Additive Manufacturing of Metals and Alloys

10. Properties of lattice structures

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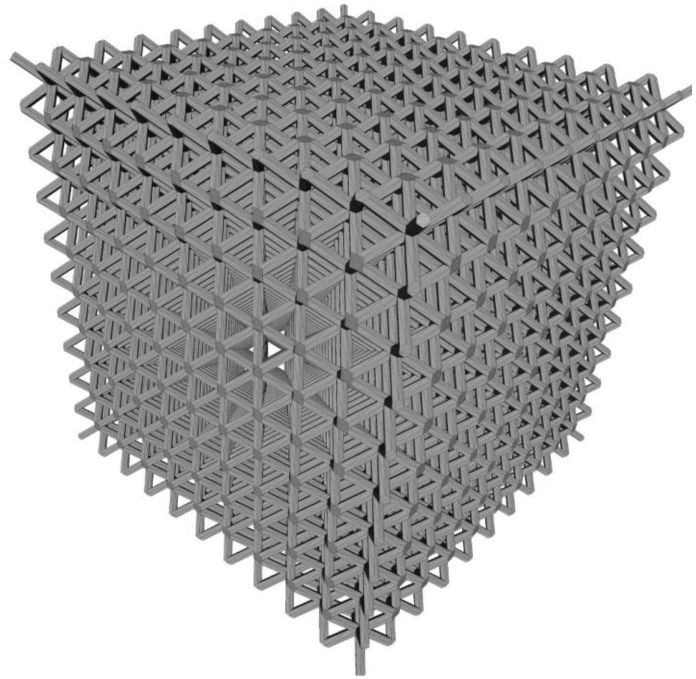
Properties of lattice structures

- What are lattice structures?
  - Definition
  - Multiscale and multifunctional materials
- Classification of lattice structures
  - bending dominated
  - stretching dominated
- AM of lattice structures: ongoing issues
  - surface roughness
  - effect of build orientation
  - post-processing
- Mechanical properties of AM lattice structures
  - static
  - dynamic
    - effect of post-processing
    - effect of loading conditions

Cellular structures include lattices and foams

Cellular structures are defined as a combination of material and space.
A cellular material is a connected 3D network of hollow or dense struts.

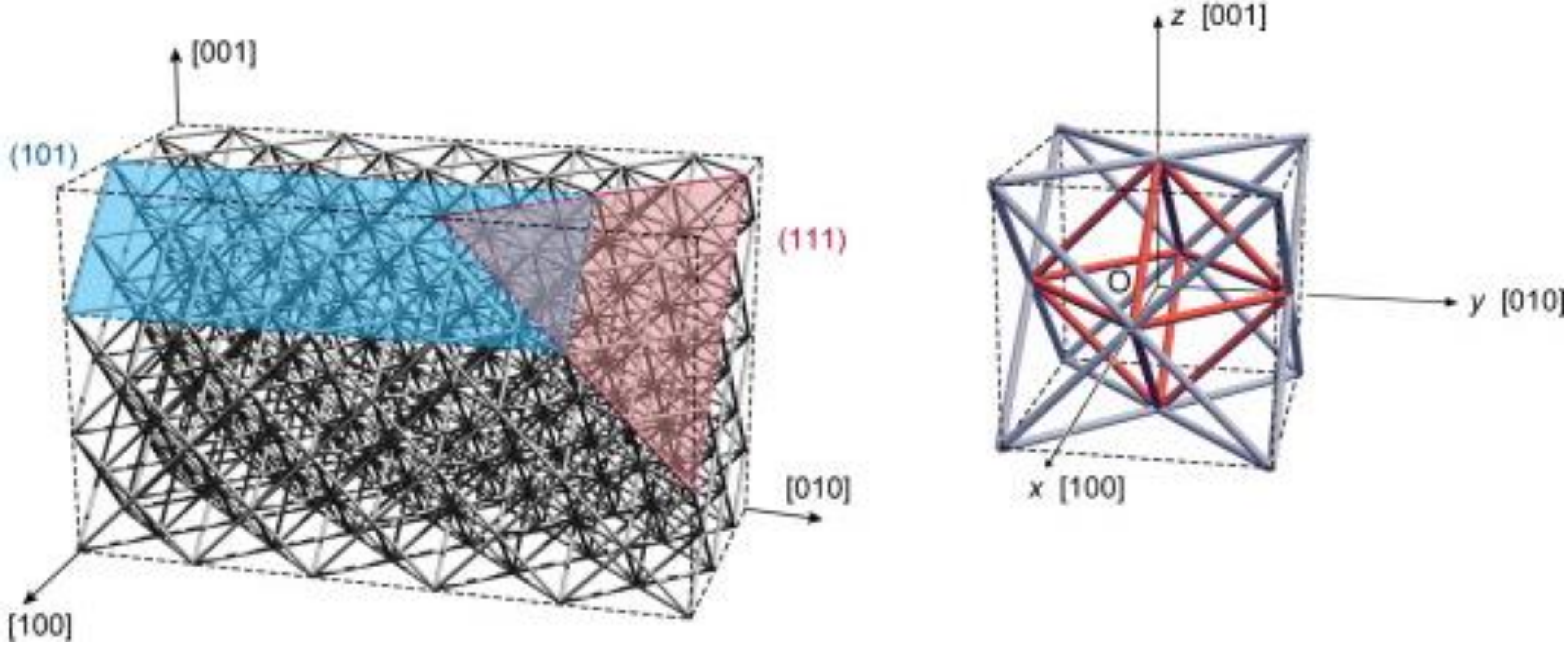
A foam is a stochastic cellular material



A lattice structure is a periodic arrangement of repeating unit cells

What are lattice structures?

Lattice structures are formed by the three-dimensional repetition of a unit cell.



An octet-truss lattice structure and its unit cell

What are lattice structures?

Properties of lattice structures depend on:

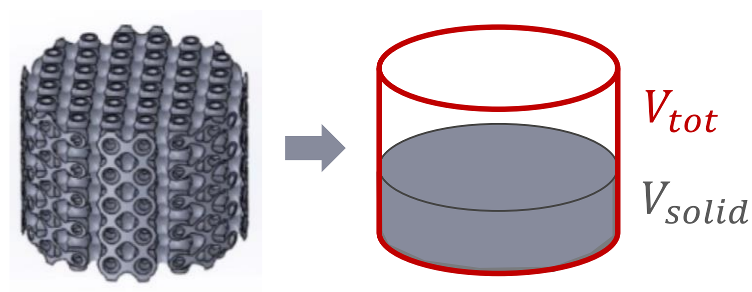
(i) the material of which the structure is made,

(ii) the shape and connectivity of the struts (Maxwell's criterion),

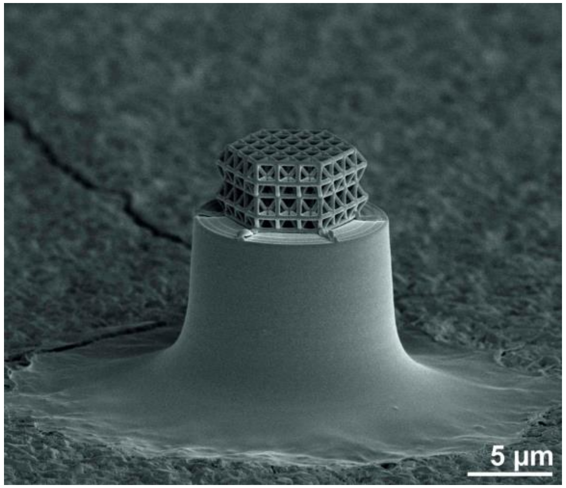
(iii) the relative density of the structure $\rho_{rel} = \frac{\tilde{\rho}}{\rho_s}$

where $\tilde{\rho}$ is the density of the structure
and ρ_s that of the solid of which it is made.

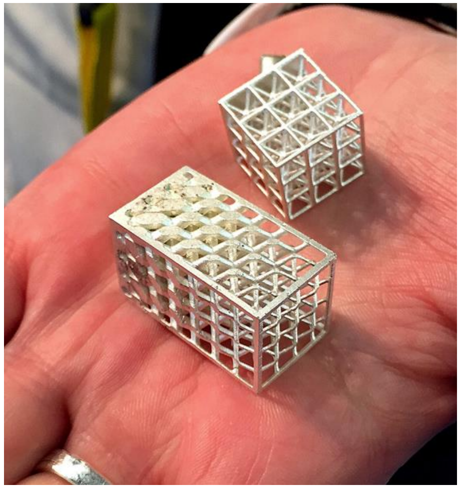
$$\rho_{rel} = \frac{\tilde{\rho}}{\rho_s} = \frac{V_{solid}}{V_{tot}}$$



Lattice structures are multiscale materials



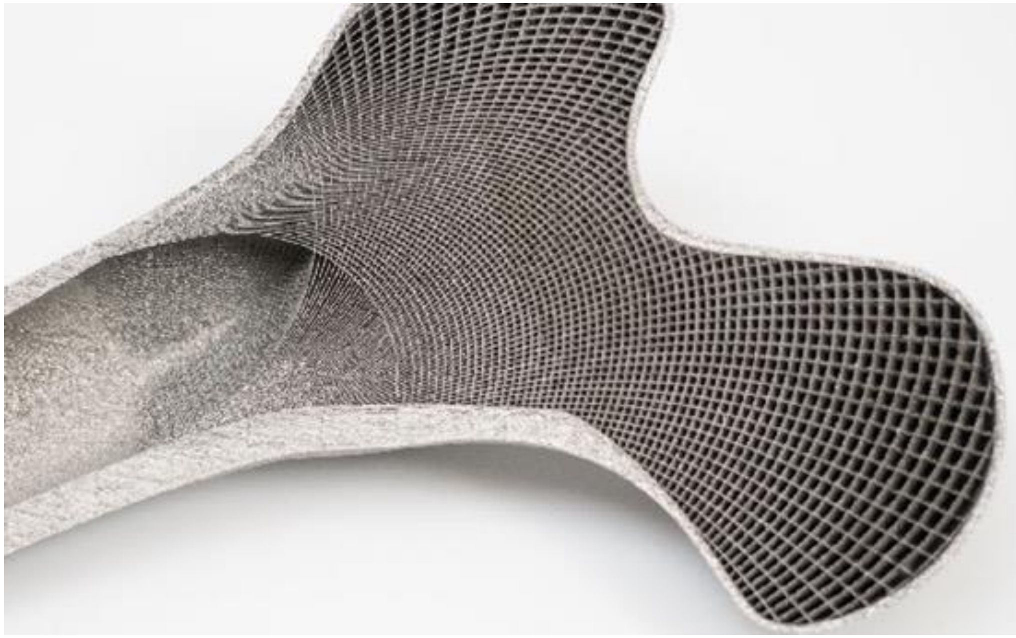
carbon nanolattice



metal lattice

orthogonal timber lattice

Lattice structures are multifunctional materials

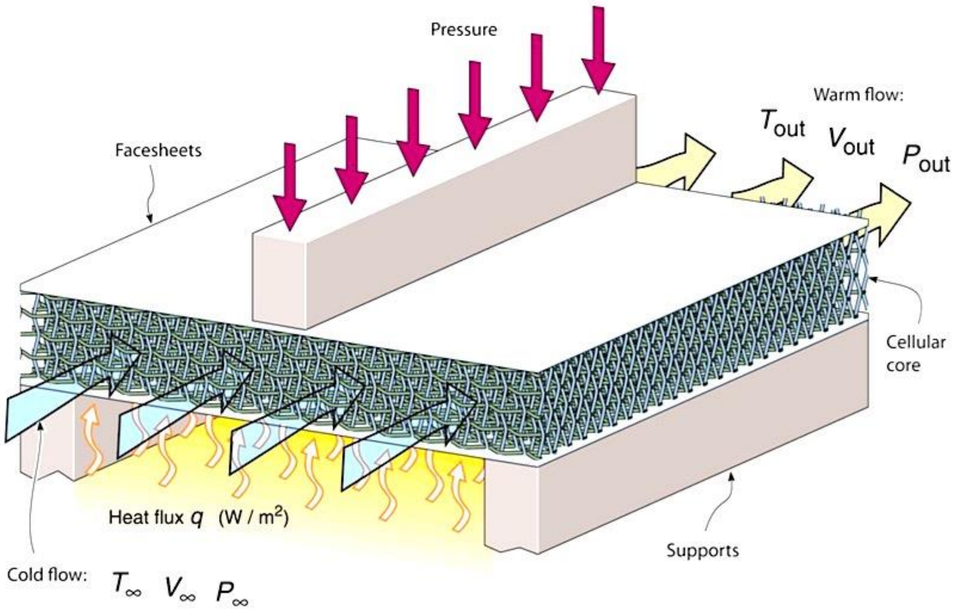


Integration of a porous structure in an implant:
⇒ stiffness reduction,
⇒ no stress shielding

Interconnected porosity:
⇒ favoured vascularization and bone growth

Biocompatibility and **long-term osseointegration**

Lattice structures are multifunctional materials



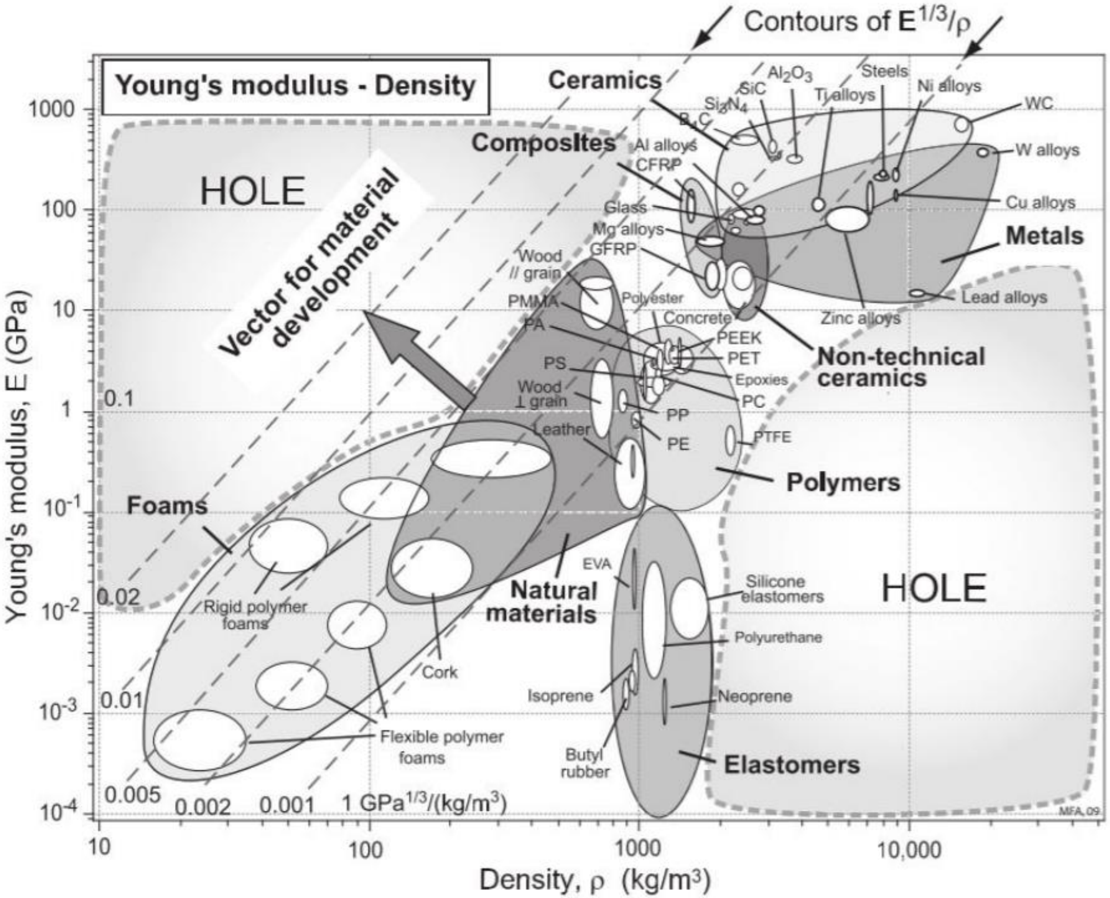
Heat exchanger using a cellular core sandwich panel

Very high surface area
$\Rightarrow$ heat transfer to the coolant

Inconel 625 prototype helicopter exhaust nozzle.

Lattice structures allow engineers to « fill holes in the material-property space ».

Example: in order to produce parts with higher stiffness-to-density ratio, monolithic materials are not sufficient and the development of architectured materials is needed.



Ashby, Mike. "Designing architectured materials." *Scripta Materialia* 68.1 (2013): 4-7.

Properties of lattice structures

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- Mechanical properties of AM lattice structures
  - static
  - dynamic

Classification of lattice structures

Two types of lattice structures can be distinguished:

- bending-dominated
- stretching-dominated.

This distinction is based on the connectivity **of the structure.**

Maxwell's stabiliy criterion :

$M = b - 2j + 3$, in 2D

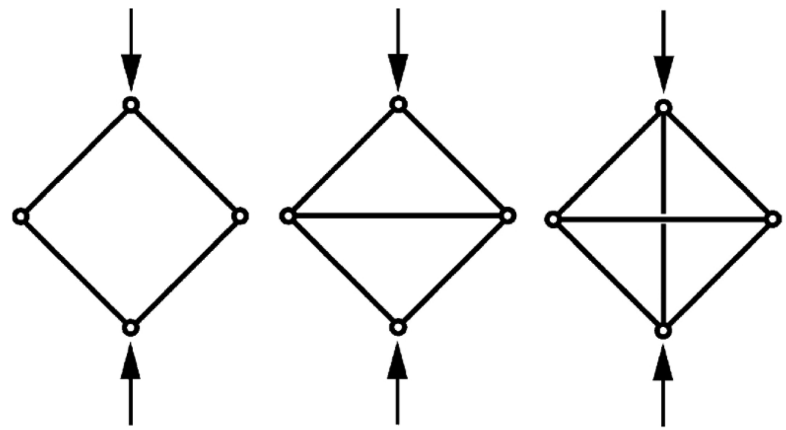
$M = b - 3j + 6$, in 3D

b: number of struts

j: number of nodes

in a unit cell

$M < 0$: bending dominated
$M = 0$: stretching dominated
$M > 0$: over-constrained



Ashby, Michael F. "The properties of foams and lattices." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364.1838 (2006): 15-30.

Classification of lattice structures

Maxwell's stability criterion :

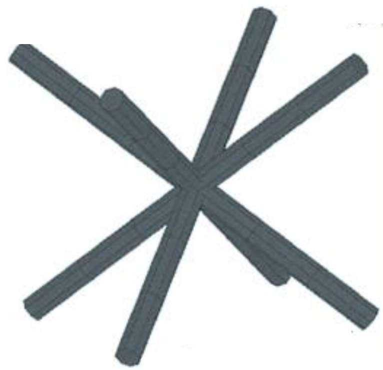
M = b – 2j + 3, in 2D

M = b – 3j + 6, in 3D

b: number of struts

j: number of nodes

BCC

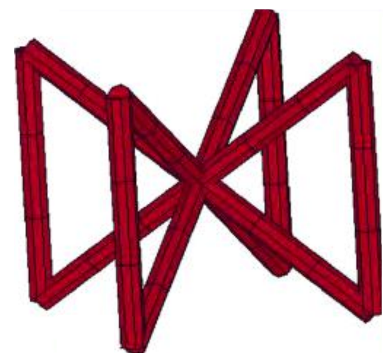


b = 8

j = 9

M = -13

BCC with Z strut

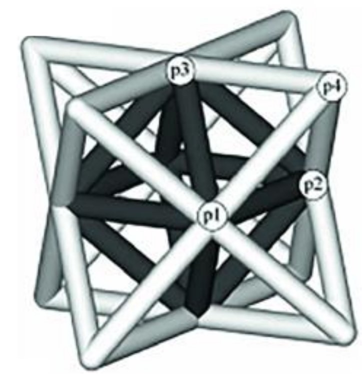


b = 12

j = 9

M = -9

Octet-truss



b = 36

j = 14

M = 0

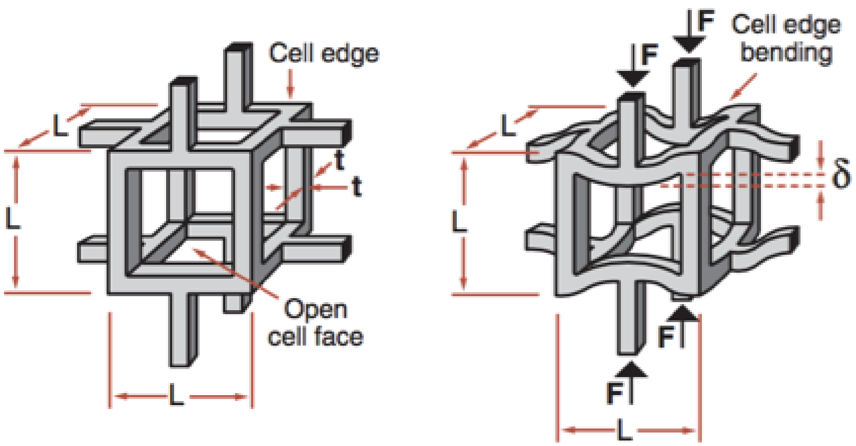
M < 0 : bending dominated

M = 0 : stretching dominated

M > 0 : over-constrained

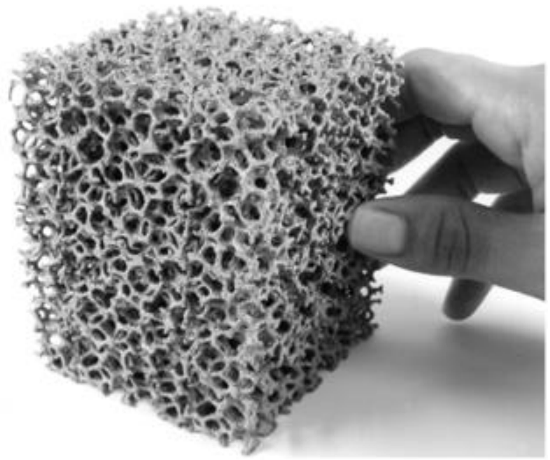
Ashby, Michael F. "The properties of foams and lattices." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364.1838 (2006): 15-30.

Bending-dominated structures



If $b - 3j + 6 < 0$, the low connectivity of the struts allows them to bend when the lattice is loaded.

Foams are typical examples of bending-dominated cellular structures.



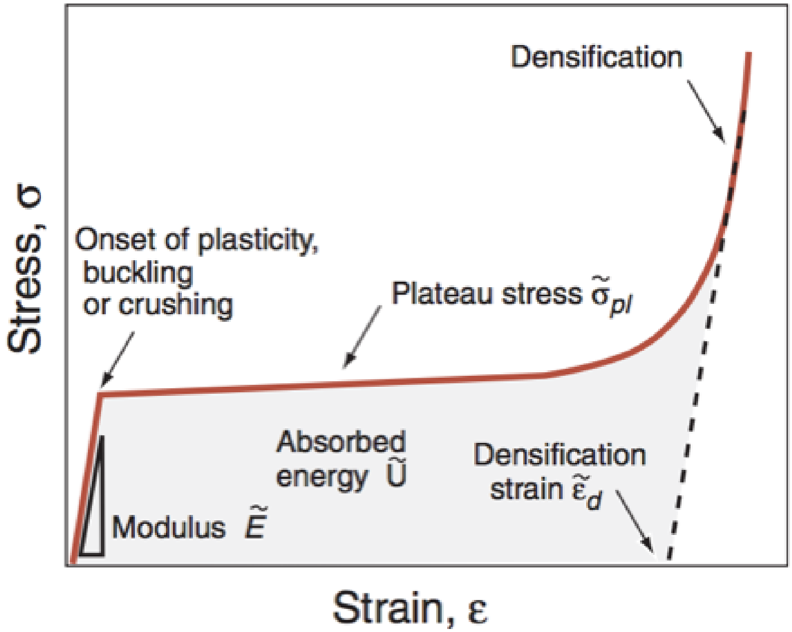
Ashby, Michael F. "The properties of foams and lattices." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364.1838 (2006): 15-30.

Bending-dominated structures

Estimation of the useful energy that a foam can absorb per unit volum:

$$\widetilde{U} \approx \tilde{\sigma}_{pl}\tilde{\varepsilon}_d,$$

where $\tilde{\sigma}_{pl}$ is the plateau stress, and $\tilde{\varepsilon}_d$ the densification strain.



Ashby, Michael F. "The properties of foams and lattices." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364.1838 (2006): 15-30.

Stretching-dominated structures

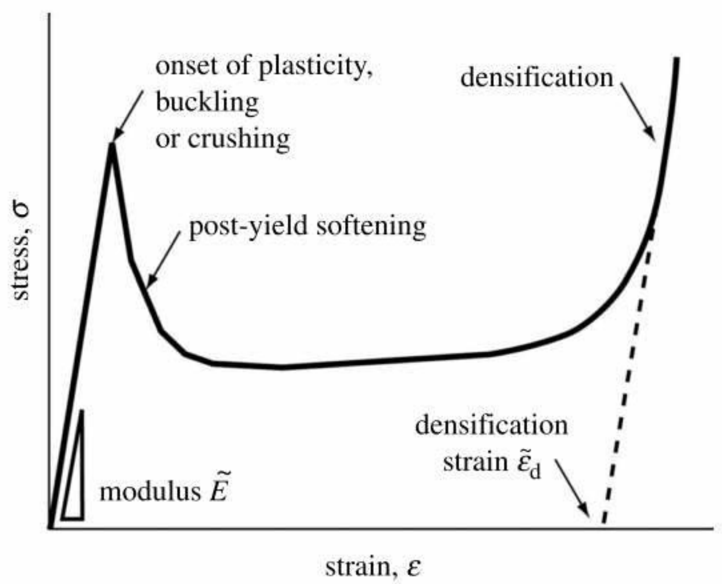
If $b - 3j + 6 \geq 0$, the high nodal connectivity of the structure suppresses bending, forcing the struts to stretch.

Isotropic behaviour: one third of the struts carries tension when it is loaded in simple tension

$$\frac{\tilde{E}}{E_s} \approx \frac{1}{3}\left(\frac{\tilde{\rho}}{\rho_s}\right)$$

where $\tilde{E}$ is the stiffness of the structure
and E_s the Young's modulus of the solid of which it is made

Quasi-static compression behaviour:



Ashby, Michael F. "The properties of foams and lattices." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 364.1838 (2006): 15-30.

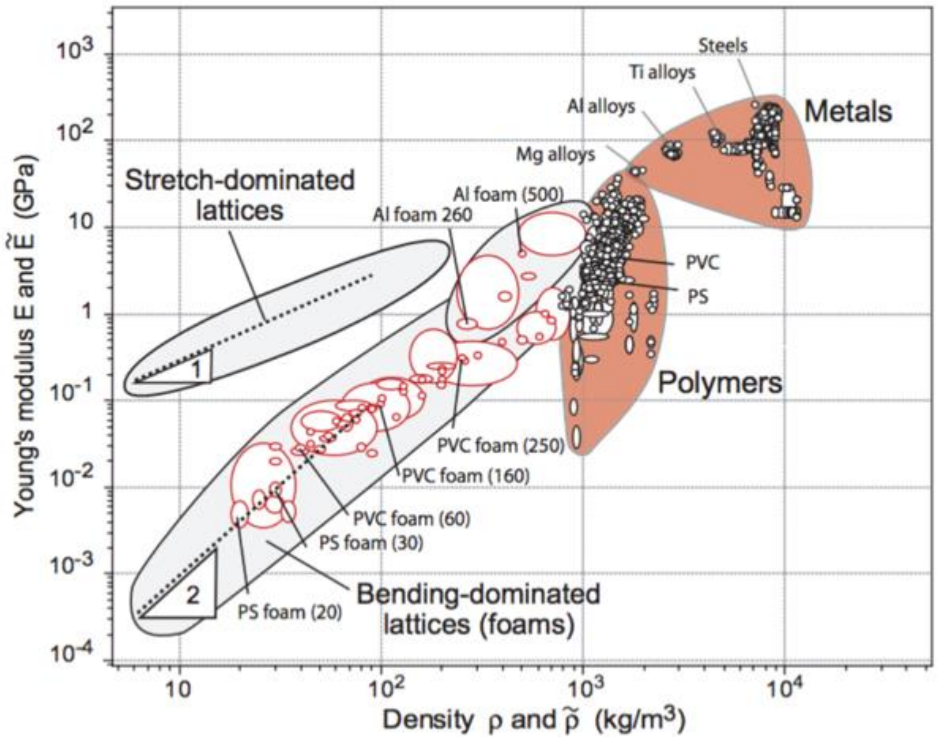
Bending vs stretching-dominated structures

Stretch-dominated lattices: $\frac{\tilde{E}}{E_s}$ scales as $\frac{1}{3}\frac{\tilde{\rho}}{\rho_s}$

$\Rightarrow$ weight efficient, stress-supporting structures

Bending-dominated lattices: $\frac{\tilde{E}}{E_s}$ scales as $\left(\frac{\tilde{\rho}}{\rho_s}\right)^2$

$\Rightarrow$ more compliant and weaker structures

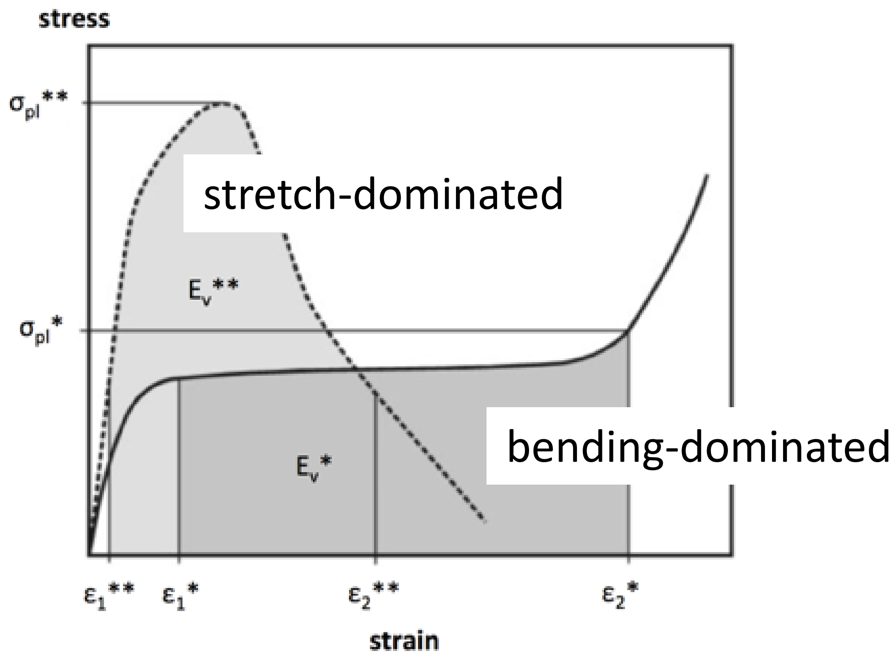


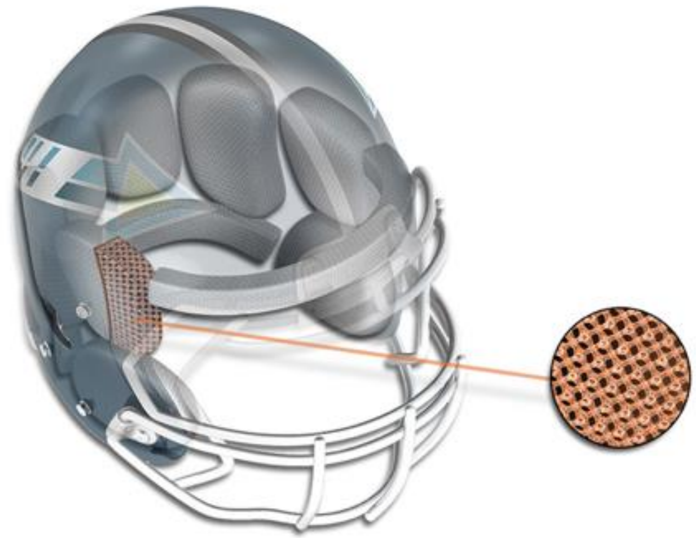
Ashby, M.F., "Hybrids to fill holes in material property space". *Philosophical Magazine*, 2005. **85**(26-27): p. 3235-3257.

Applications of stretching-dominated structures

High strength-to-weight and stiffness-to-weight ratios
$\Rightarrow$ substantial mass decrease by incorporating these structures where the maximum stresses are low in aerospace components

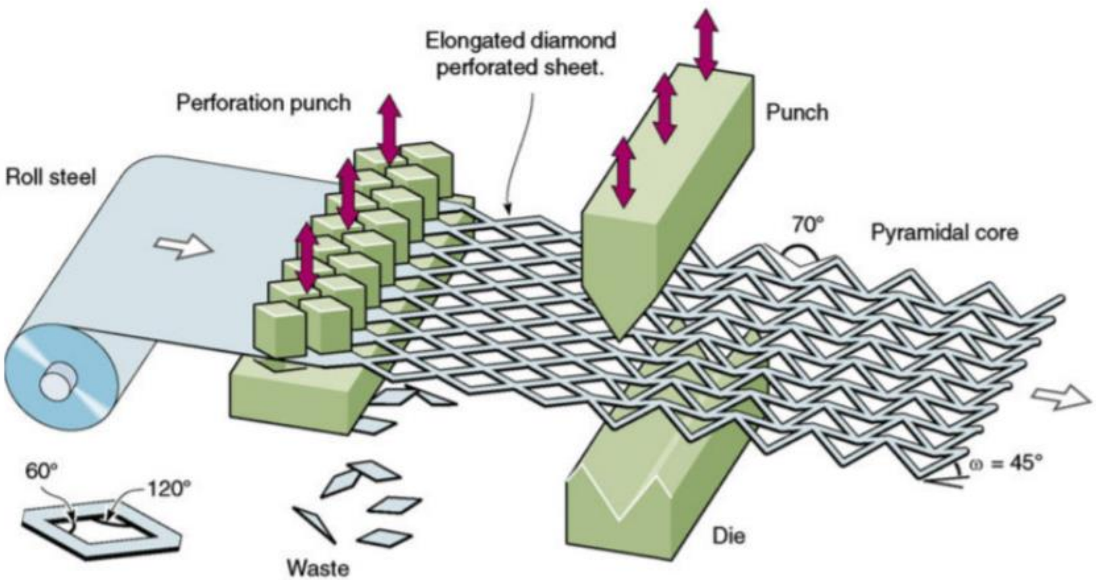
Applications of bending-dominated structures

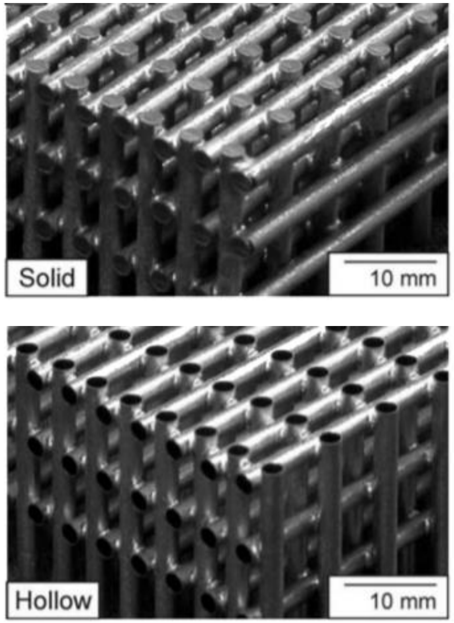




$\Rightarrow$ energy absorption applications: packaging, protection against impact…

The manufacturing of lattice structures by **conventional** techniques is **complex**





Production from an expanded metal sheet

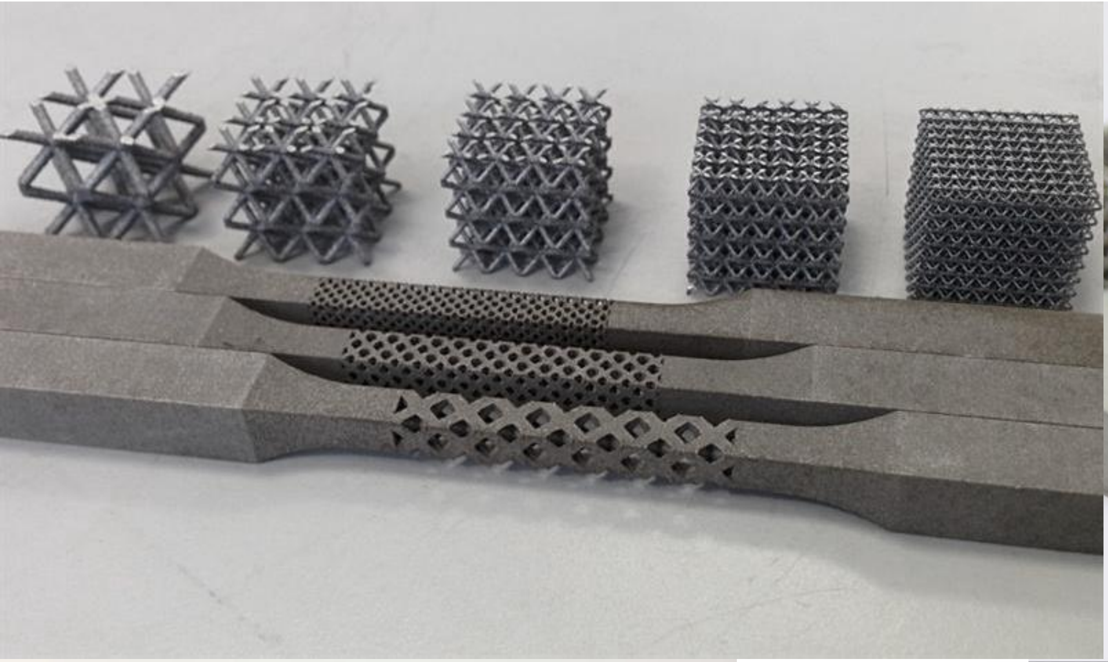
1) perforation
2) folding
3) stacking

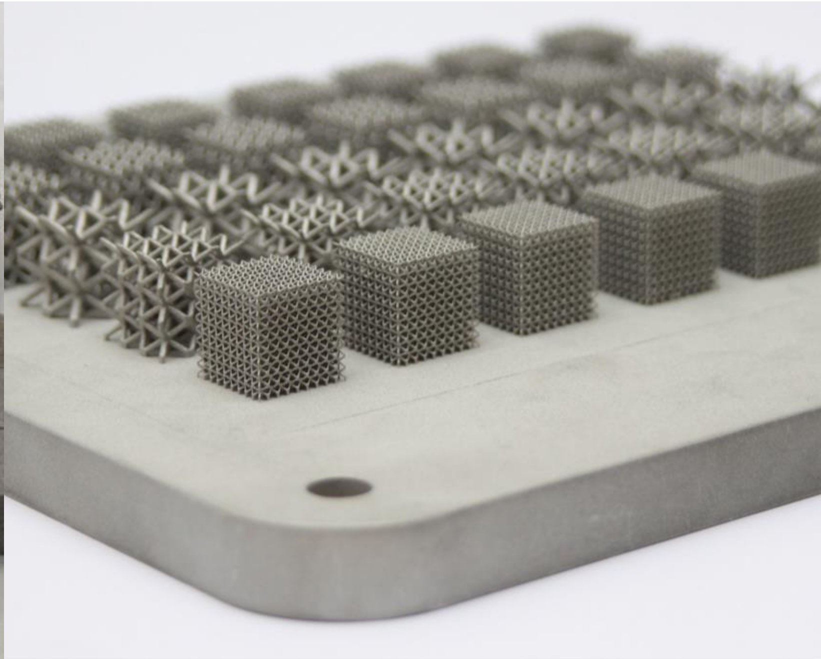
Produces a **large amount of waste** and requires the use of an alloy that is **ductile** enough to be perforated and punched.

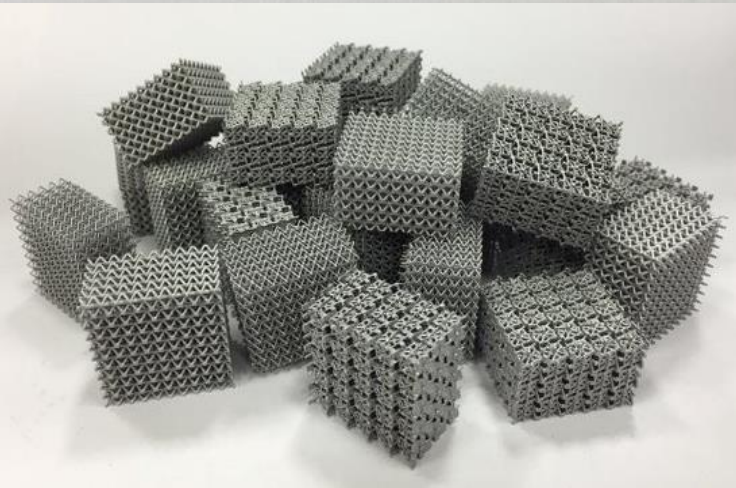
Solid or hollow metallic wire assembly

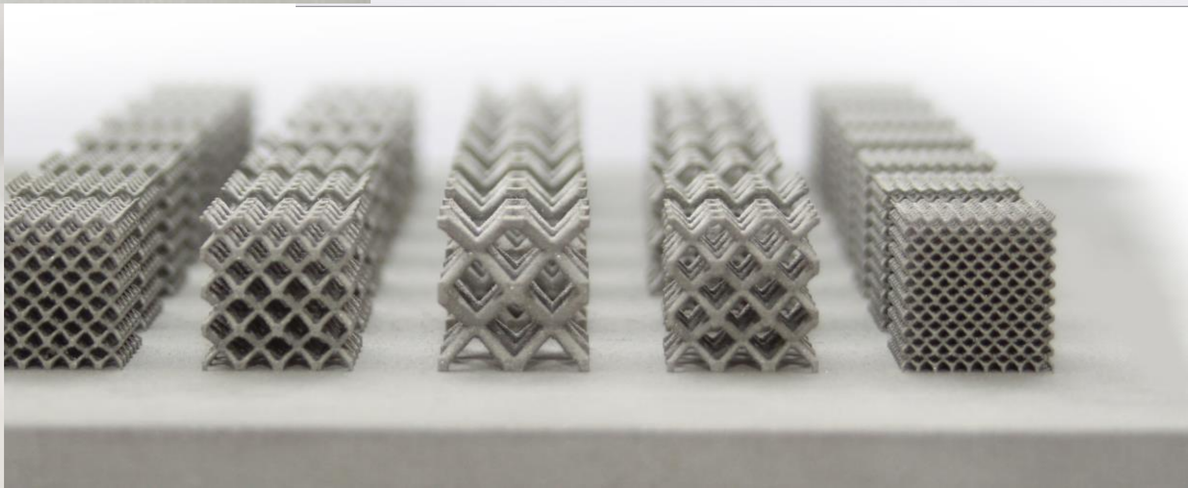
Permits only the production of a **limited amount of designs**.

AM is particularly well suited for the production of metallic lattice structures









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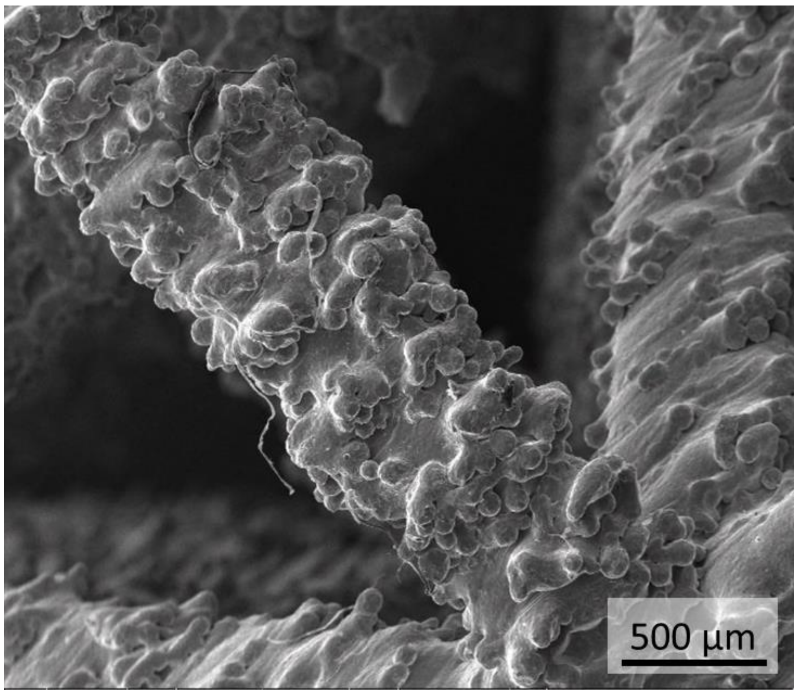
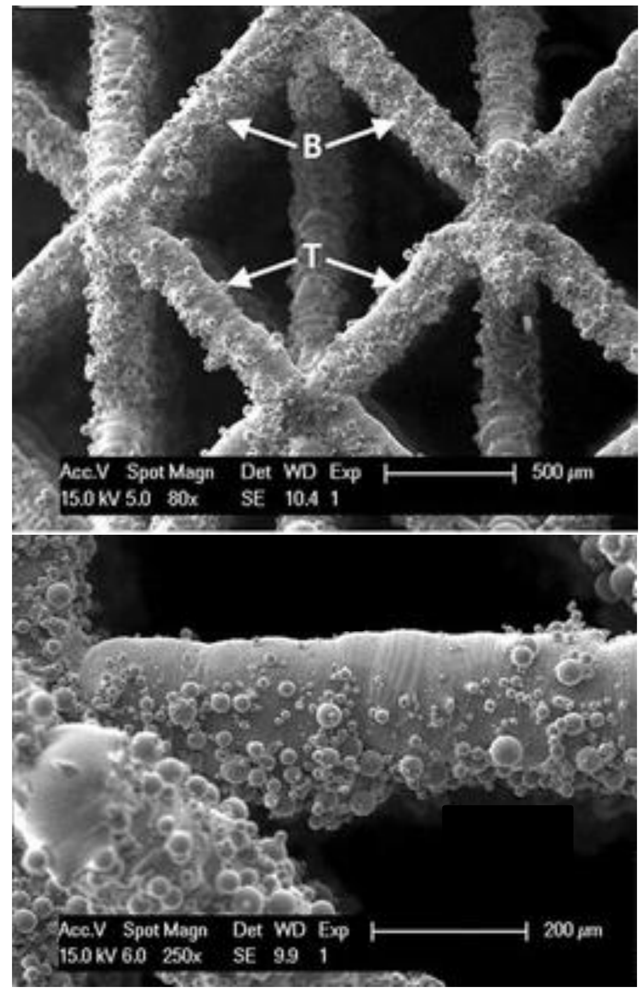
Surface roughness: EBM vs LPBF

EBM

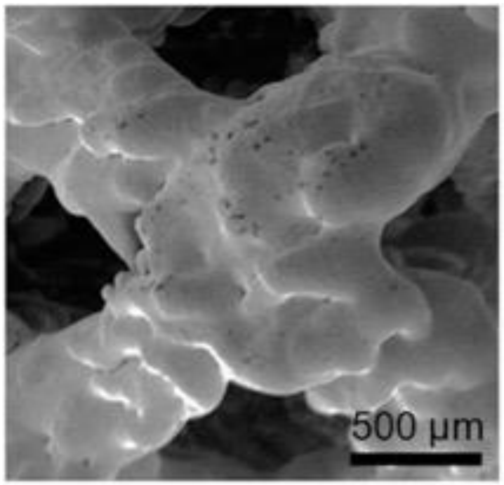


LPBF

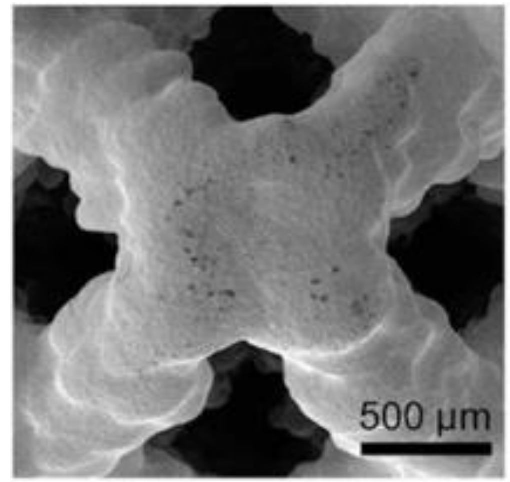


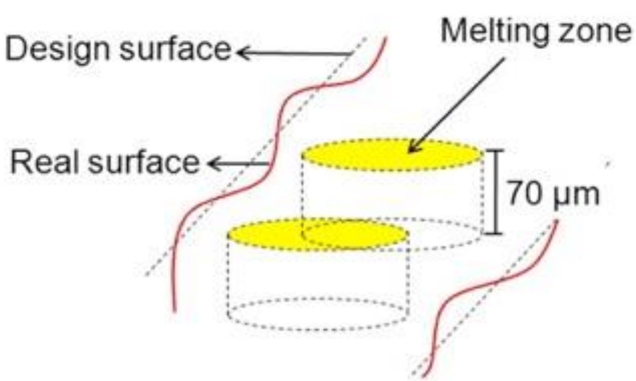
Surface roughness: staircase effect

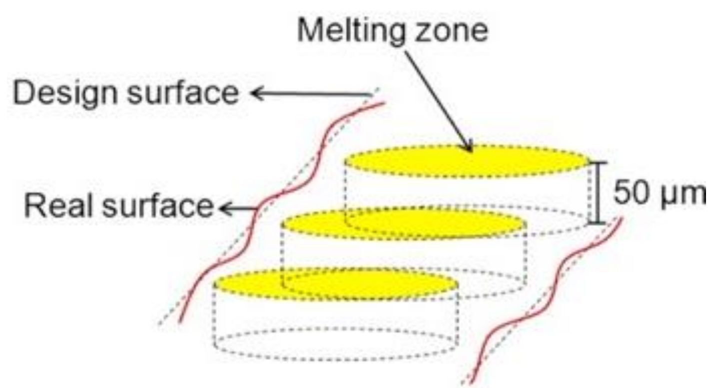
EBM



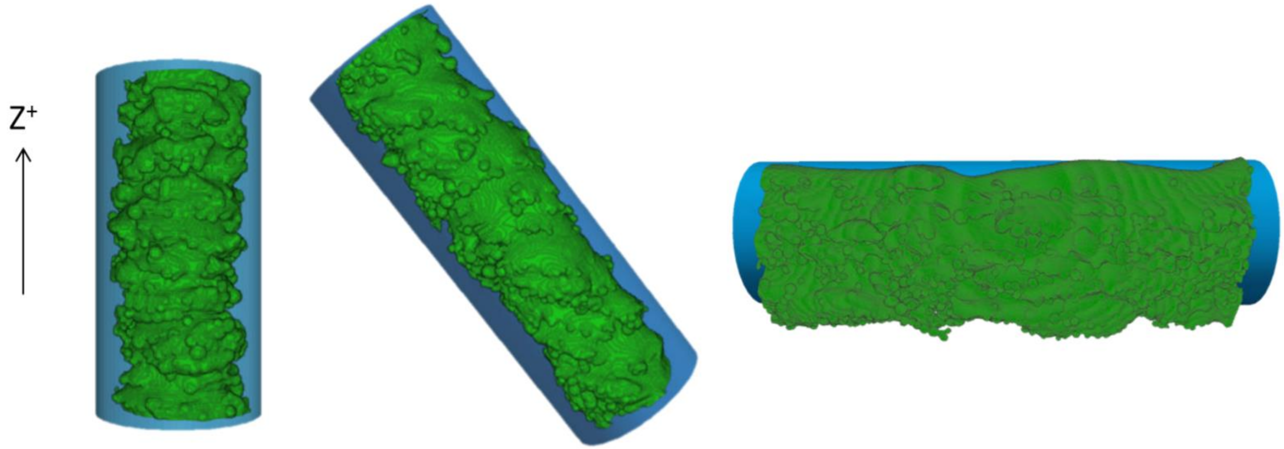
LPBF



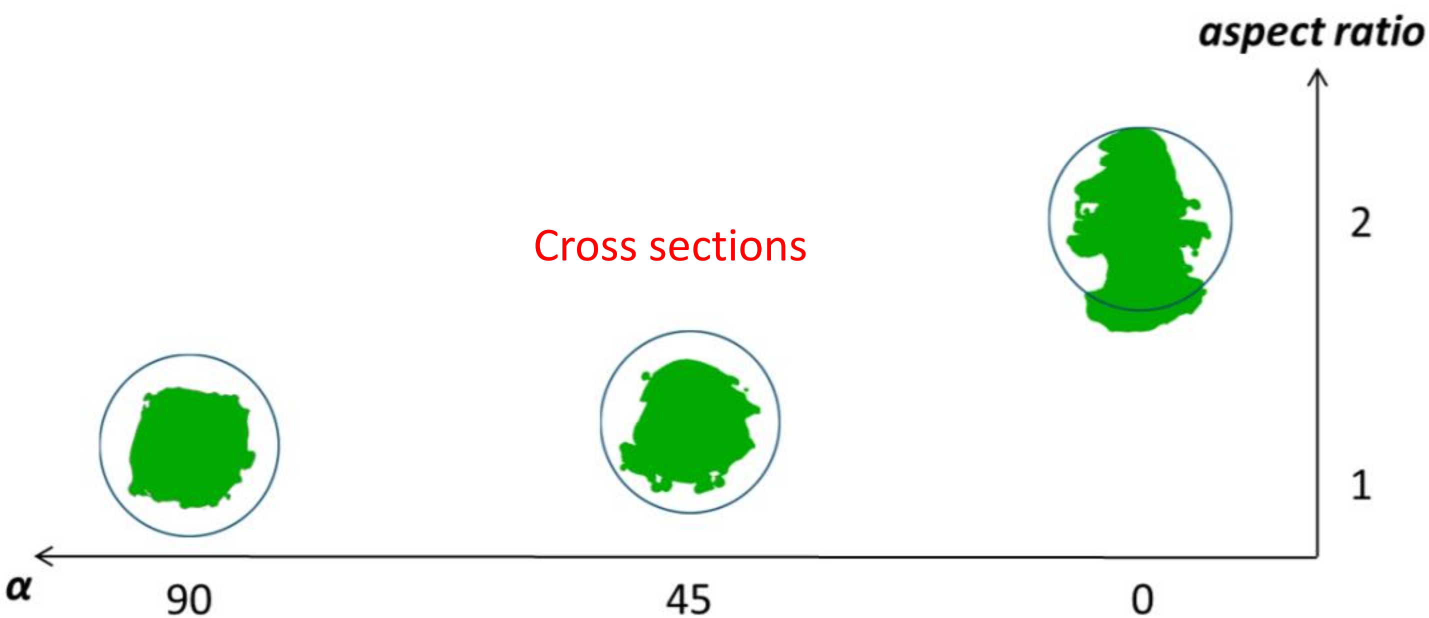




Surface roughness: effect of strut inclination



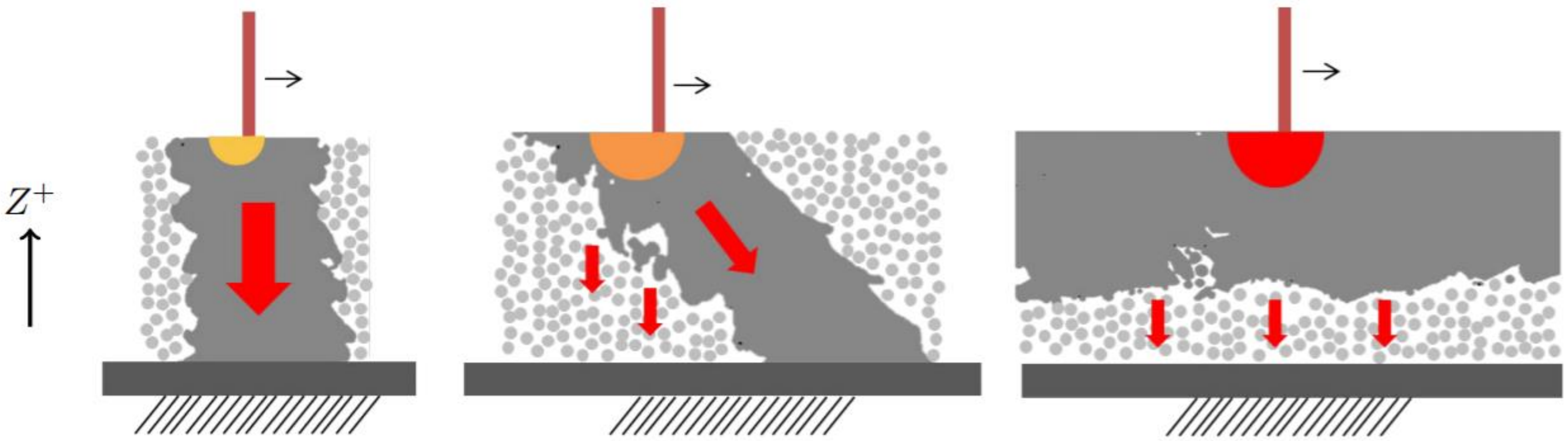
downfacing surface: dross formation



Suard, Mathieu. *Characterization and optimization of lattice structures made by Electron Beam Melting*. Diss. Grenoble Alpes, 2015.

Surface roughness: effect of strut inclination

Thermal behavior during processing for different orientations:



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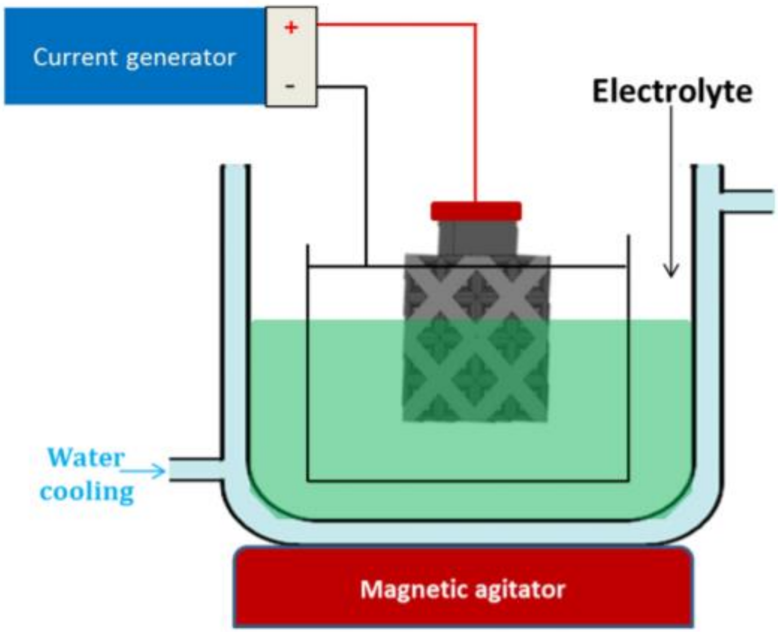
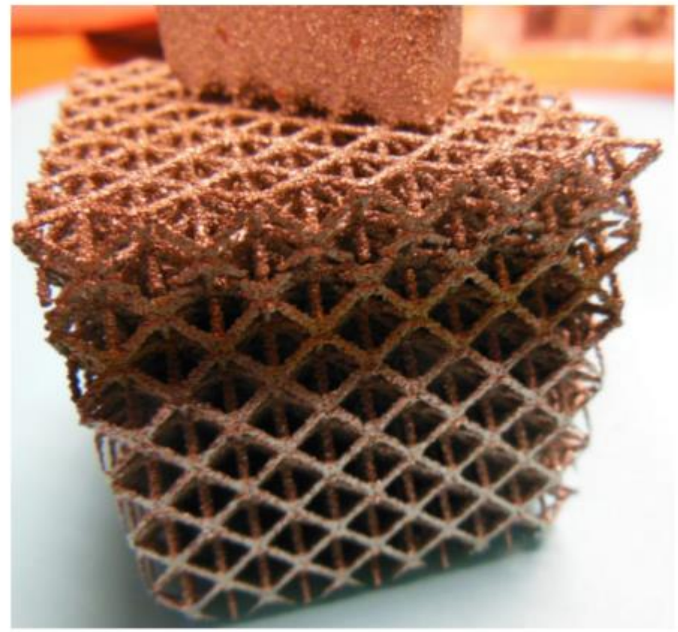
Electro-chemical polishing ECP

Ti-6Al-4V

Experimental set-up



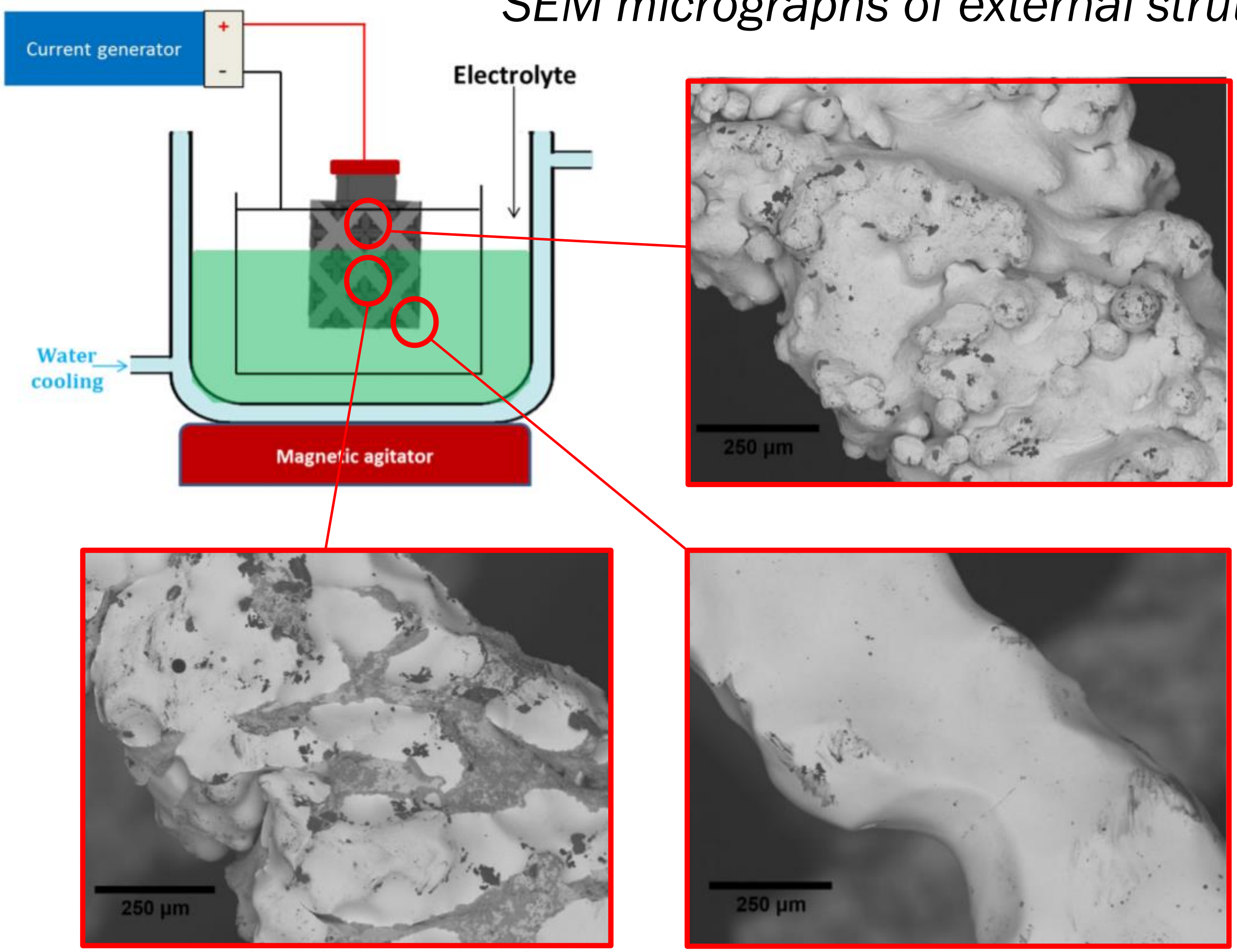


Electrolyte: vol10% of perchloric acid and vol90% of acetic acid

Suard, Mathieu. *Characterization and optimization of lattice structures made by Electron Beam Melting*. Diss. Grenoble Alpes, 2015.

Electro-chemical polishing ECP does not allow to **homogeneously** reduce surface roughness

SEM micrographs of external struts after ECP

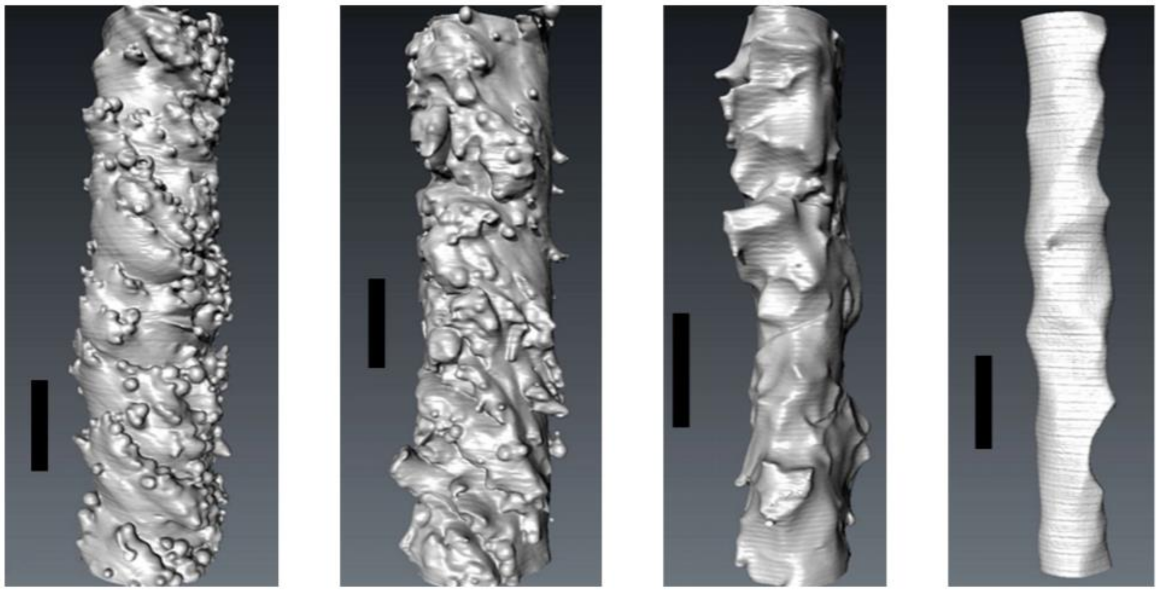


Raw strut in the emerged zone

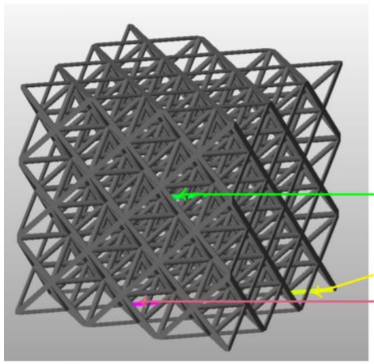
Suard, Mathieu. *Characterization and optimization of lattice structures made by Electron Beam Melting*. Diss. Grenoble Alpes, 2015.

Electro-chemical polishing ECP does not allow to homogeneously reduce surface roughness

X-ray tomography on the struts in different zones of the lattice structure.



raw internal bottom bottom corner

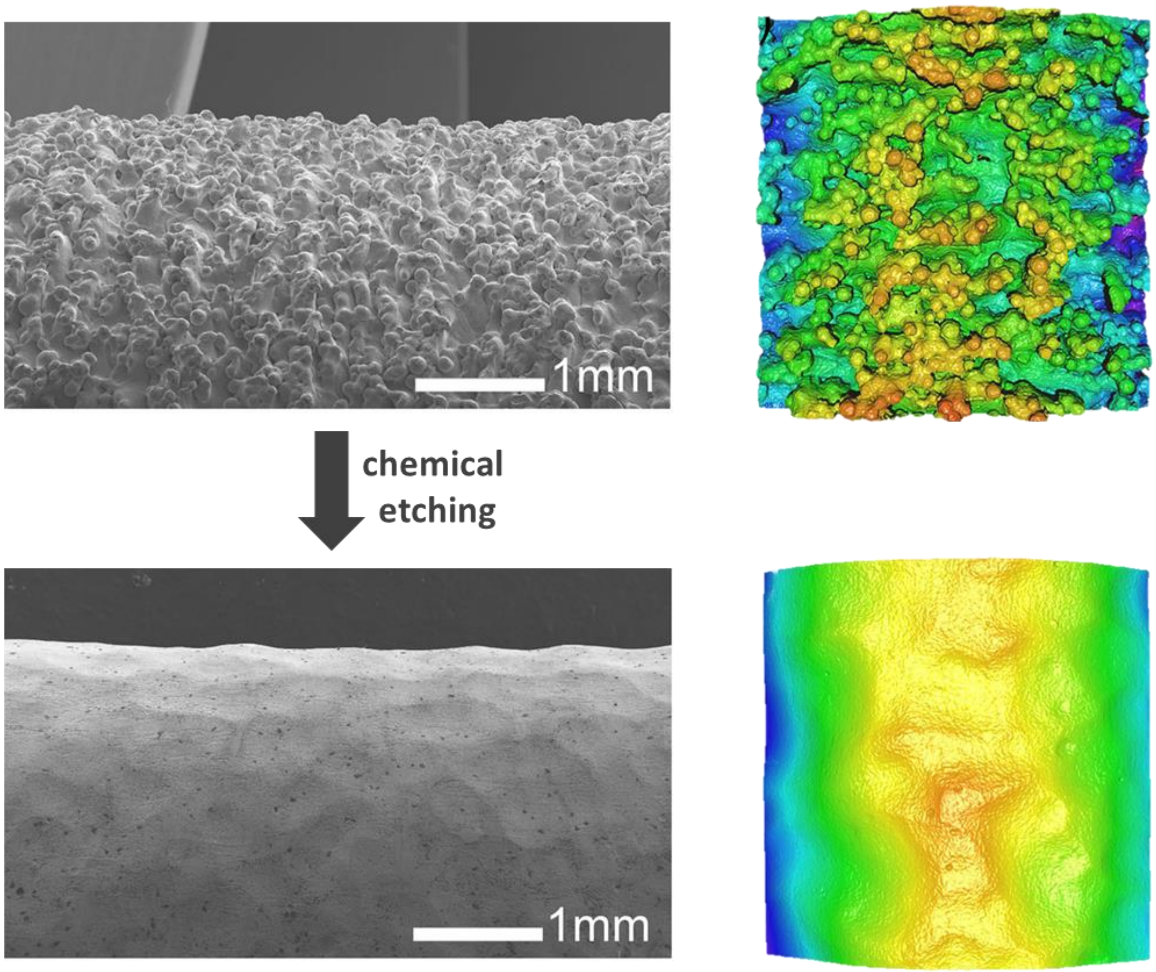


scale bar: 500 µm

Large **inhomogeneity of polishing**:
more significant roughness reduction at the edges of the lattice

Chemical etching

Chemical etchant: 3%HF, 13% HNO_3



Chemical etching

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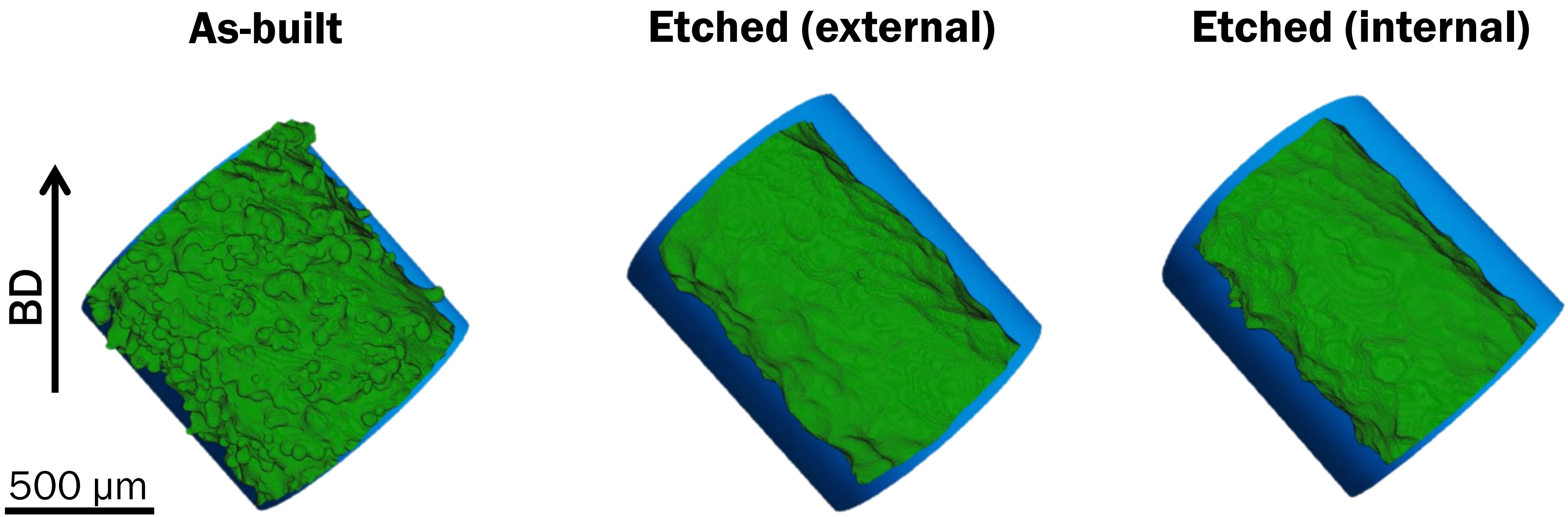
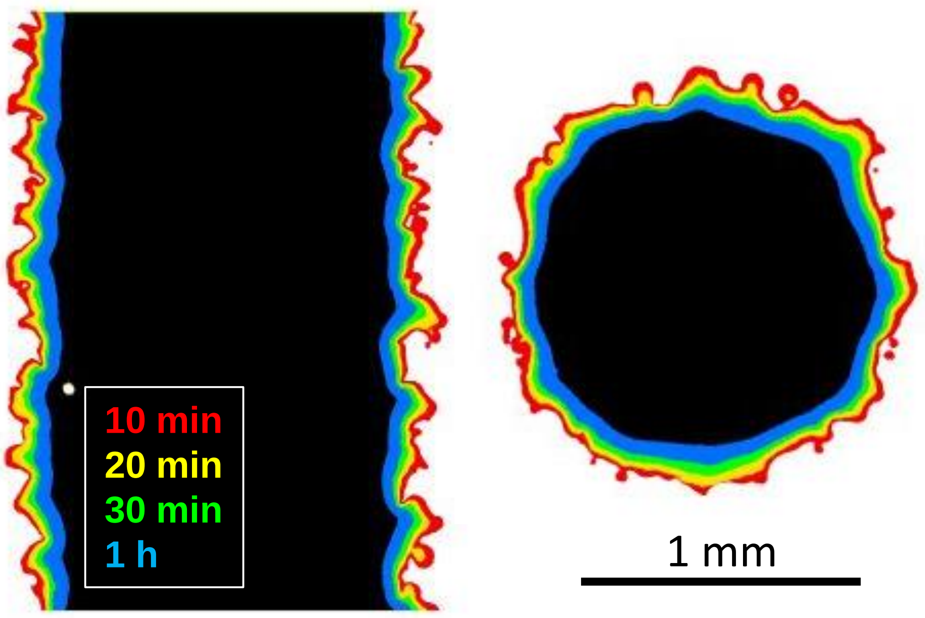


The chemical etching is homogeneous throughout the structure.

de Formanoir, Charlotte, et al. "Improving the mechanical efficiency of electron beam melted titanium lattice structures by chemical etching." *Additive Manufacturing* 11 (2016): 71-76.

Chemical etching: effect of etching time

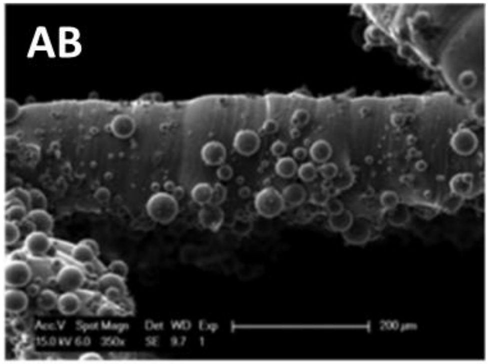


The grains of powder stuck to the surface are the first to be removed.

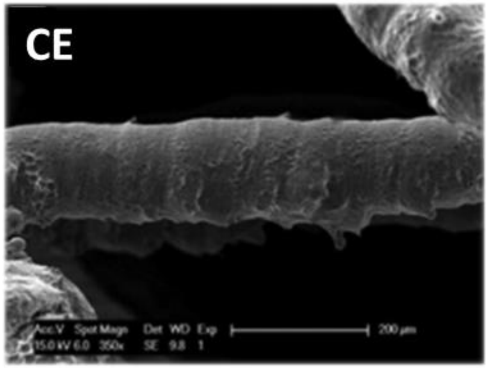
Lhuissier, Pierre, et al. "Geometrical control of lattice structures produced by EBM through chemical etching: Investigations at the scale of individual struts." *Materials & Design* 110 (2016): 485-493.

Combination of chemical etching and ECP

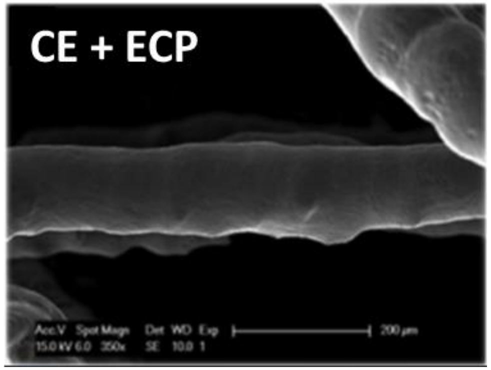
The combination of etching and electrochemical polishing with HF-based solutions has proven to be effective to obtain a **more controlled and homogeneous roughness** throughout the structures .



Chemical etching is mainly used to remove the partially melted or partially sintered particles on the surface.

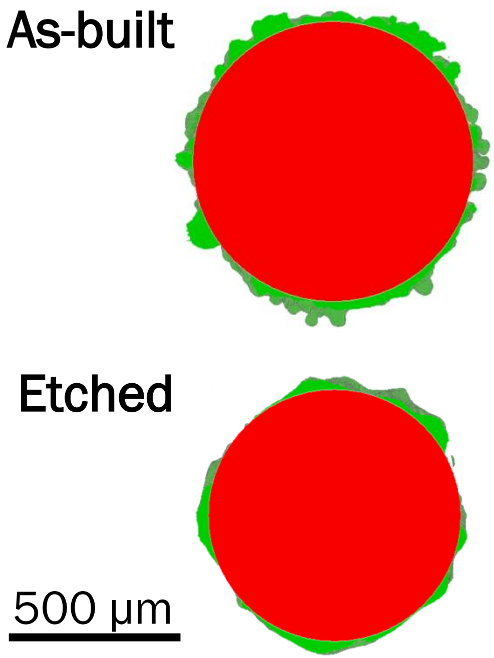


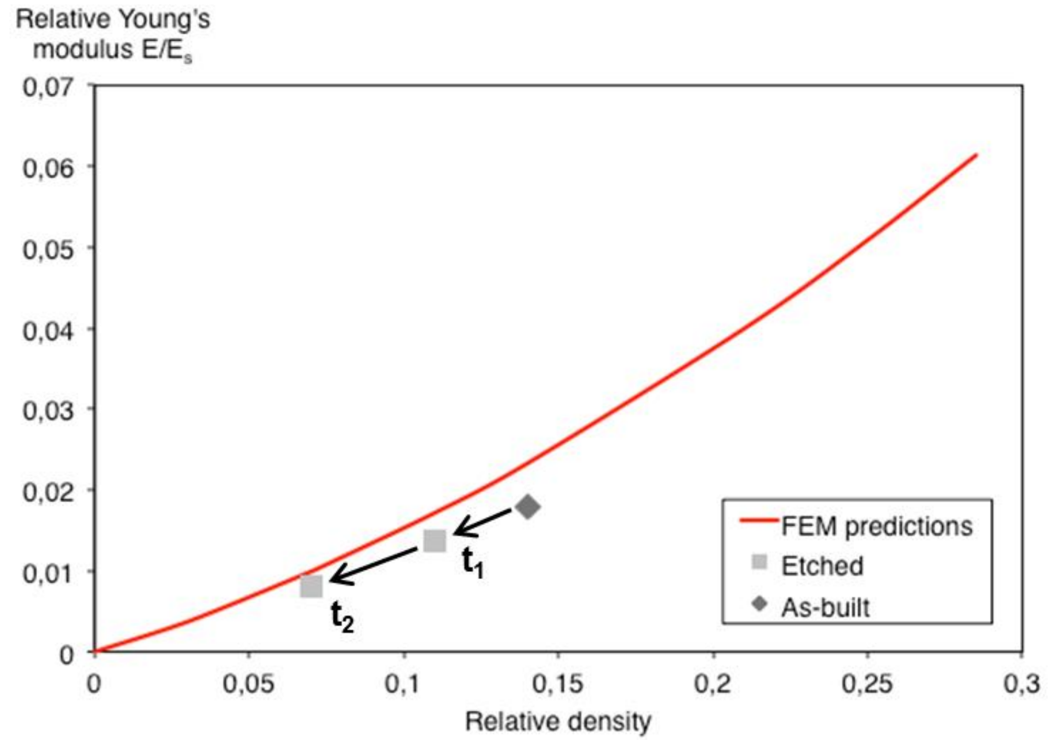
Then, electrochemical polishing is used to make the surface of the part more uniform and smooth.



CE + ECP leads to a significant loss in strut thickness, which should be taken into account anticipatively in the design of the structure.

Etching results in a mechanical behavior closer to the « ideal » FEM predictions





Chemical etching results in an increase in the proportion of mechanically efficient matter

The relative difference between the measured and the theoretical stiffness decreases as the etching time increases.

de Formanoir, Charlotte, et al. "Improving the mechanical efficiency of electron beam melted titanium lattice structures by chemical etching." *Additive Manufacturing* 11 (2016): 71-76.

Effect of post-processing on fatigue

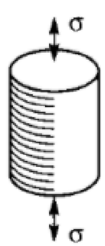
Experimental approach

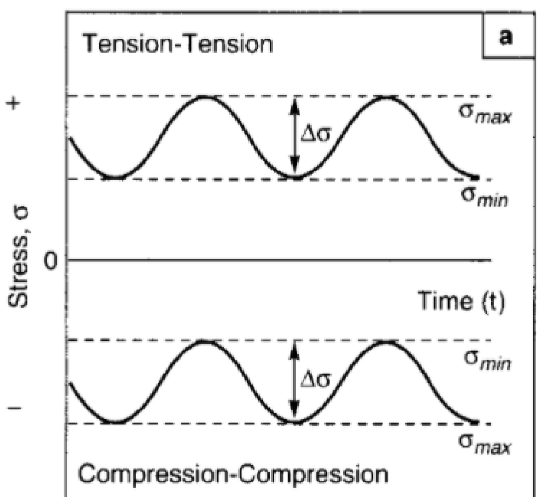
Ultrasonic cleaning
Thermal treatment: SR, HIP
Surface treatment: CE, ECP

AS-BUILT SCAFFOLD ρ_{rel_AB}

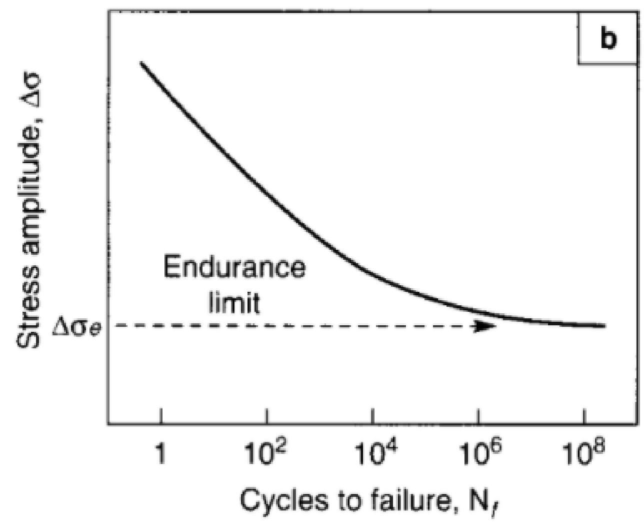
FINAL SCAFFOLD $\rho_{rel\_f} < \rho_{rel\_AB}$

Fatigue testing



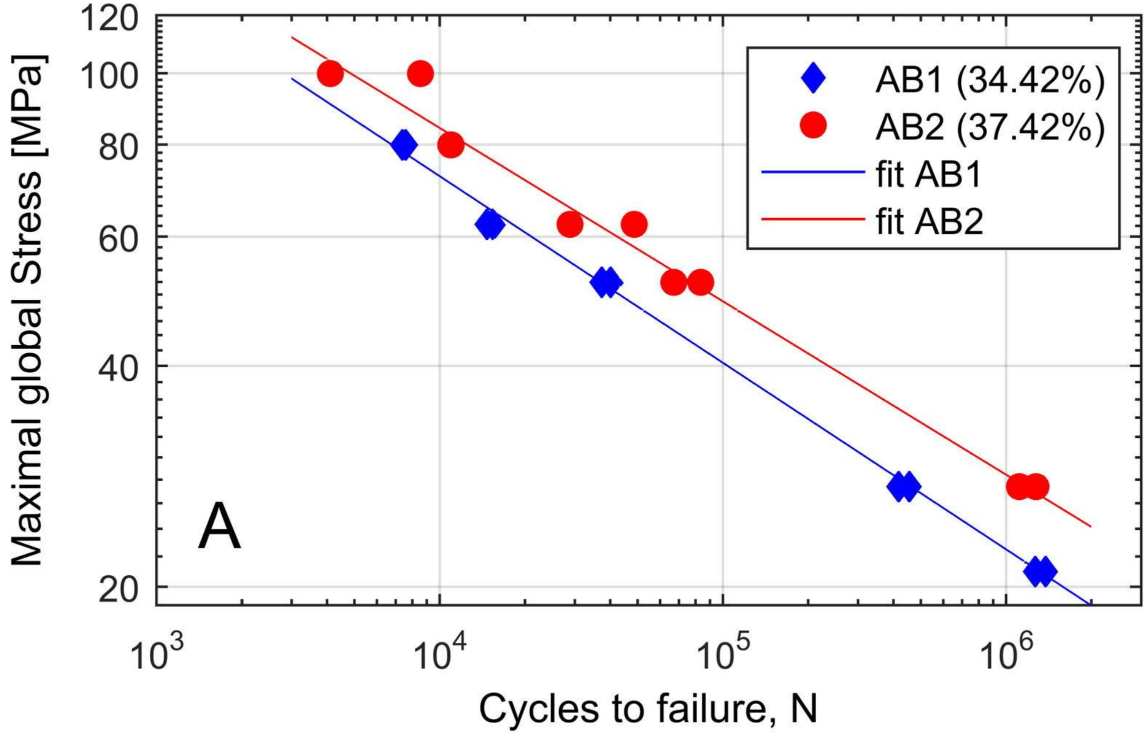


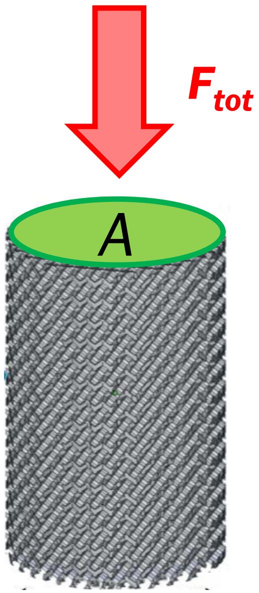
Wöhler curve



Global stress approach

Behavior of the porous material as a whole: a higher relative density results in an increased fatigue life.





$$\sigma = \frac{F_{tot}}{A}$$

How do we account for the difference in relative density when comparing the fatigue behavior before and after post-processing?

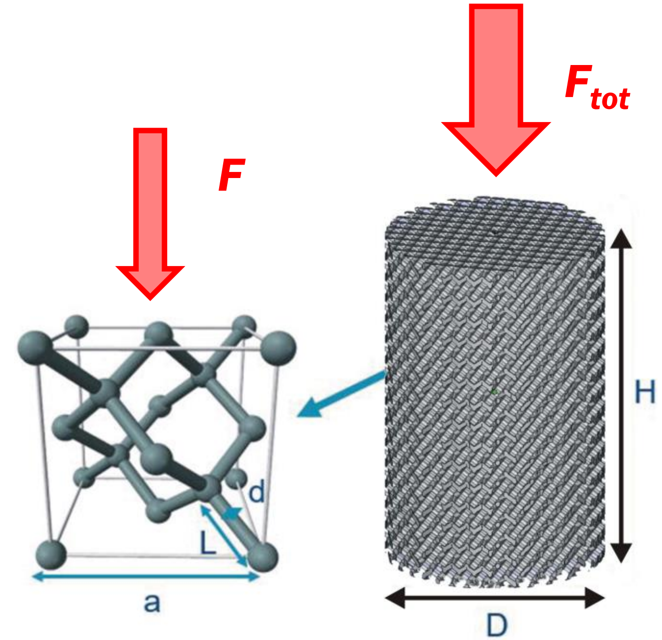
Van Hooreweder, Brecht, et al. "Improving the fatigue performance of porous metallic biomaterials produced by Selective Laser Melting." *Acta biomaterialia* 47 (2017): 193-202.

Local stress method

$$S_B = \frac{My}{I} = \frac{FLd\cos\theta}{4I} \quad \text{with:}$$

$$I = \frac{\pi d^4}{64} \qquad y = \frac{d}{2} \qquad M = \frac{1}{2}FL\cos\theta$$

$$S_A = \frac{F\sin\theta}{A} \quad \text{with} \quad A = \frac{\pi d^2}{4}$$

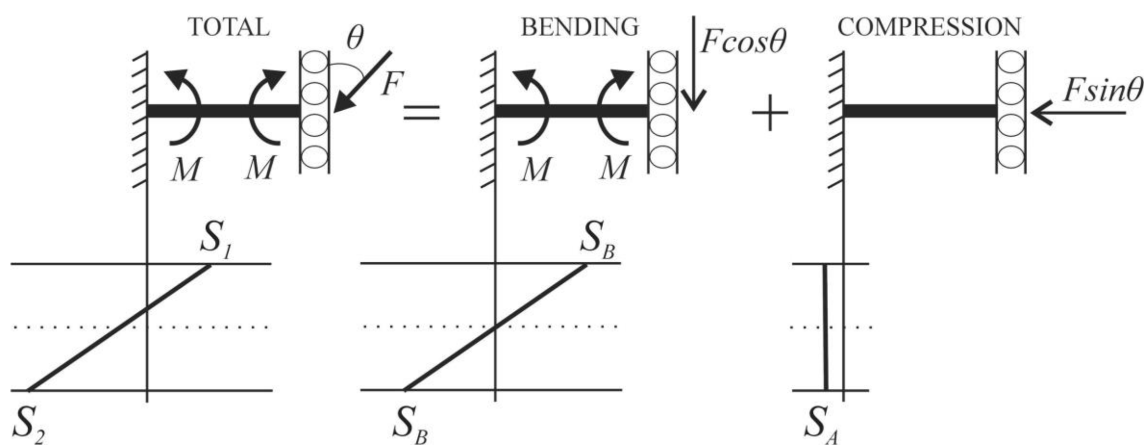


Maximum tensile stress in the struts:

$$S_1 = S_B - S_A = F\left(\frac{16L\cos\theta}{\pi d^3} - \frac{4\sin\theta}{\pi d^2}\right)$$

$$F = \frac{F_{tot}}{number\ of\ load\ bearing\ struts}$$

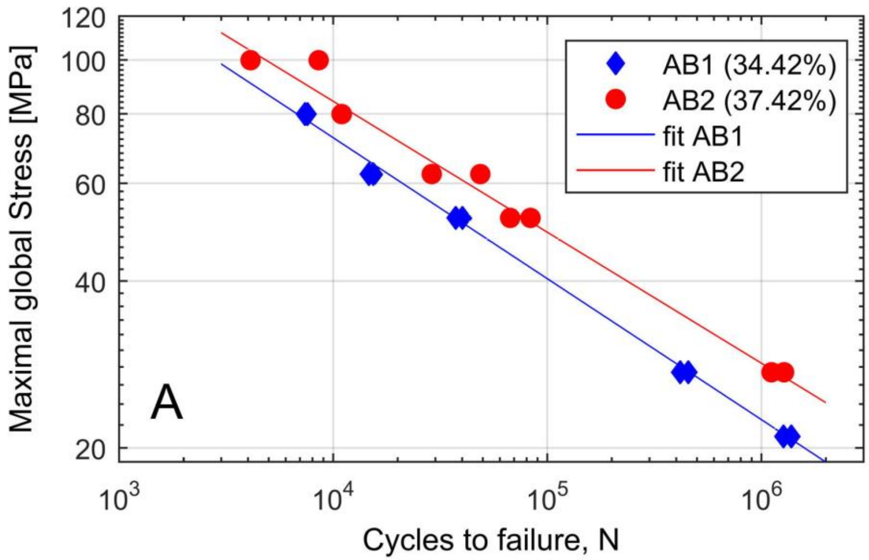
Compression-compression formulation



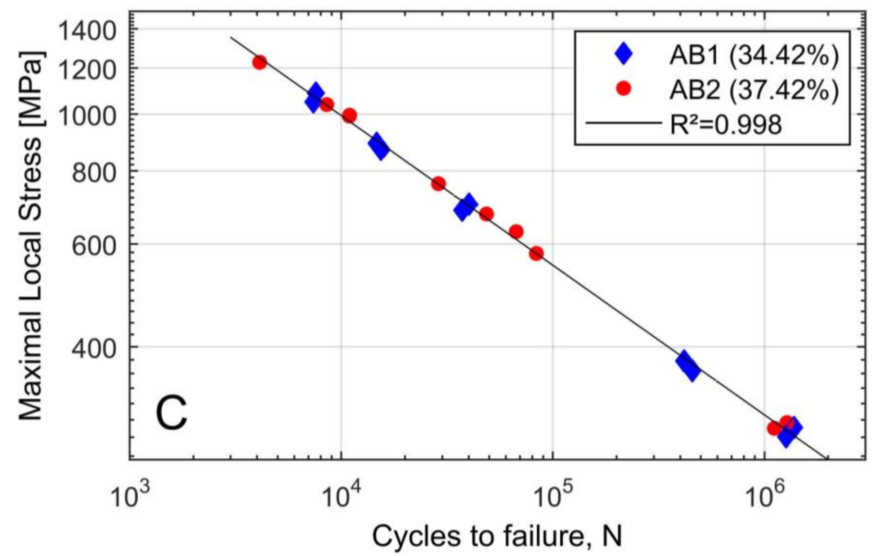
Van Hooreweder, Brecht, et al. "Improving the fatigue performance of porous metallic biomaterials produced by Selective Laser Melting." *Acta biomaterialia* 47 (2017): 193-202.

Fatigue performance: LSM vs global

Ti-6Al-4V



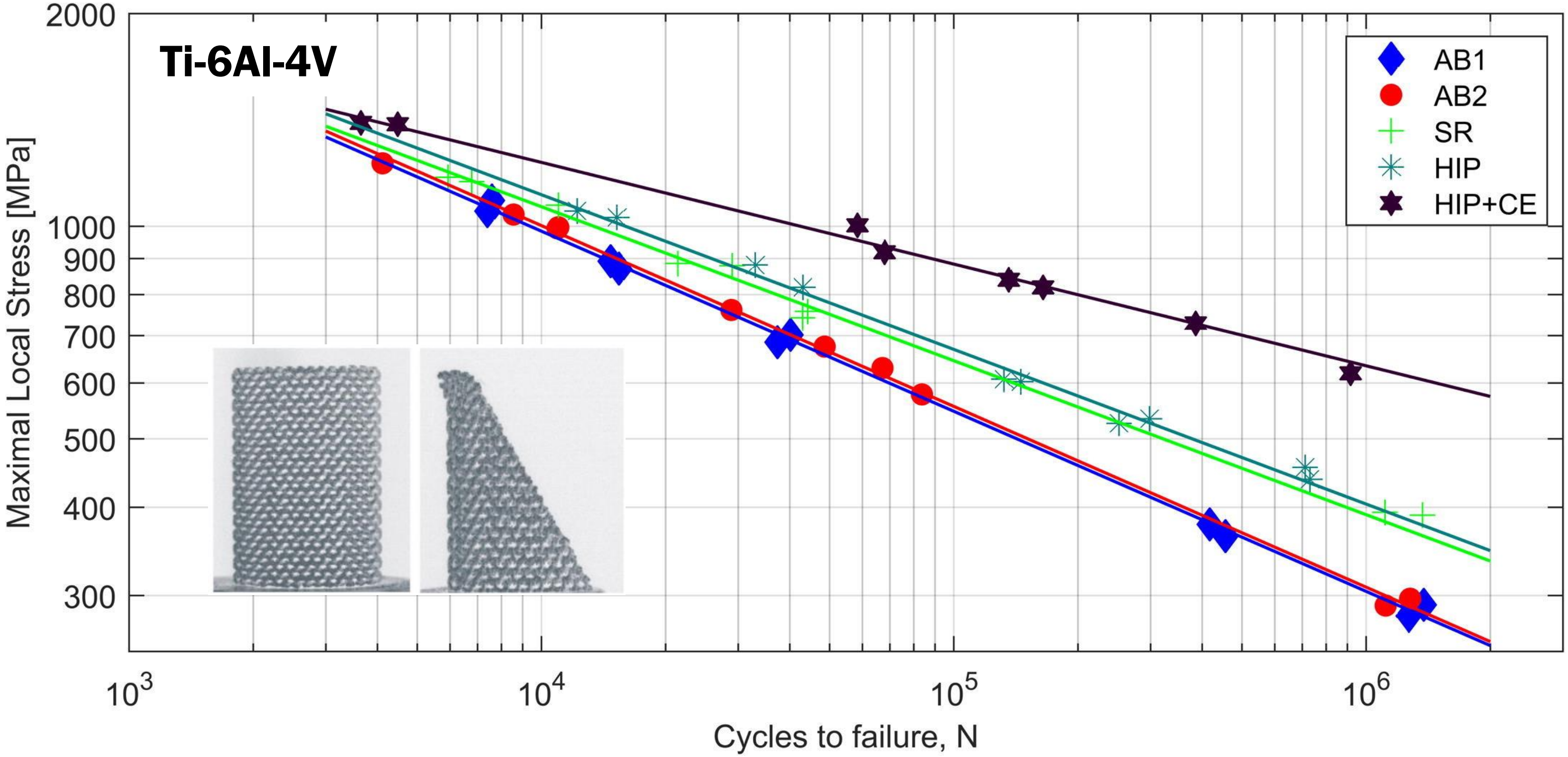
Global method



Local Stress Method

Van Hooreweder, Brecht, et al. "Improving the fatigue performance of porous metallic biomaterials produced by Selective Laser Melting." *Acta biomaterialia* 47 (2017): 193-202.

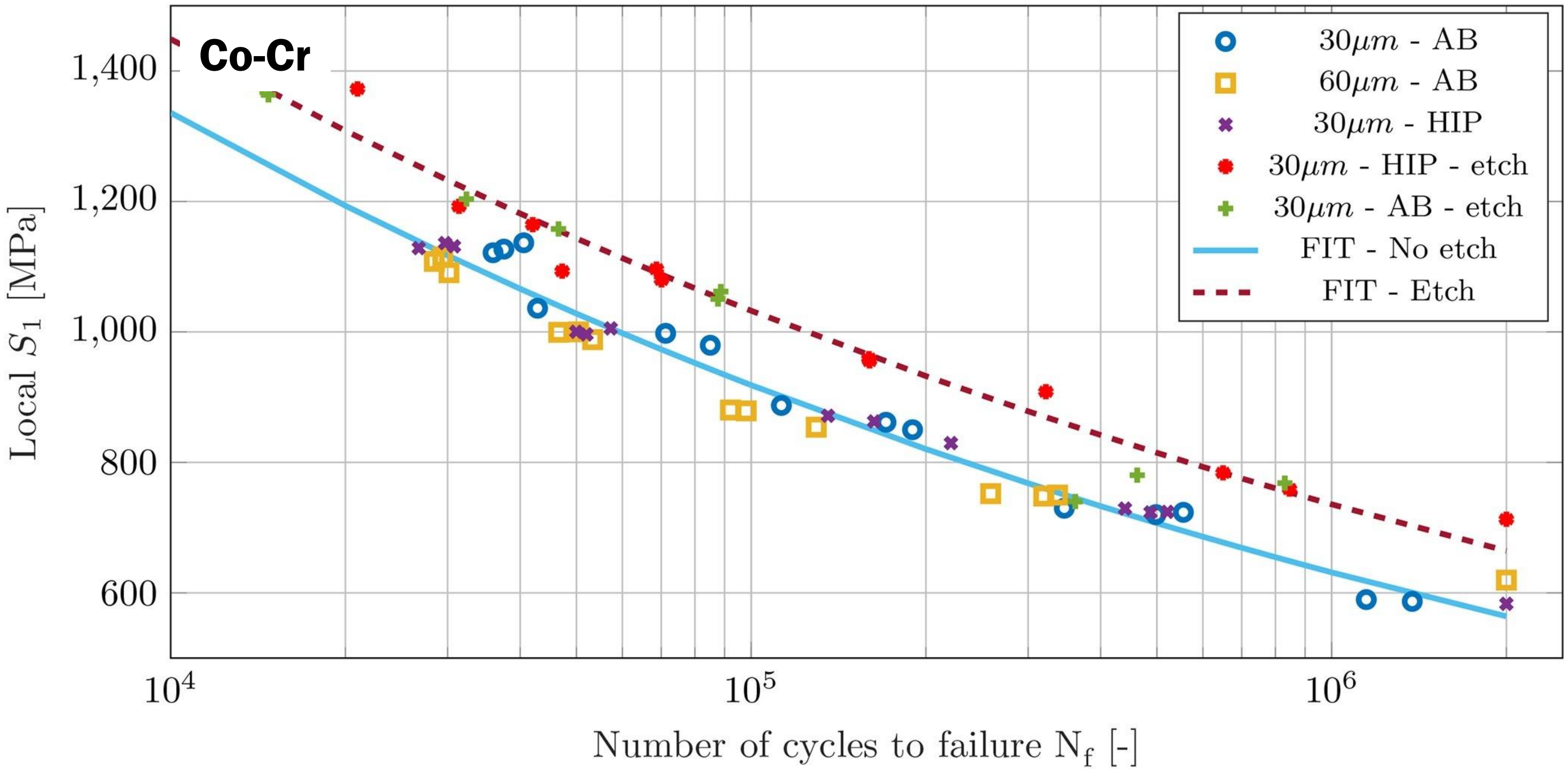
Fatigue performance: effect of post-treatments



Chemical etching significantly improves the mechanical efficiency of the structure.
In Ti64, SR and HIP improve the fatigue life to some extent.

Van Hooreweder, Brecht, et al. "Improving the fatigue performance of porous metallic biomaterials produced by Selective Laser Melting." *Acta biomaterialia* 47 (2017): 193-202.

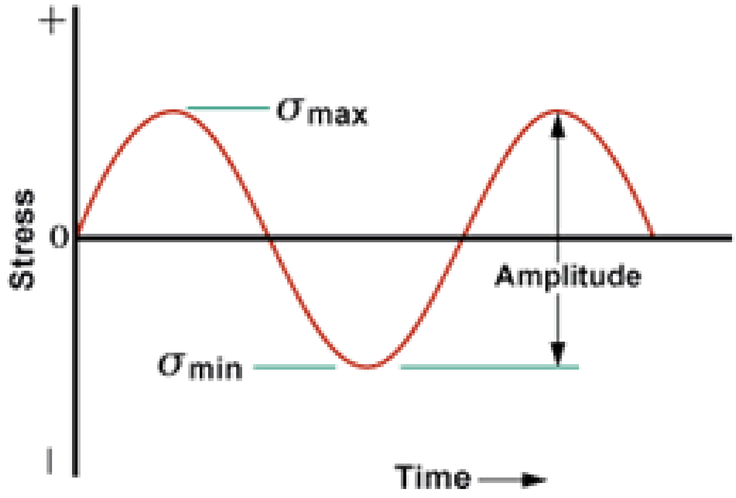
Fatigue performance: effect of post-treatments



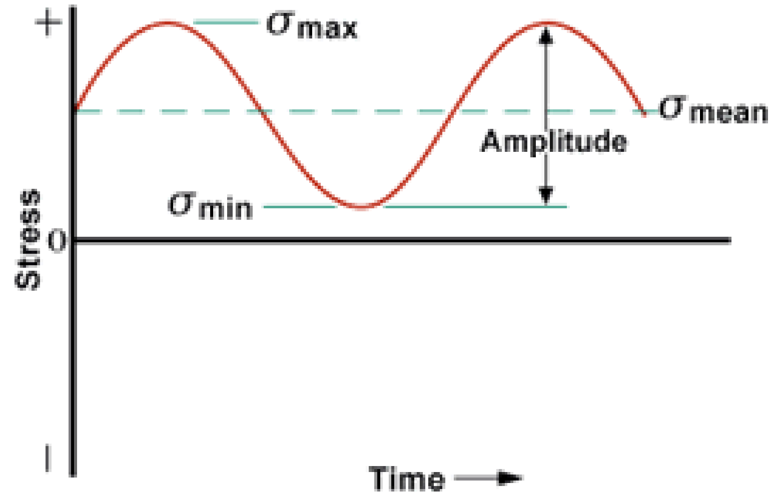
Chemical etching significantly improves the mechanical efficiency of the structure.
In Co-Cr, there is no clear effect of HIP on the fatigue life.

Cutolo, Antonio, et al. "Influence of layer thickness and post-process treatments on the fatigue properties of CoCr scaffolds produced by laser powder bed fusion." *Additive Manufacturing* 23 (2018): 498-504.

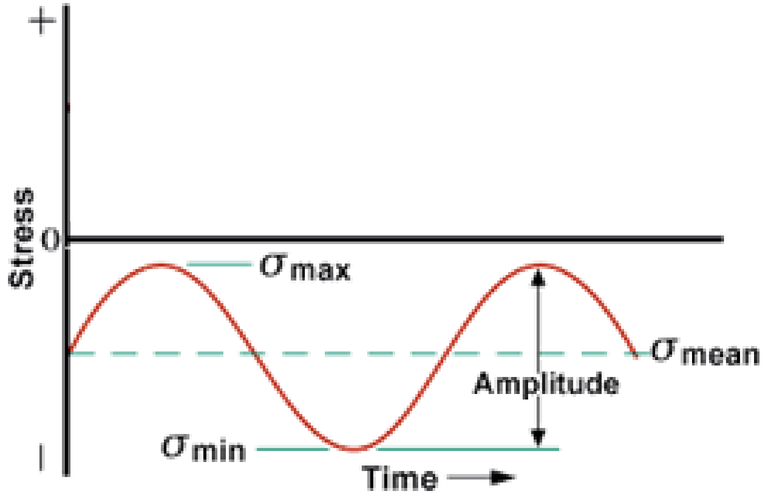
Fatigue performance: effect of loading conditions



Tension-compression



Tension-tension



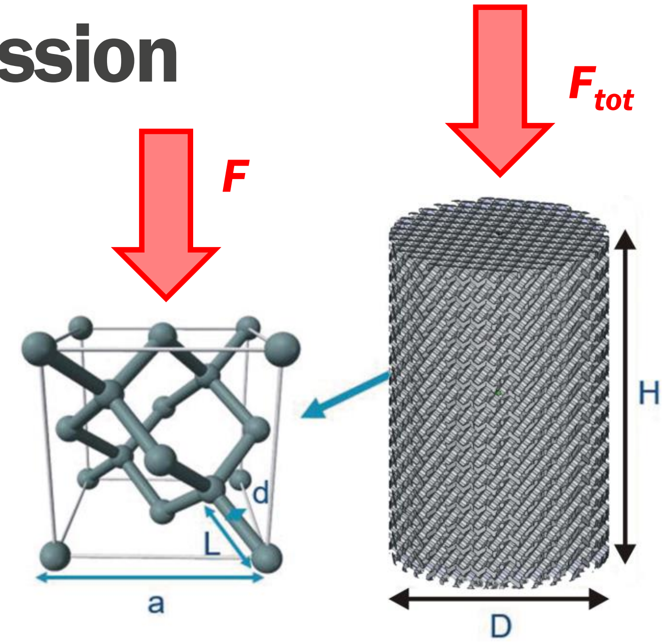
Compression-compression

Local stress method - compression

$$S_B = \frac{My}{I} = \frac{FLd\cos\theta}{4I}$$ with:

$$I = \frac{\pi d^4}{64} \qquad y = \frac{d}{2} \qquad M = \frac{1}{2}FL\cos\theta$$

$$S_A = \frac{F\sin\theta}{A}$$ with $A = \frac{\pi d^2}{4}$

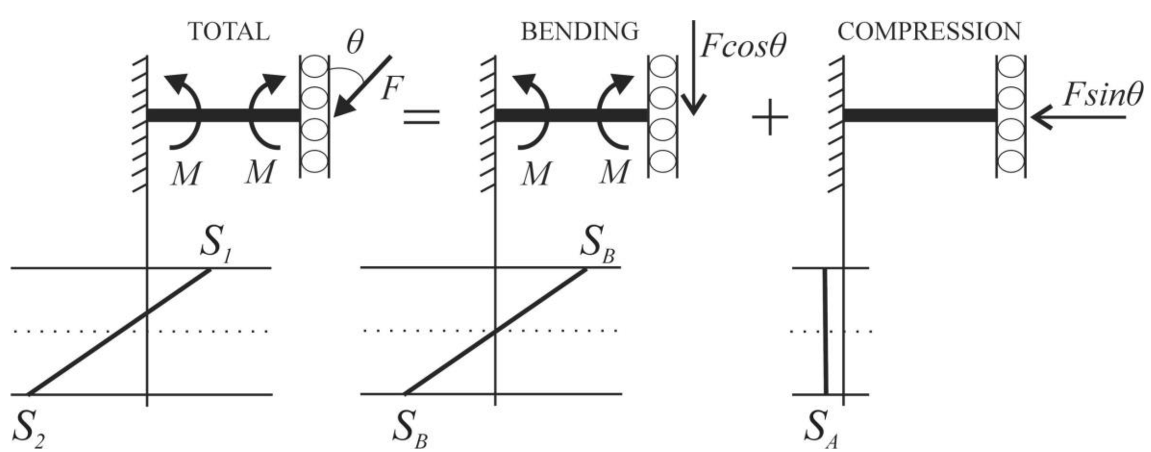


Maximum tensile stress in the struts:

$$S_1 = S_B - S_A = F\left(\frac{16L\cos\theta}{\pi d^3} - \frac{4\sin\theta}{\pi d^2}\right)$$

$$F = \frac{F_{tot}}{number\ of\ load\ bearing\ struts}$$

Compression-compression formulation

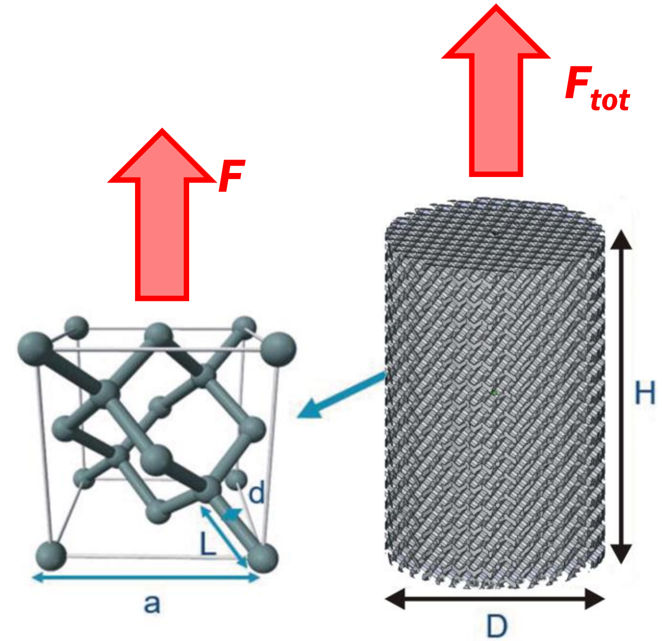


Local stress method - tension

$$S_B = \frac{My}{I} = \frac{FLd\cos\theta}{4I} \quad \text{with:}$$

$$I = \frac{\pi d^4}{64} \qquad y = \frac{d}{2} \qquad M = \frac{1}{2}FL\cos\theta$$

$$S_A = \frac{F\sin\theta}{A} \quad \text{with} \quad A = \frac{\pi d^2}{4}$$

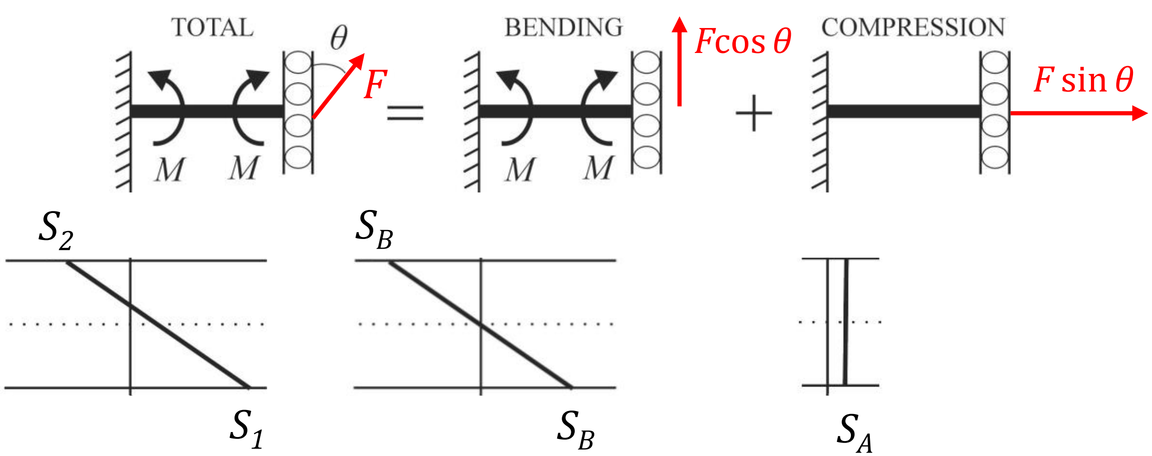


Maximum tensile stress in the struts:

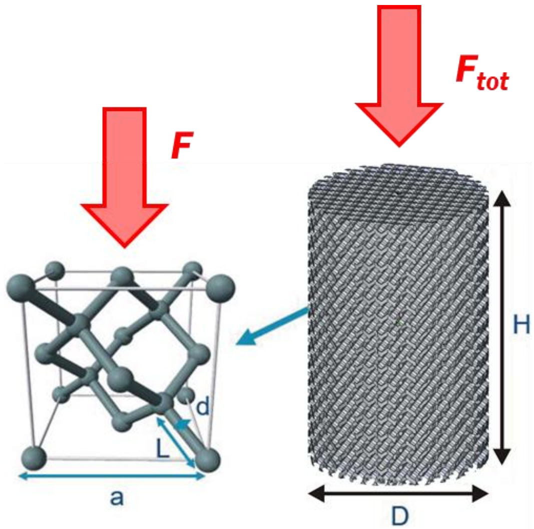
$$\boxed{S_1 = S_B + S_A = F\left(\frac{16L\cos\theta}{\pi d^3} + \frac{4\sin\theta}{\pi d^2}\right)}$$

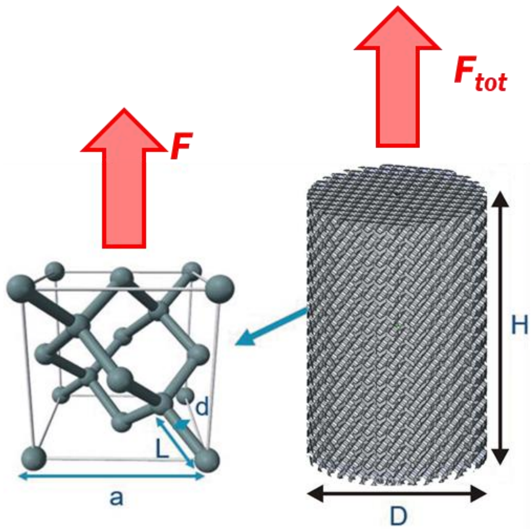
$$F = \frac{F_{tot}}{number\ of\ load\ bearing\ struts}$$

Tension-tension formulation



Fatigue performance: effect of loading conditions





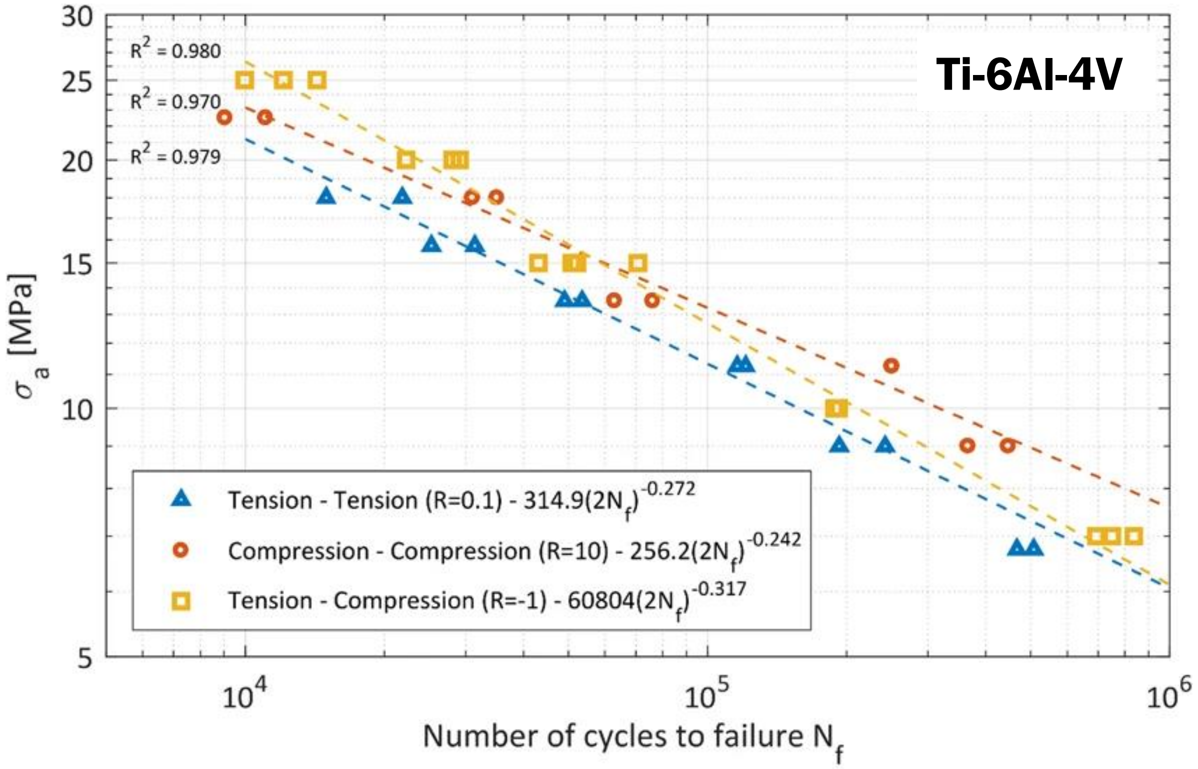
$$S_1 = S_B - S_A = F\left(\frac{16L\cos\theta}{\pi d^3} - \frac{4\sin\theta}{\pi d^2}\right) < S_1 = S_B + S_A = F\left(\frac{16L\cos\theta}{\pi d^3} + \frac{4\sin\theta}{\pi d^2}\right)$$

The same absolute global stress value generates a higher maximum tensile stress in tension than in compression.

$\Rightarrow$ **Lattice structures have a shorter fatigue life when they are loaded in tension than when they are loaded in compression**

Lietaert, Karel, et al. "Fatigue life of additively manufactured Ti6Al4V scaffolds under tension-tension, tension-compression and compression-compression fatigue load." *Scientific reports* 8.1 (2018): 1-9.

Fatigue performance: effect of loading conditions



The same absolute global stress value generates a higher maximum tensile stress in tension than in compression.

⇒ **Lattice structures have a shorter fatigue life when they are loaded in tension than when they are loaded in compression**

Lietaert, Karel, et al. "Fatigue life of additively manufactured Ti6Al4V scaffolds under tension-tension, tension-compression and compression-compression fatigue load." *Scientific reports* 8.1 (2018): 1-9.