Time-dependent properties of mechanical metamaterials for orthopaedic implants

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UK Metamaterials Network Health Challenge Sandpit

University of Wolverhampton, 18th September 2024

Acknowledgements

Imperial College London

Prof. Jonathan Jeffers

Stelios Kechagias

Dr Shaaz Ghouse

Aisha Mehmood

Funding: NIHR, EPSRC

Department of Engineering Science

University of Oxford

Alexandra Sevcenco

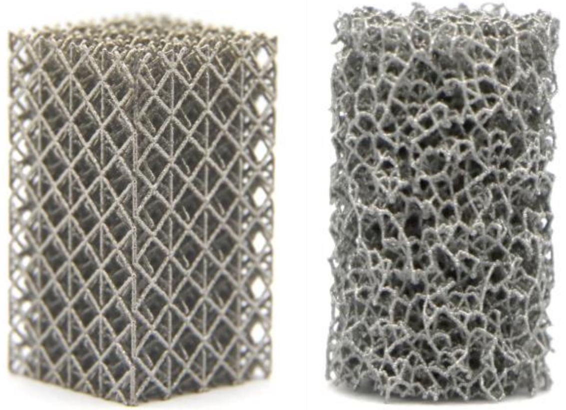
Dr Peter Walters

Prof. Clive Siviour

Background – medical implant materials

Architected implant materials

Porous metal lattice materials (Ti)



Match bone modulus:

E_{bone}: ~1-10 GPa

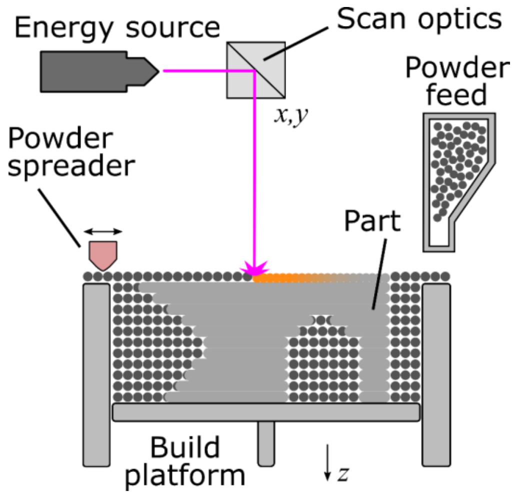
E_{Ti}: ~100 GPa

Minimise stress shielding

Additive manufacturing

Metal powder bed fusion

CP-Ti, Ti-6Al-4V



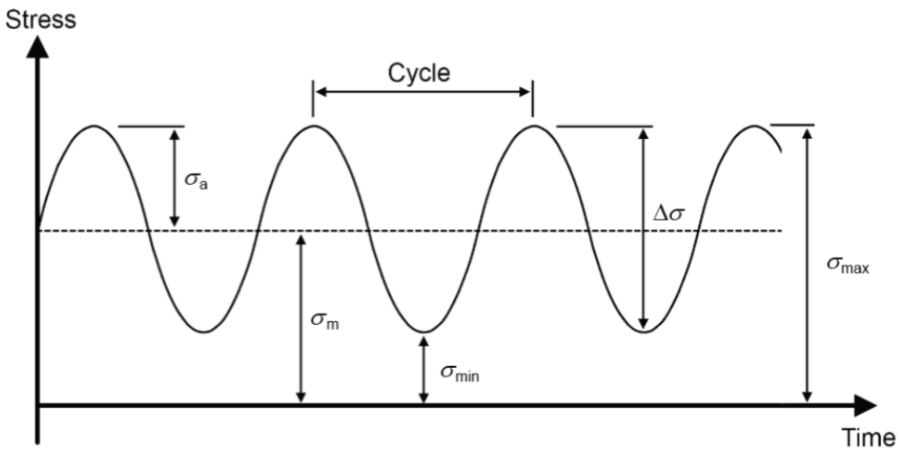
PBF: Suitable resolution for lattice structures

Oosterbeek et al., *Addit. Manuf.* 78 (2023): 103896.; Sundfeldt et al., *Acta Orthop.* 77.2 (2006): 177-197.

Key challenges

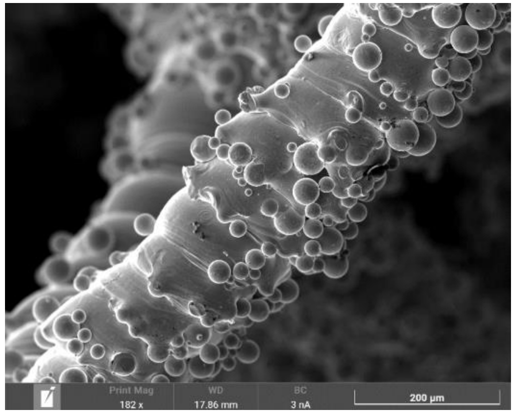
Fatigue resistance

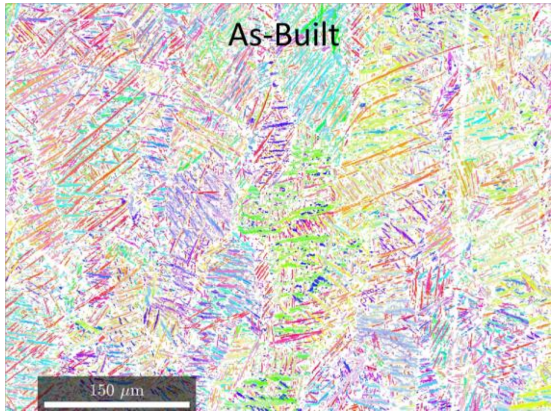
- Cyclic loading – crack initiation and propagation
- **Implants:** Physiological loading cycles



Major weakness of AM components

- Rough surface with many flaws
- Brittle, stressed microstructure





Ghouse, **Oosterbeek** et al., (2021) *Addit. Manuf.*, 47, p. 102262; comsol.com; think3d.in/an-overview-of-3d-printed-metal-implants/

Fatigue resistance - metallurgy

Heat treatments

- HIP (Hot isostatic pressing)
- **Vacuum heat treatment →**

As-built

$\sigma_{f,10^6}$ = 4.9 MPa

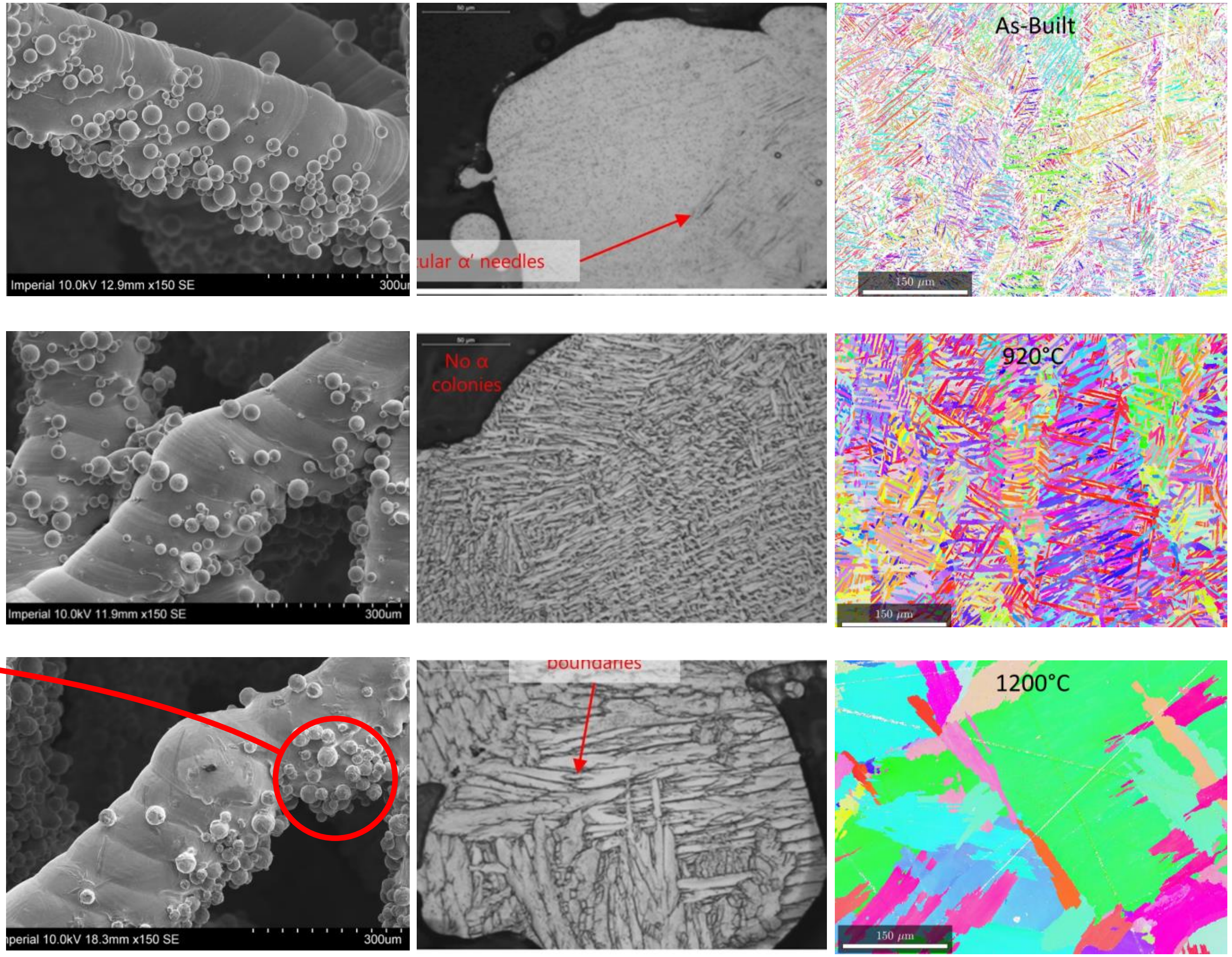
920°C

$\sigma_{f,10^6}$ = 7.7 MPa

1200°C

$\sigma_{f,10^6}$ = 8.5 Mpa

(73% increase)



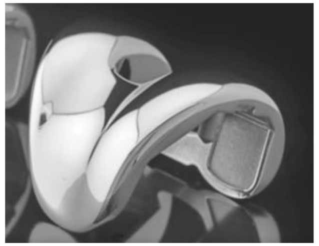
Semi-fused particles remain

- Reduced wettability
- Increased risk of metal debris

Ghouse, **Oosterbeek** et al., (2021) *Addit. Manuf.*, 47, p. 102262

Fatigue resistance – surface finish

Stream/drag finishing
(mechanical abrasive media)



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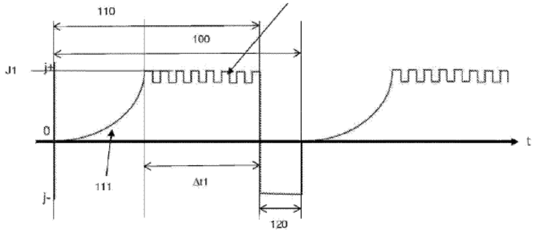
Chemical etching

- HF, HNO_3
- Problems with over/under etching, infiltration

Chemical-electrochemical polishing

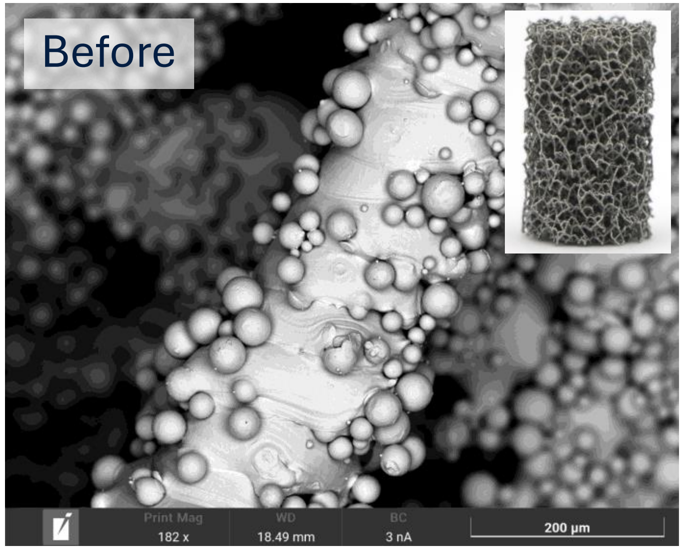
- Hirtisation®
- Acid + electrolyte, pulsed current + superimposed micropulses

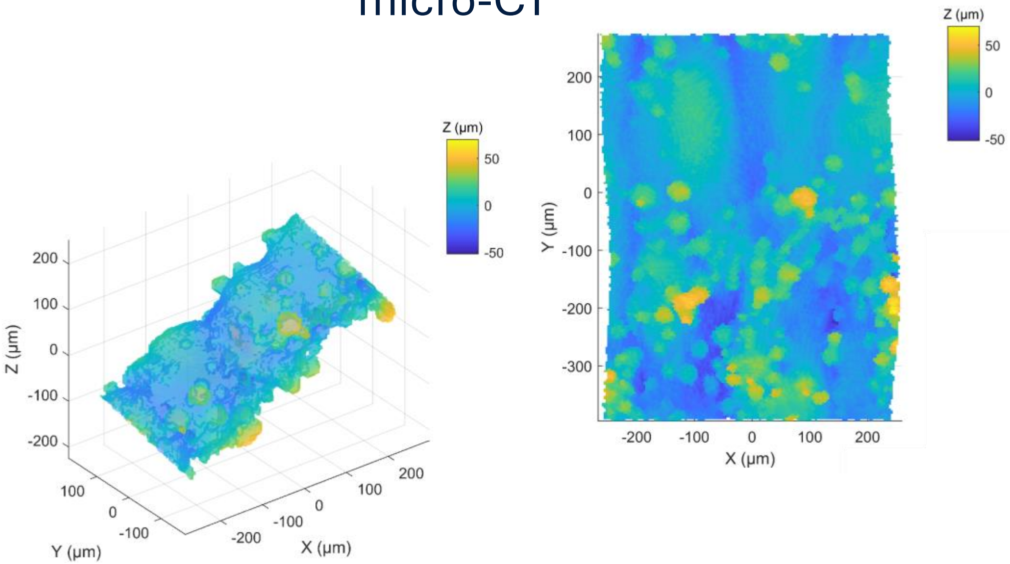


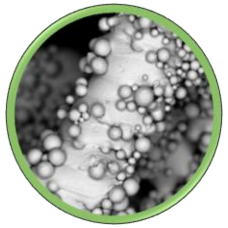
Strut surface treatment

SEM

micro-CT



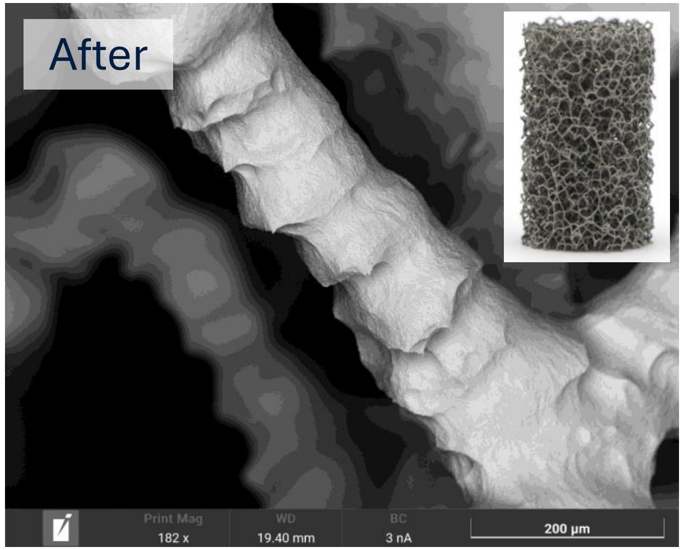


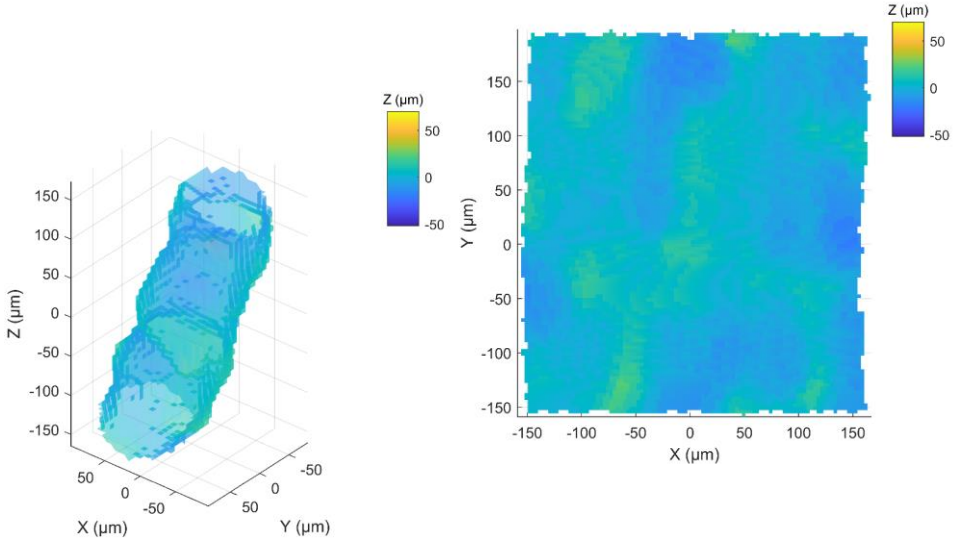


Sa = 12 µm

D_{eq} = 230 µm

- Semi-fused particles





Sa = 6 µm

D_{eq} = 130 µm

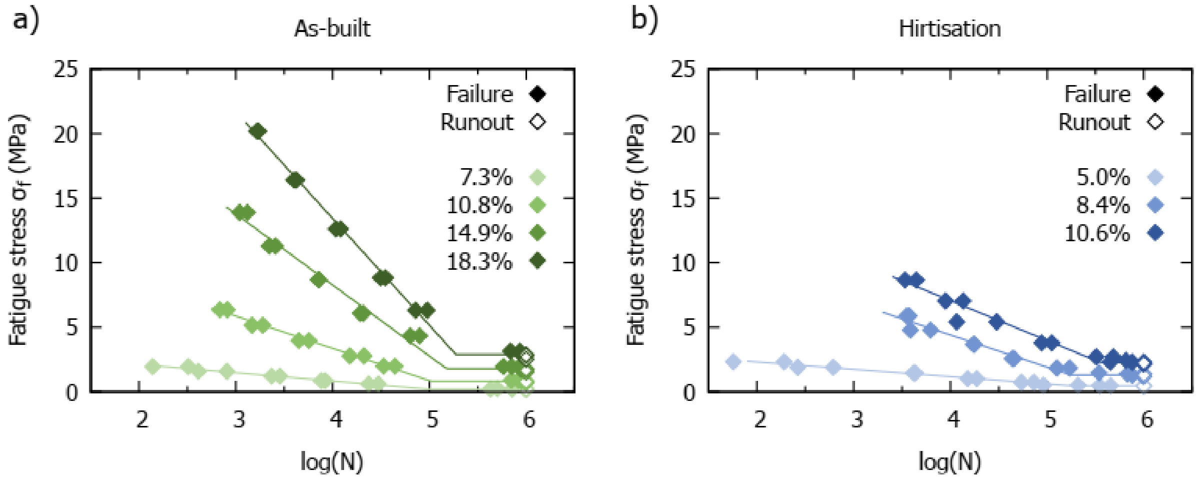
- Semi-fused particles removed

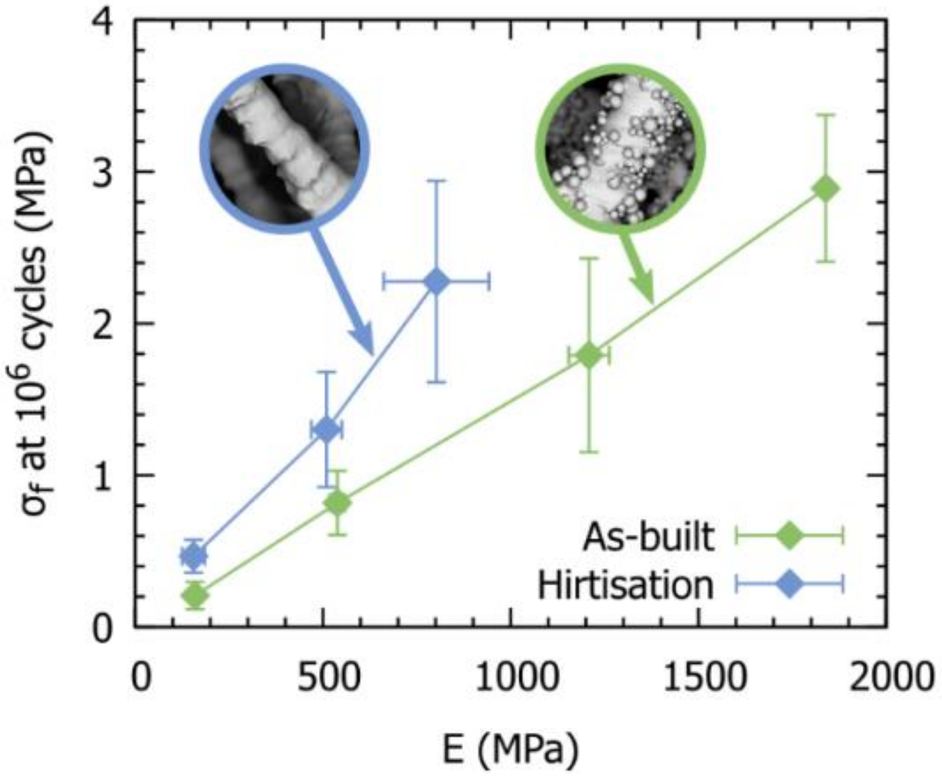
Oosterbeek et al., *Addit. Manuf.* 78 (2023): 103896.; **Oosterbeek** et al., *SoftwareX* 18 (2022): 101043.

Design and fatigue

Fatigue strength σ_f at 10^6 cycles:

– Reduced in absolute terms (material loss)





– ~90% increase in fatigue strength/modulus ratio (σ_f/E)

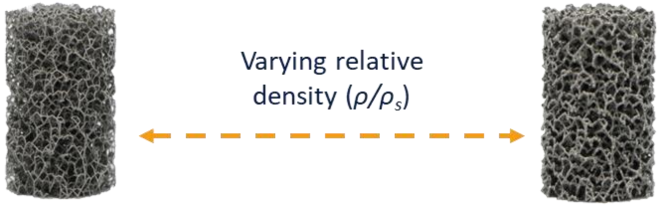
– Implant designed to match bone stiffness will have 90% higher σ_f

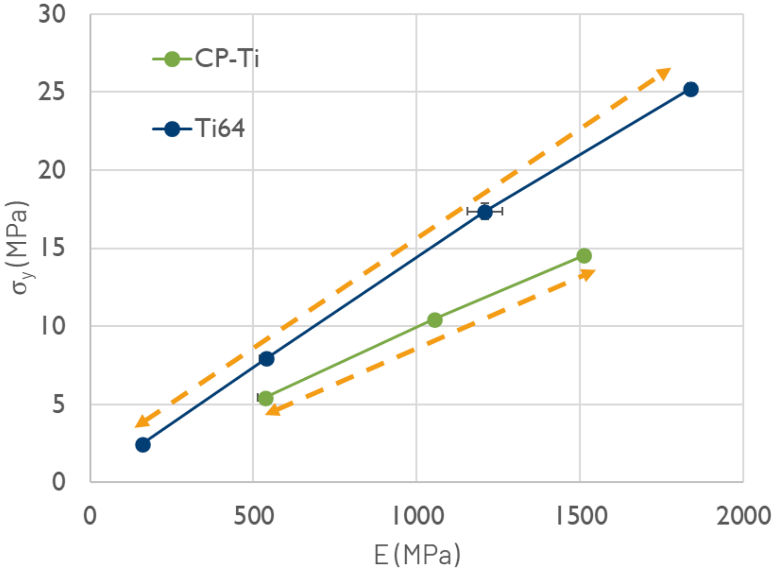
Longer lasting implants

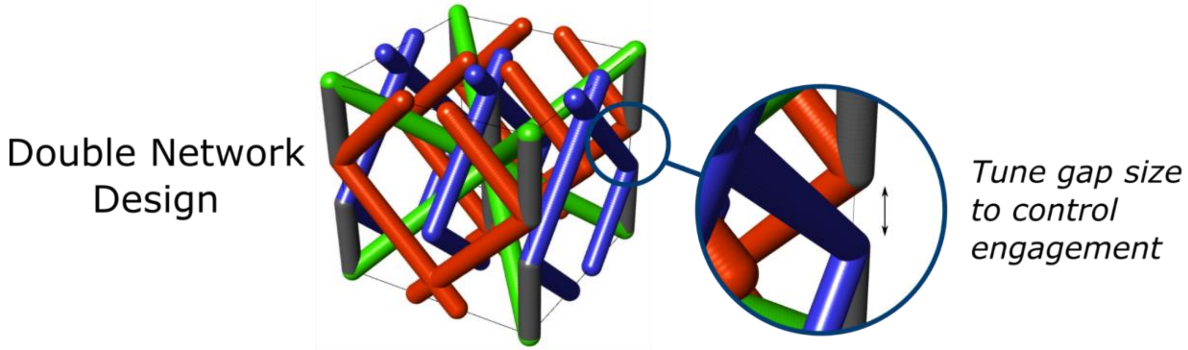
Oosterbeek et al., *Addit. Manuf.* 78 (2023): 103896.

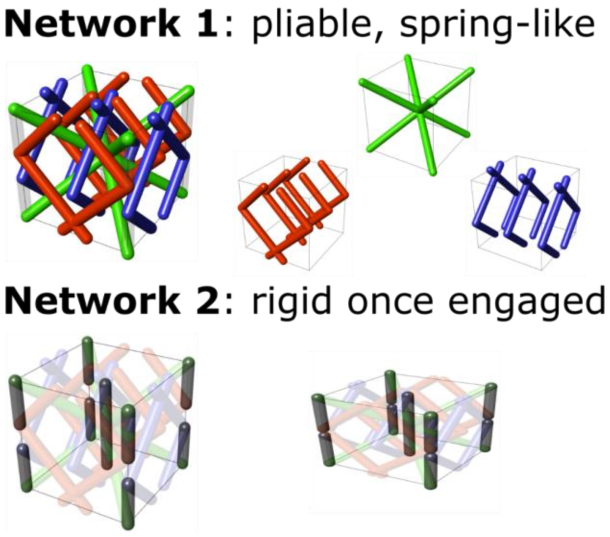
Decoupling strength and stiffness

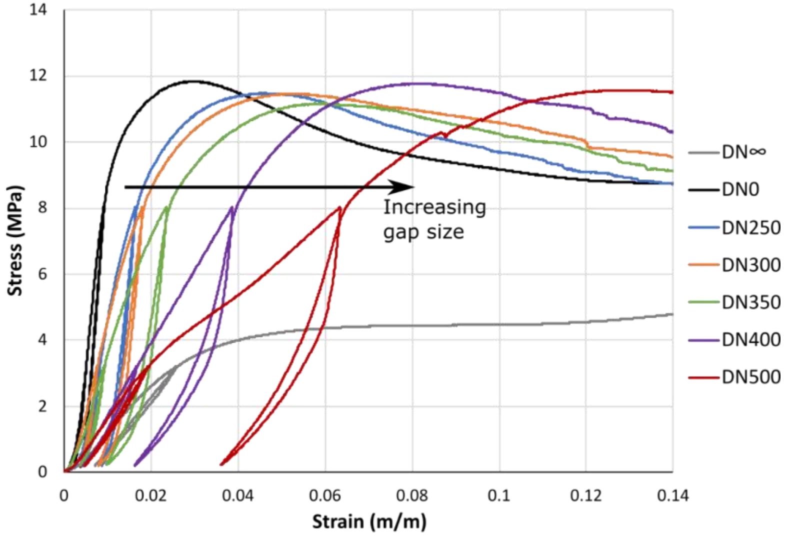
- Matching bone modulus (trabecular: 100 – 2000 MPa) can make achieving high strength difficult
  - Bone strength ~50 MPa



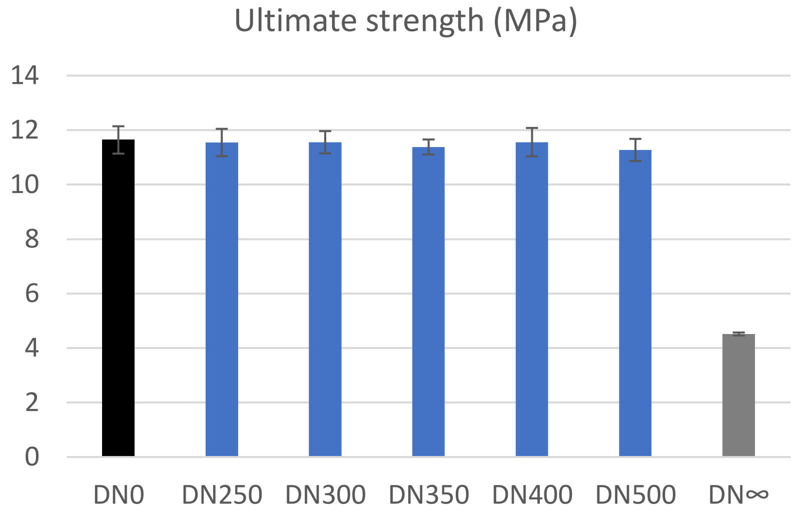


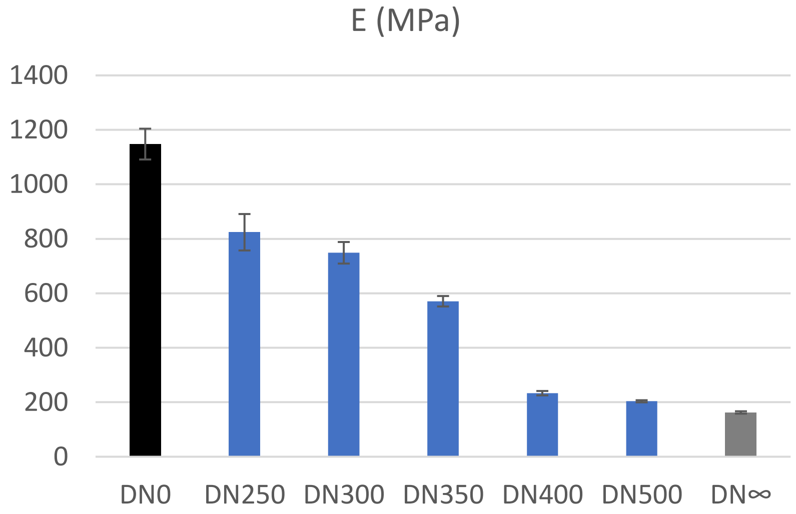


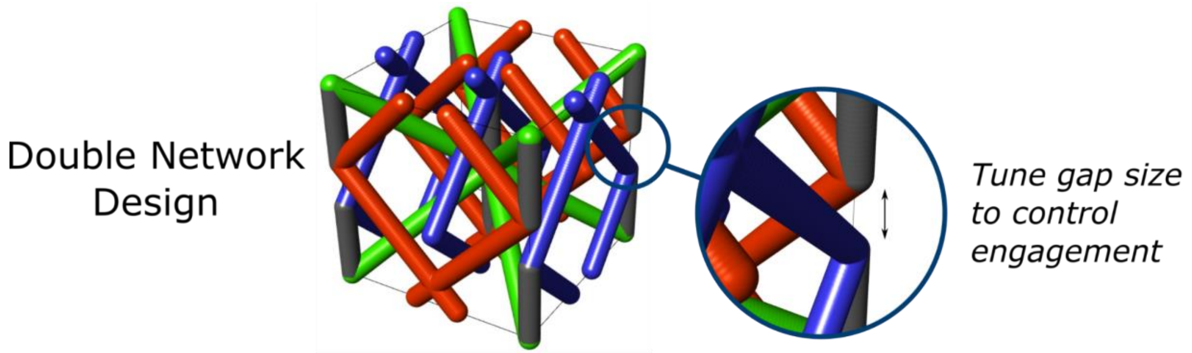


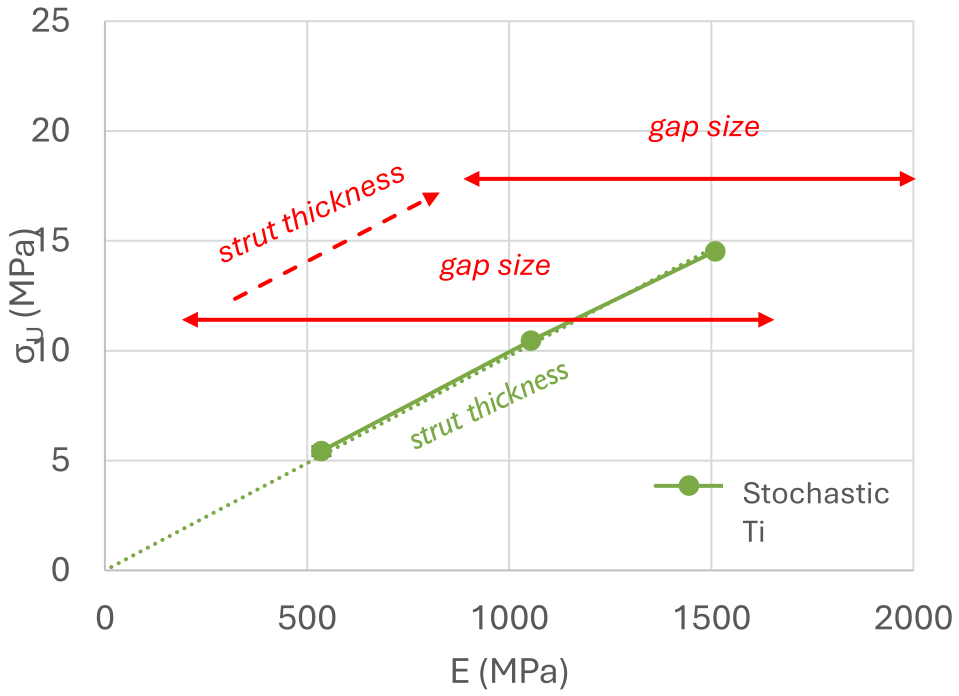


Decoupling strength and stiffness





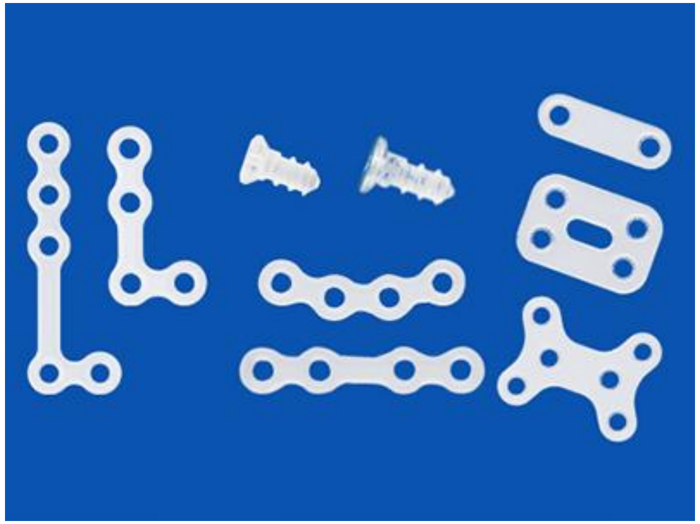


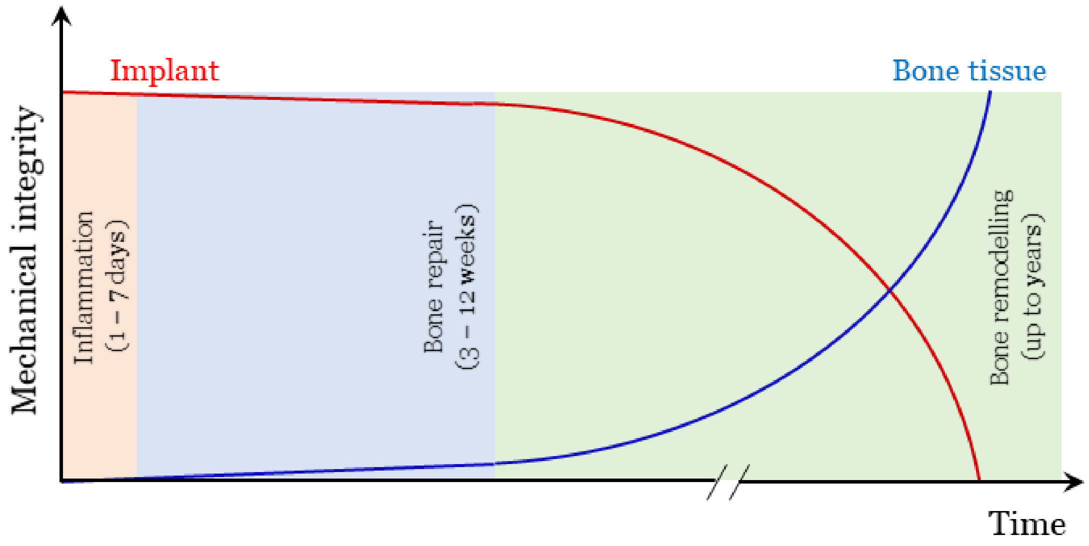


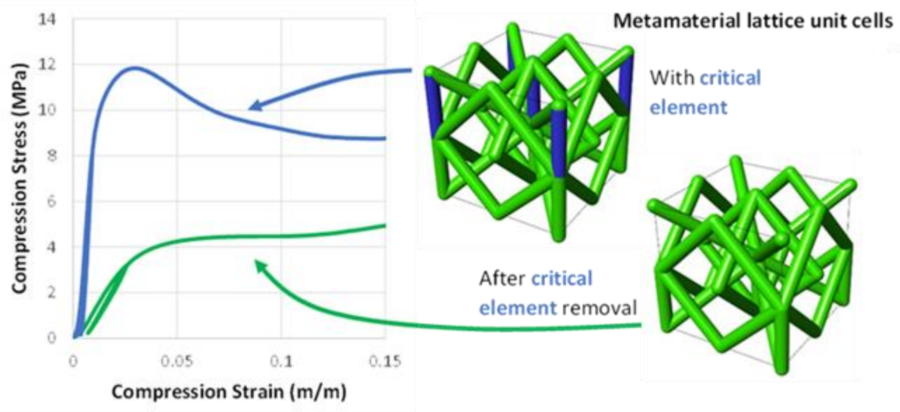
Engagement of 2nd network could also extend fatigue life… ongoing

Time-dependent properties

- Fatigue in metallic metamaterial lattices
- **Biodegradable metamaterial lattices**







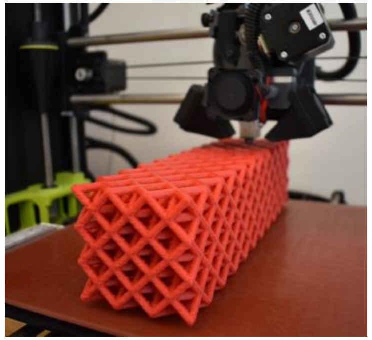
- Temporary implants (plates, screws etc.)
- Control degradation profile through metamaterial design

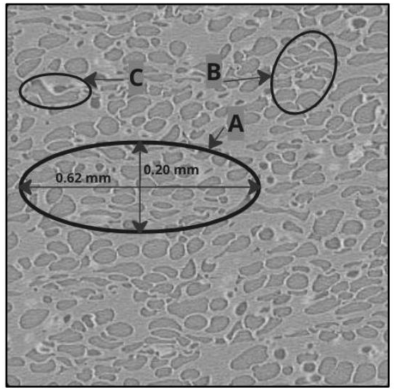
Nachtsheim et al., *PAMM 22.1 (2023): e202200326.;* GRAND FIX™ CMF https://www.gunze.co.jp/medical/e/products/item_gf_cmf.html

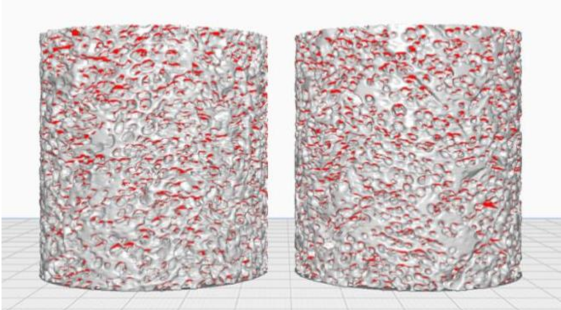
Degradable polymer foams

Traditionally 3D printing can only control porosity on a macroscale.

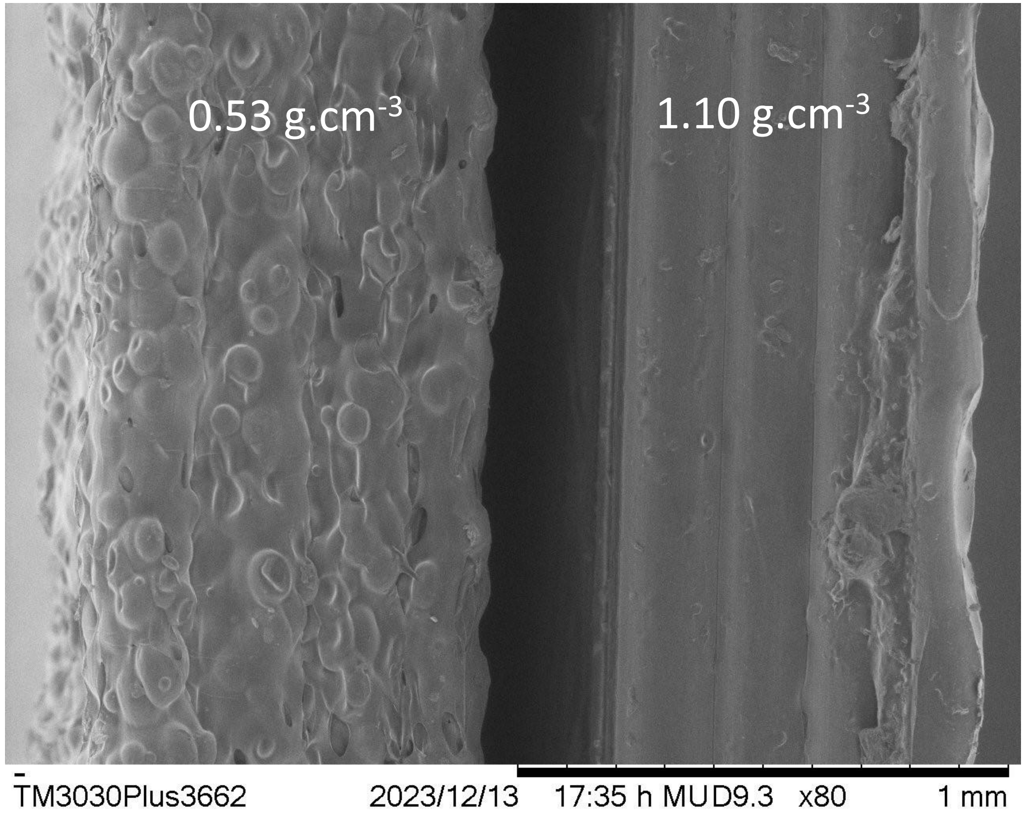
Foaming filaments allow microporosity within a single layer.

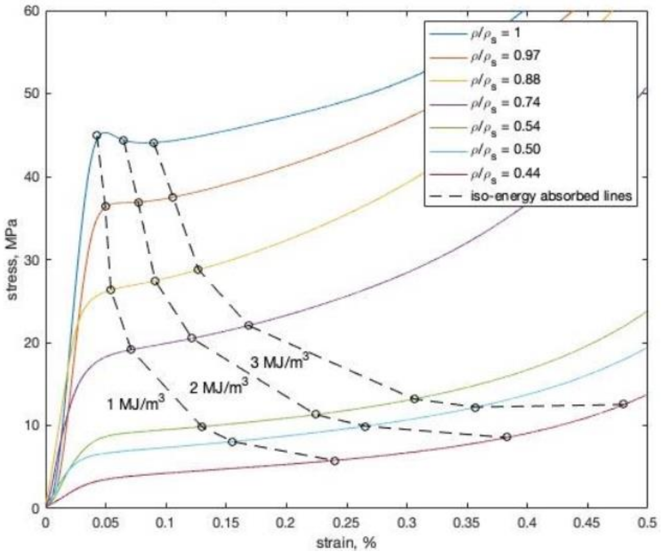


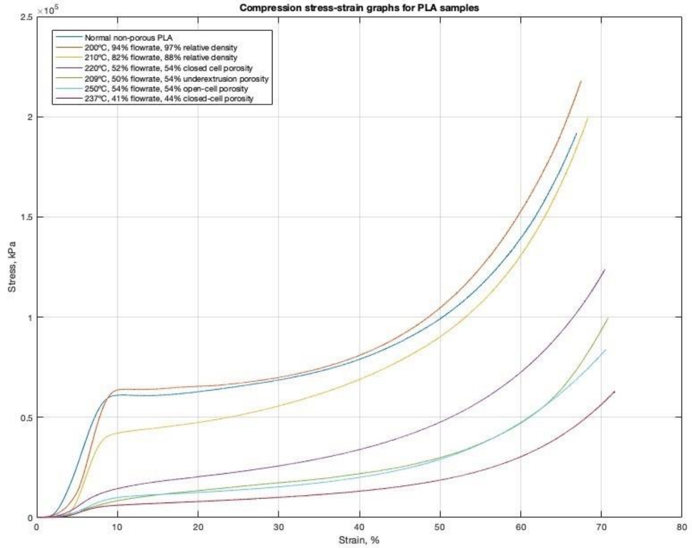




Tuning mechanical properties: strength, energy absorption

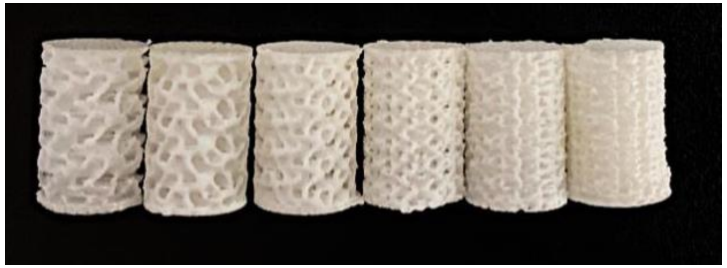


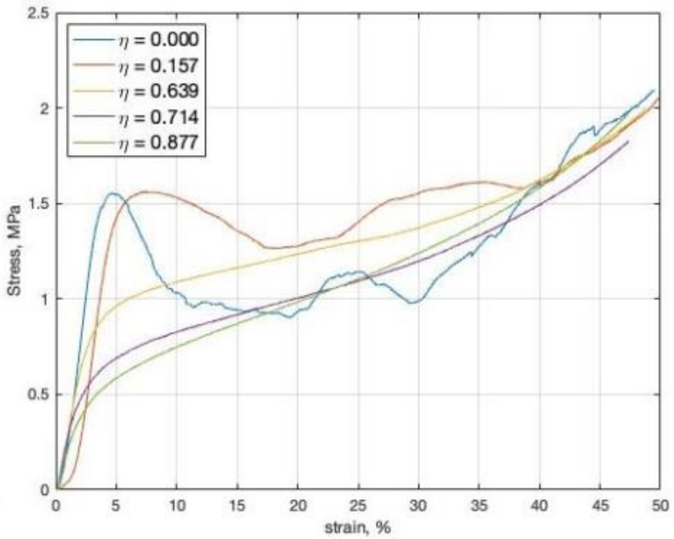




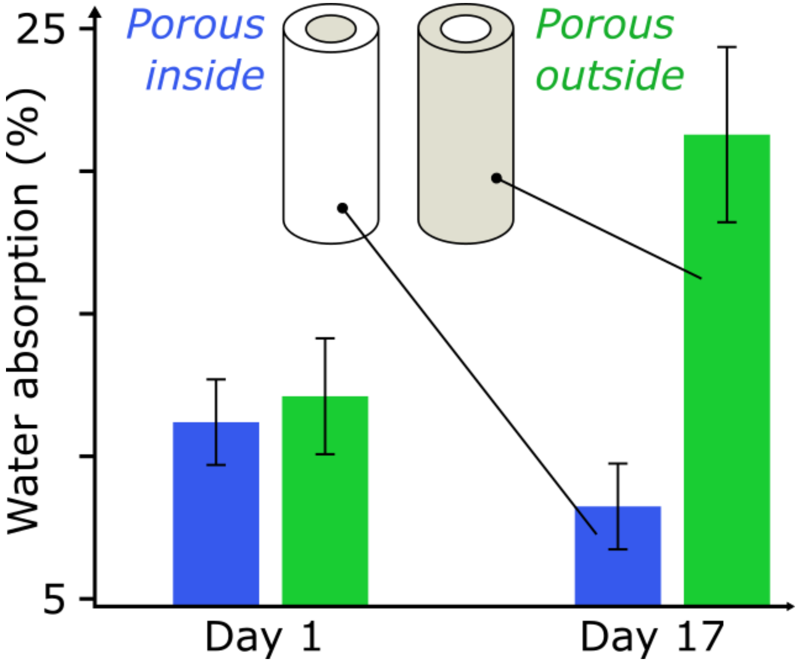
Degradable polymer foams

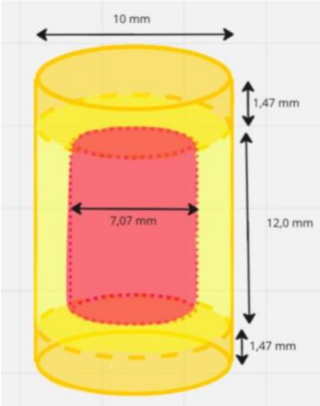
- Tuning mechanical properties with constant density
- Hierarchical foams: altering porosity length scale





- Metamaterial design parameter to control material degradation

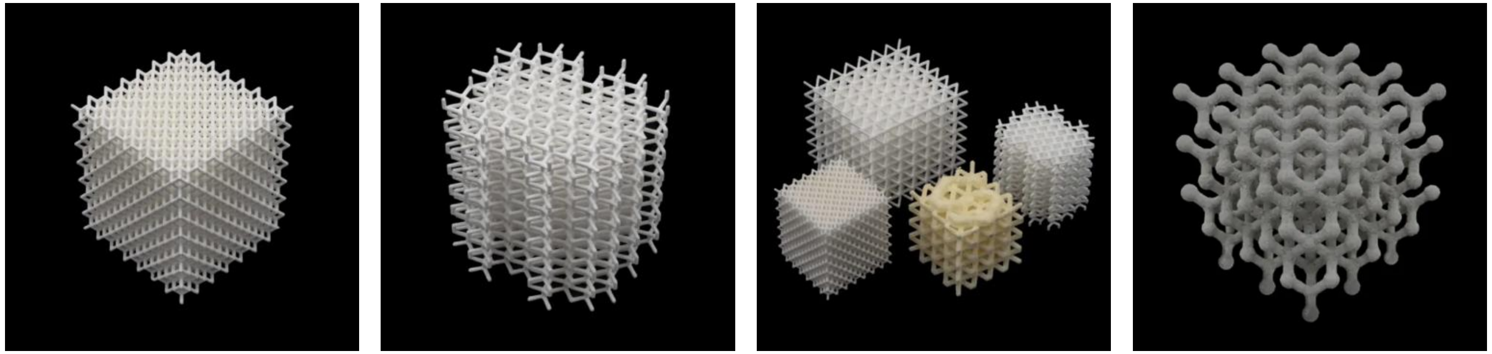


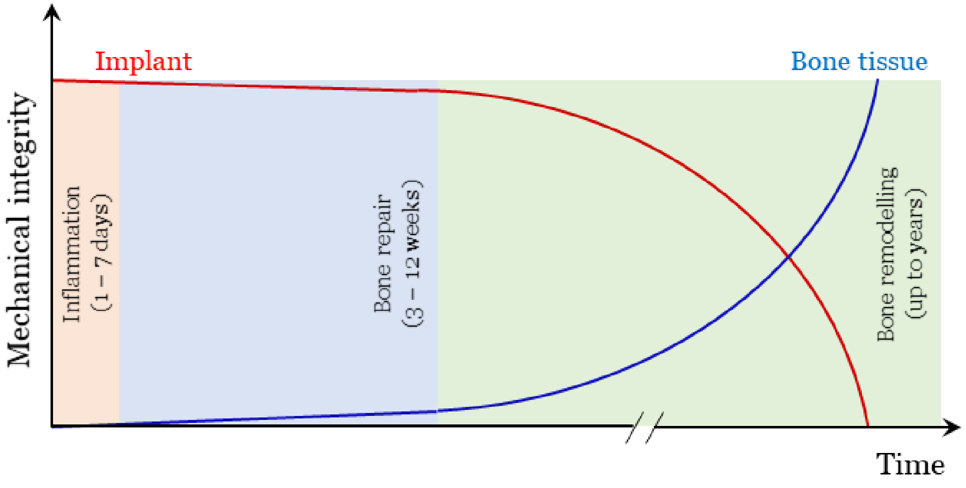


- Increased water absorption – key precursor to slow polymer degradation

Future work

- Powder bed fusion of biodegradable metamaterial lattices
  - Polymers and polymer-ceramic composites
  - Detailed metamaterial lattice structures





Thanks for listening!

Questions?