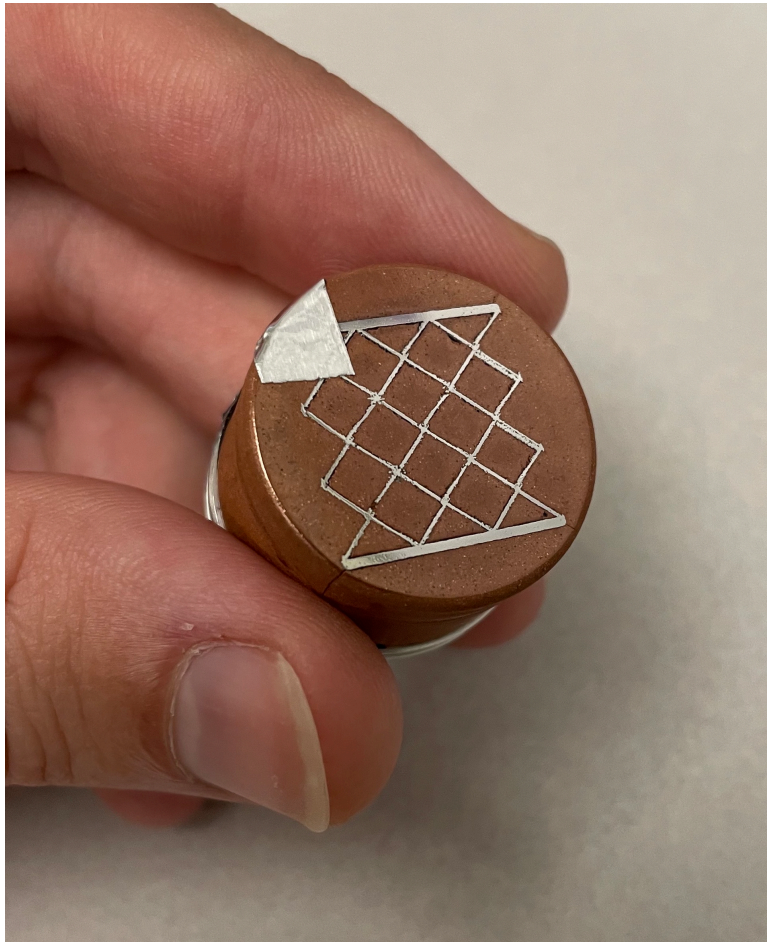


[4] Galarraga, H., et al. (2017). "Effects of heat treatments on microstructure and properties of Ti-6Al-4V ELI alloy fabricated by electron beam melting (EBM)." Materials Science and Engineering: A **685**: 417-428.

Printed test lattices

One set of annealed nodes

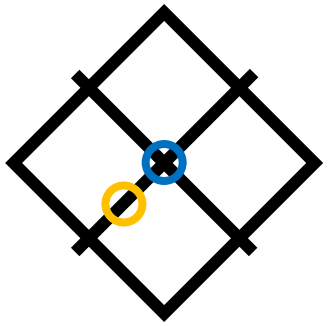




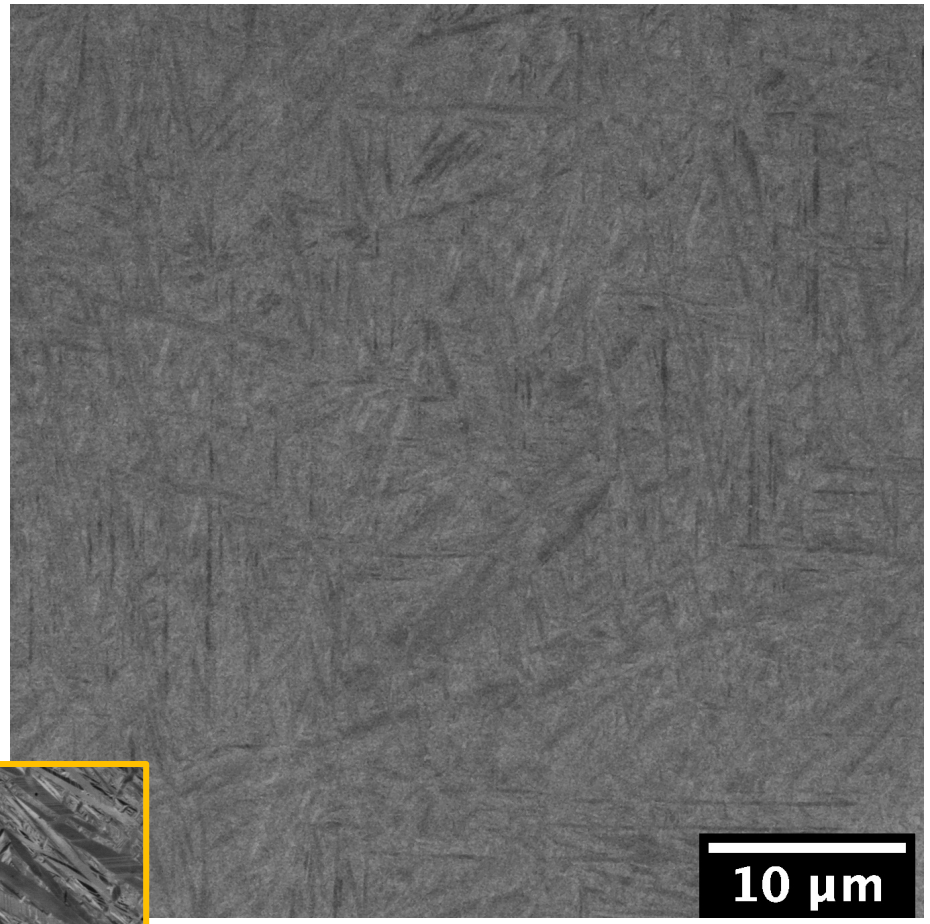
Polished for imaging

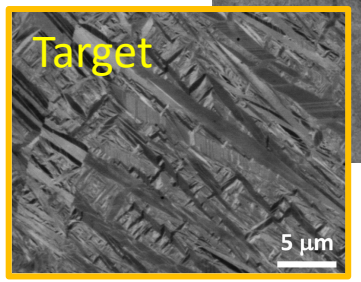
Microstructure of the struts vs nodes in a DiAM annealed lattice

Backscatter

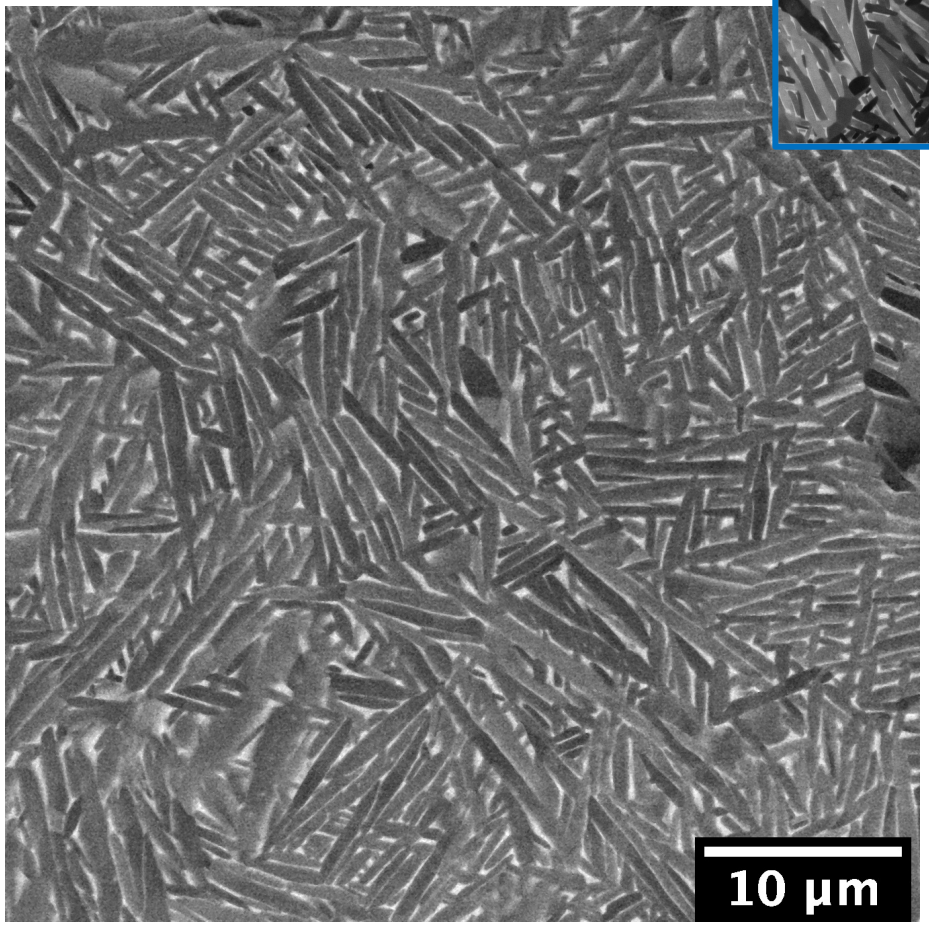


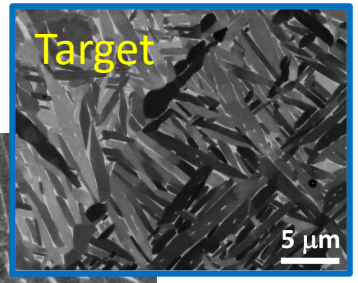
Strut





Node

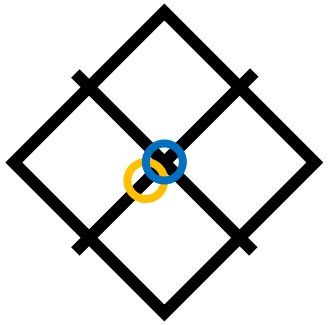




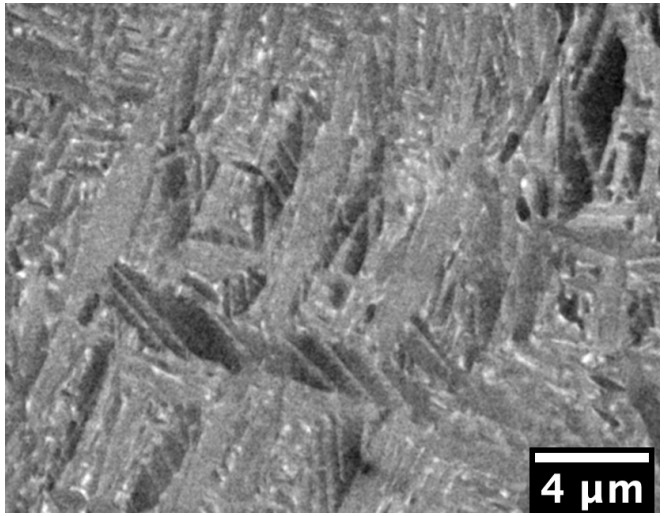
Lighter areas indicate high Z elements (V a β stabalizer)
Darker areas indicate low Z elements (Al an α stabalizer)

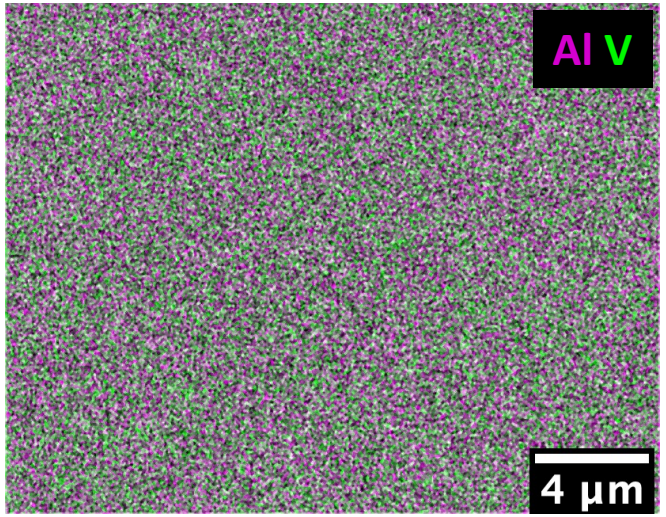
Nodes show chemical partitioning

EDS
Energy
Dispersive
Spectroscopy

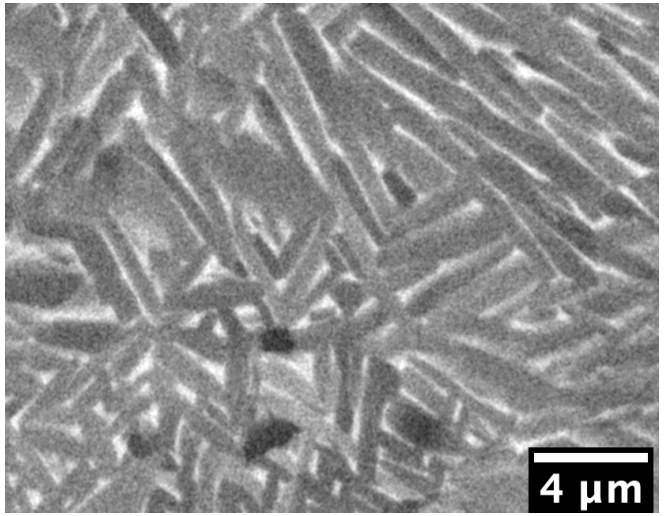


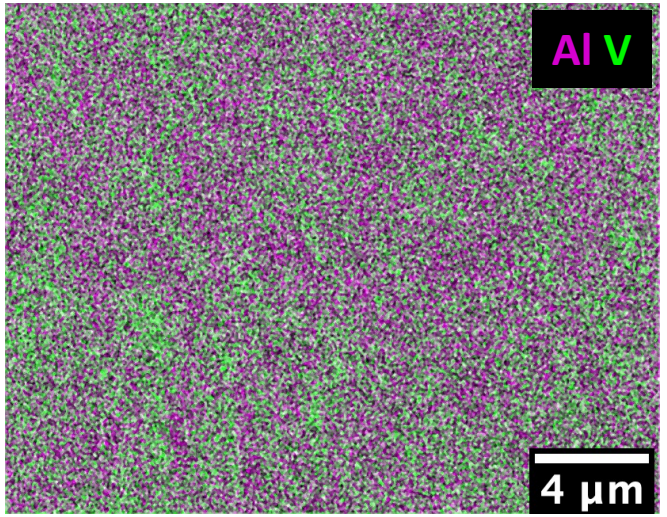
Strut (near node)





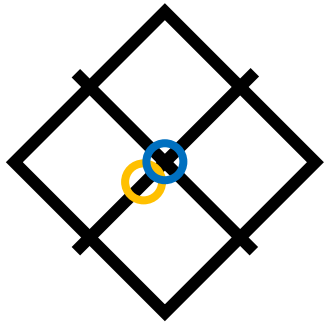
Node





Nodes show significant β formation

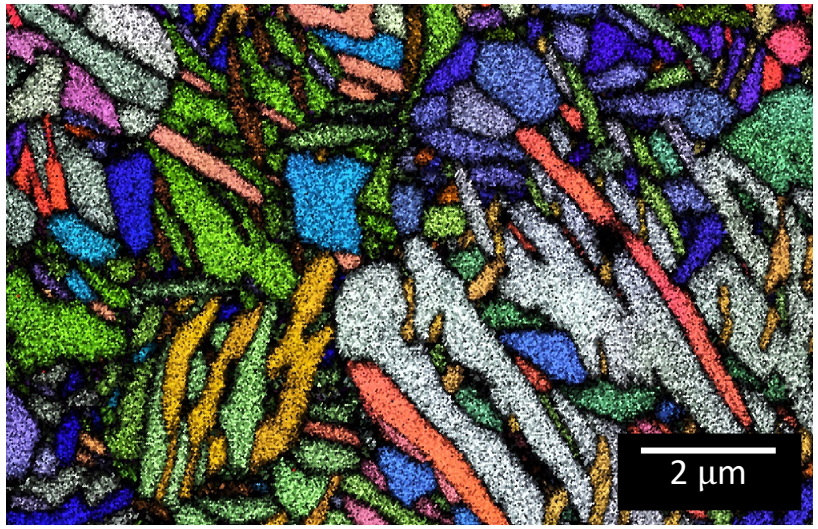
EBSD
Electron
Back**S**catter
Diffraction

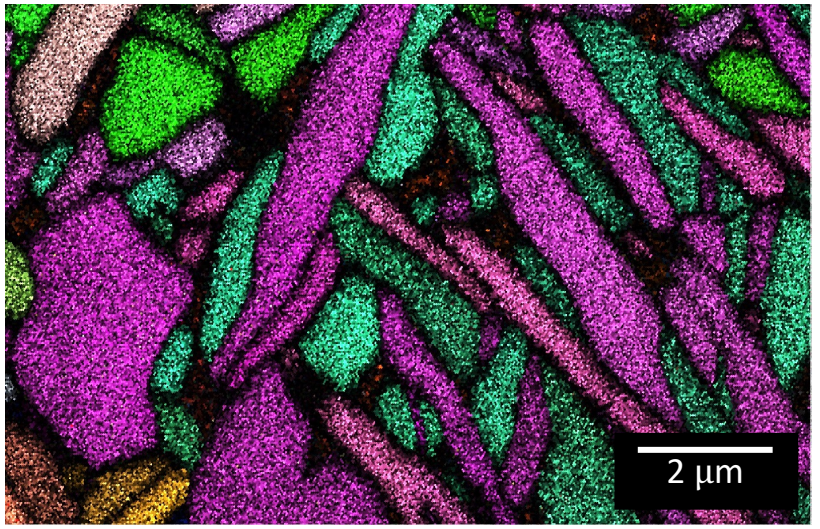


Strut (near node)

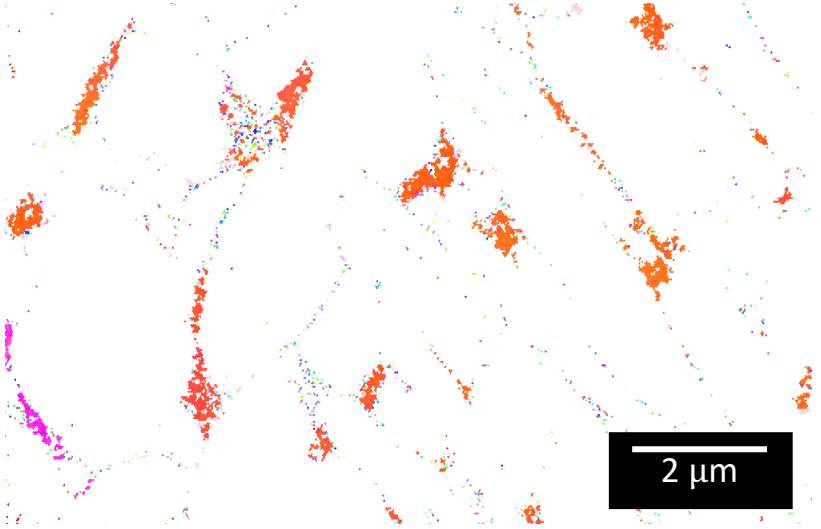
Node

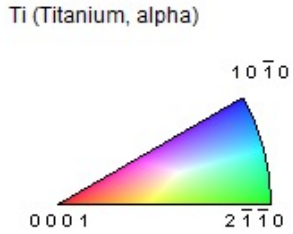
IPF/CI $\alpha + \beta$

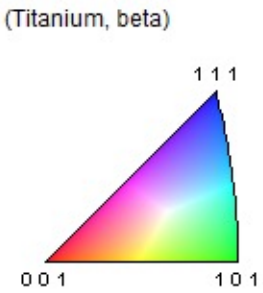




IPF β Only



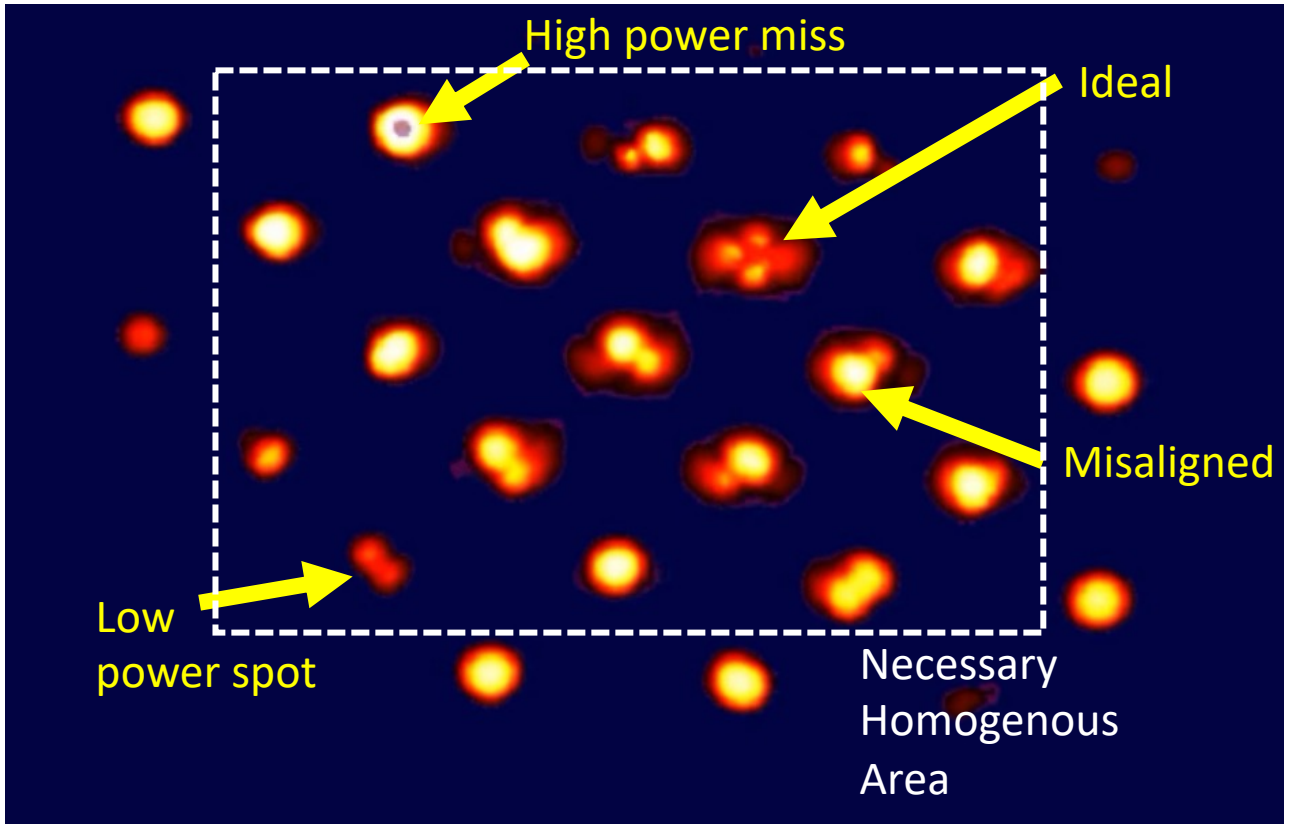




Problems of laser inhomogeneity

Uniform Node Heating

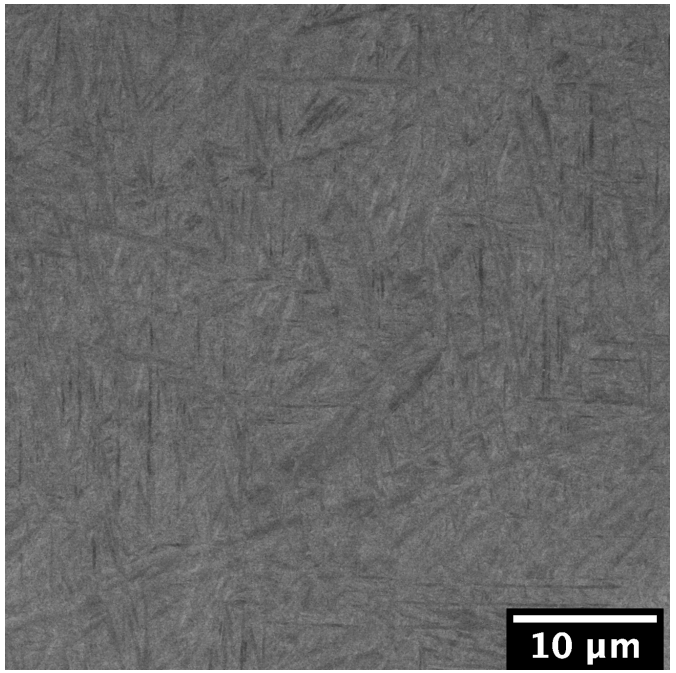
- Mask/node alignment
- Diode lasers have “hot spots”
- Homogenizer set up is not ideal



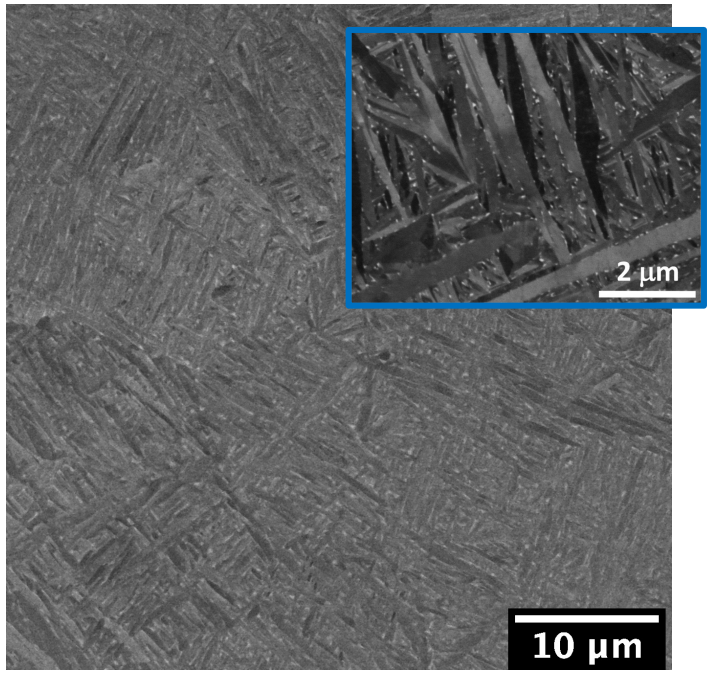
Microstructural control

- Some struts show transformation
- Transformation gradient across nodes (powder heating)

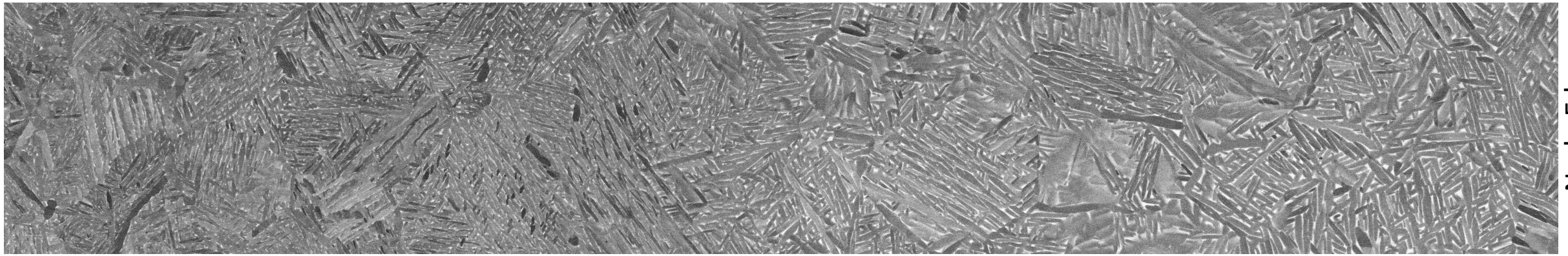
"ideal" strut



"heat affected" strut



Node transformation gradient



Coarser w/ more β

20 µm

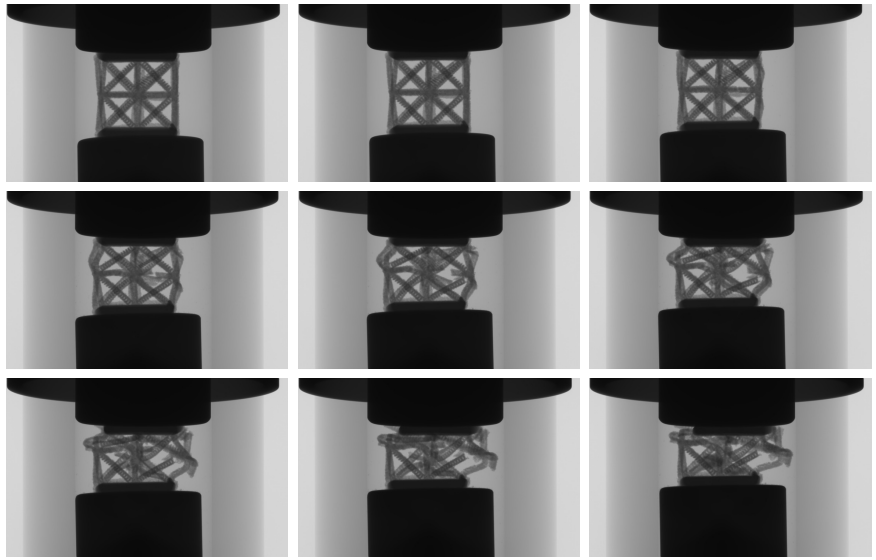
Where is the project headed?

Near term:

- Print test cylinders with different laser anneal parameters to validate against the CCT diagram

Long term:

- Fix beam homogenization (new homogenizer or new laser)
- Reinstall the DiAM light valve/image filter
- Print and crush full lattices with a variety of anneal parameters



in-situ μCT compression

Questions?