Lecture 4

Can bio-inspired design useful for designing super resistant structures?

Some recent results

in collaboration with M. Maurizi and C. Gao

What is BiE

(1452 –1519)

"Nature is the source of all true knowledge. She has her own logic, her own laws, she has no effect without cause nor invention without necessity. "

"Human subtlety will never devise an invention more beautiful, more simple or more direct than does nature because in her inventions nothing is lacking, and nothing is superfluous. "

- Leonardo da Vinci

(1881 –1963)

Scientists discover what is, engineers create what never was.

--Theodore von Kármán

BiE (Bionics, Biomimetics, Bio-Inspired design)

A new interdisciplinary scientific discipline that discovers and implements biological principles and functionality to new engineering solutions/technology.

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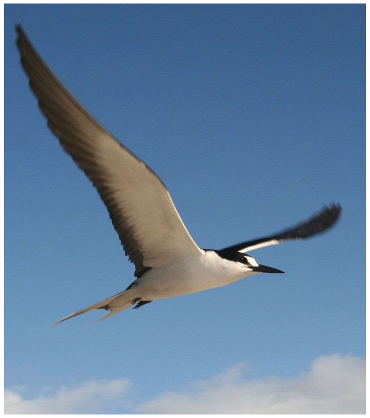
https://www.youtube.com/watch?v=gzm7yD-JuyM

https://www.youtube.com/watch?v=7R5-3UKFRvY

Examples

Birds: implementation of a principle (flying by buoyancy)



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

Shells: implementation of design (composite material)

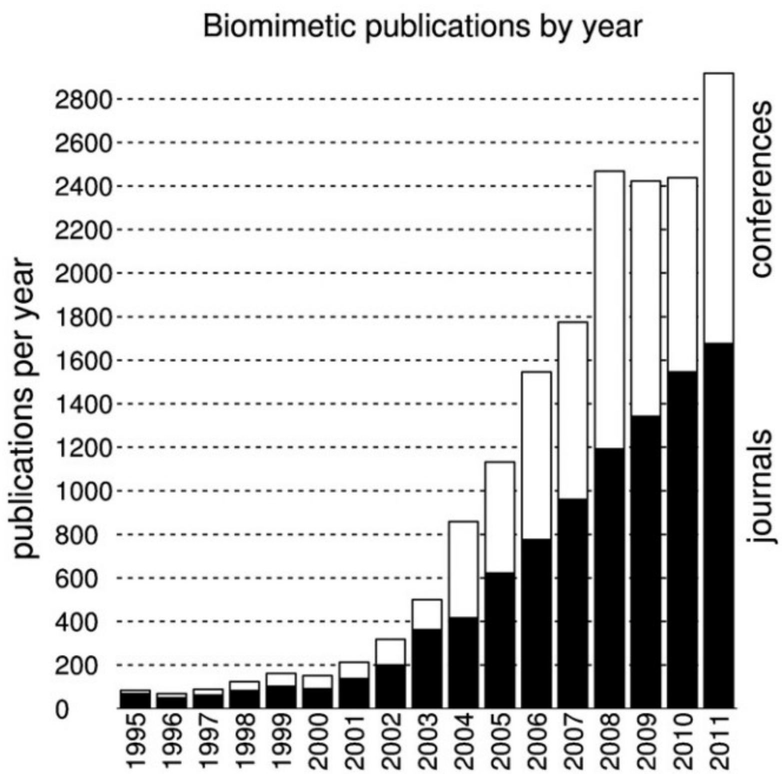
https://asknature.org/strategy/siphuncle-controls-buoyancy/

Gecko: Implementation of functionality (adhesion by structuring)

https://www.nationalgeographic.com

What is BiE

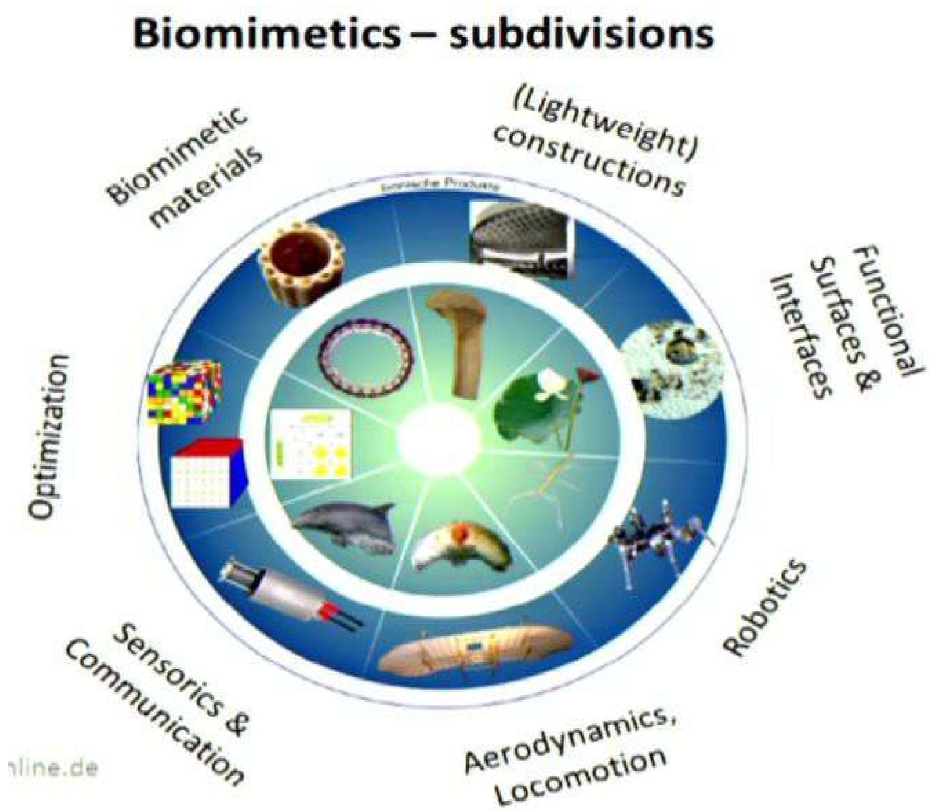
Biomimetics is a rapidly growing field of research worldwide.



A total of approx. 18000 publications

Source: The state of art in biomimetics, Lepora et al. 2013, Bioinspiration and Biomimetics 8, 0130001 (11pages)

What is BiE

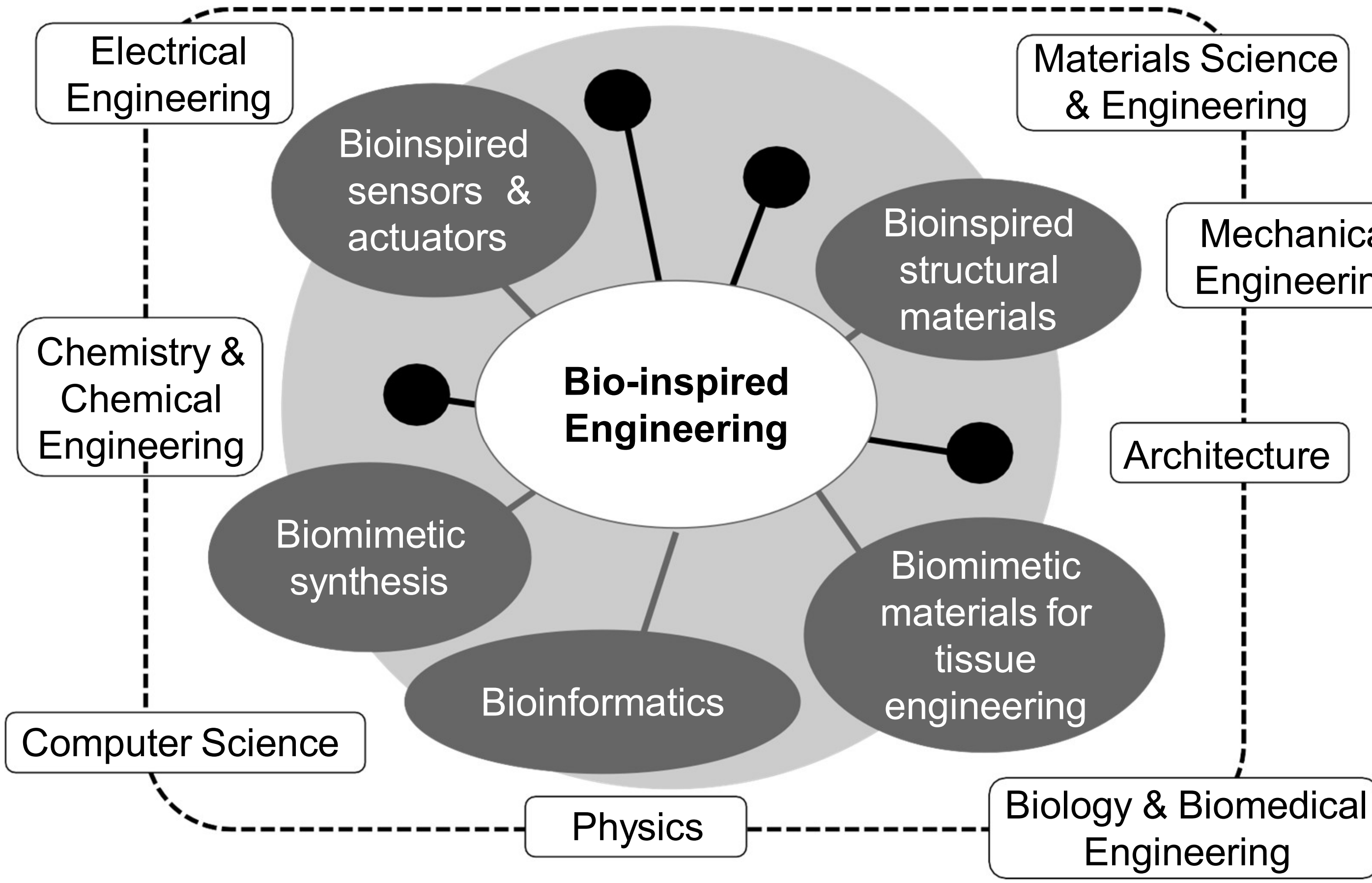


Biomimetics – subdivisions
Biomimetic materials
(Lightweight) constructions
Functional Surfaces & Interfaces
Robotics
Aerodynamics, Locomotion
Sensorics & Communication
Optimization

BiE is truly interdisciplinary!

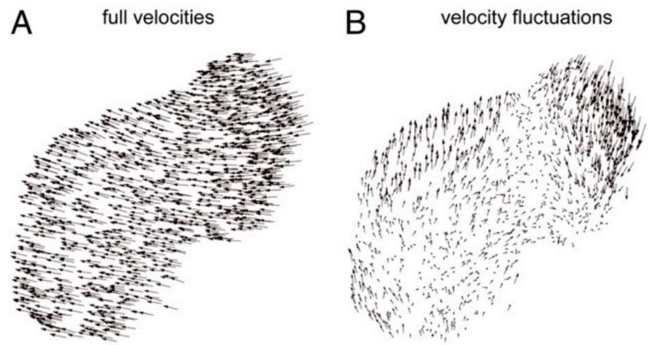
Biological systems are multi-functional!

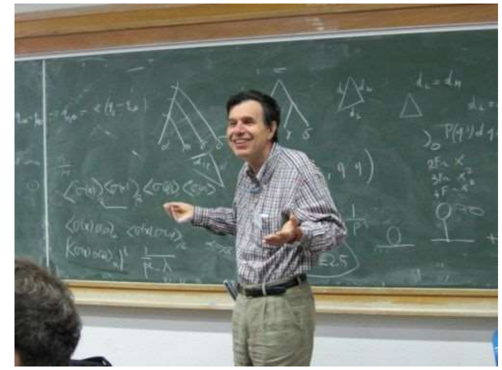
BiE is truly interdisciplinary!



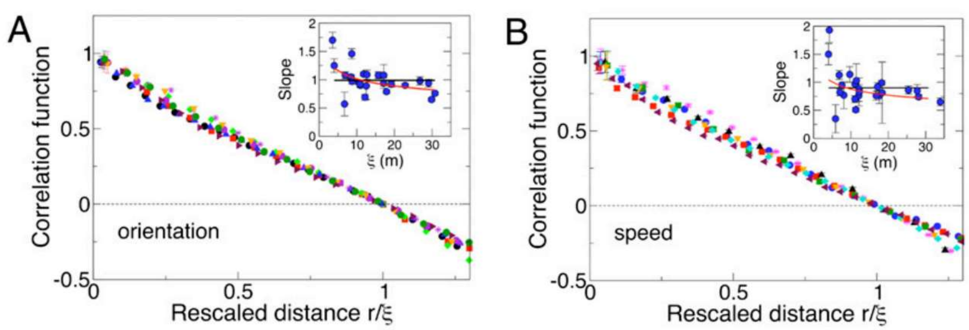
Song, PhD Thesis (2011)

Inspiration from Nature can lead to great achievements





Most studies in collective animal behavior have aimed to understand how a globally ordered state may emerge from simple behavioral rules. Less effort has been devoted to understanding the origin of collective response, namely the way the group as a whole reacts to its environment.

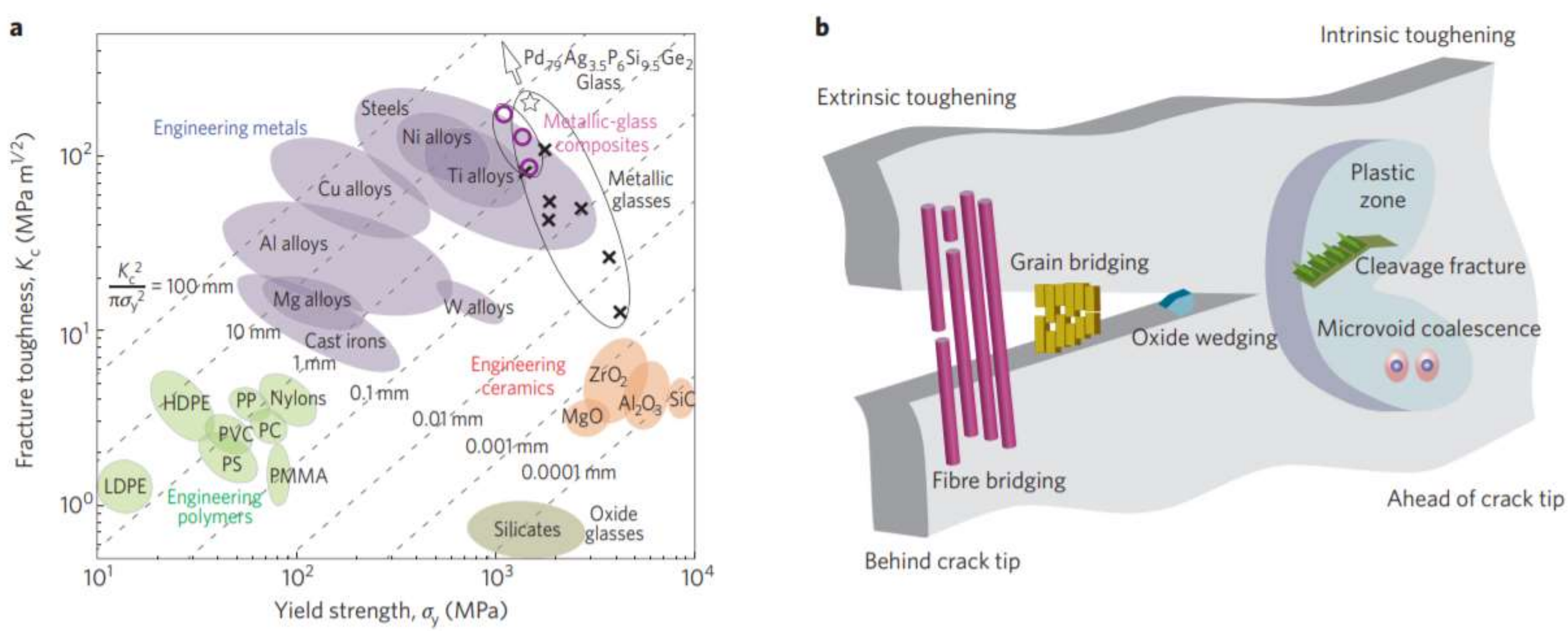


Spatial correlation does not have a constant value, but it scales with the linear size of the flock. This result indicates that behavioral correlations are scale free.

Parisi, PNAS | June 29, 2010 | vol. 107 | no. 26 | 11865–11870

The conflicts between strength and toughness

- The attainment of both strength and toughness is a vital requirement for most structural materials
- Unfortunately, these properties are generally mutually
- Natural structures can defeat the conflict of strength versus toughness achieving unprecedented levels of damage tolerance



Conflicts of strength versus toughness

R. Ritchie (2011), Nature Materials

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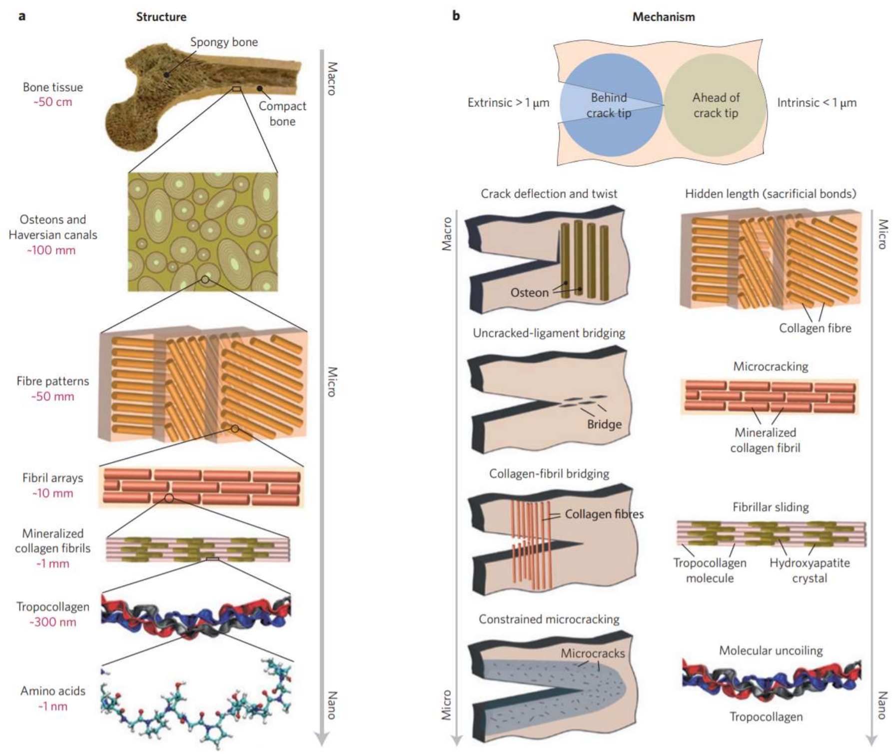


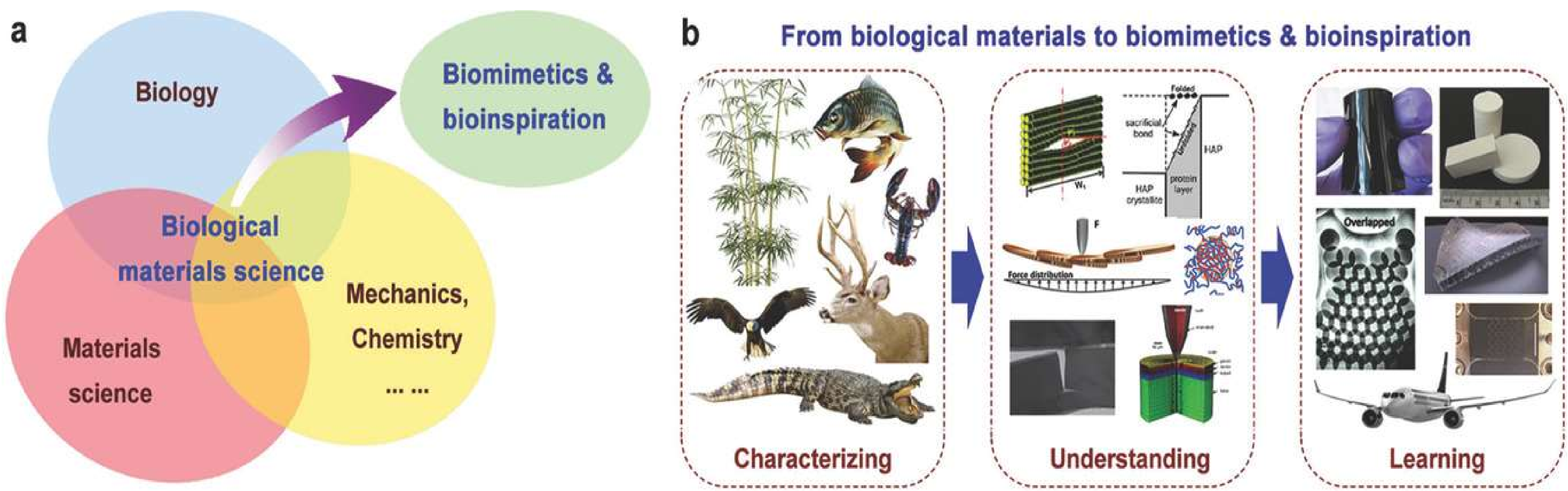
Seven levels of hierarchy

The structure of bone showing the seven levels of hierarchy with the prevailing toughening mechanisms.

R. Ritchie (2011), Nature Materials

Bioinspired Design in Structural Integrity

We have merely “scratched the surface” of trying to mimic these critical properties, which must remain a key focus of the bioinspired design of new smart materials and systems in the future.



R. Ritchie (2019), Advance Materials

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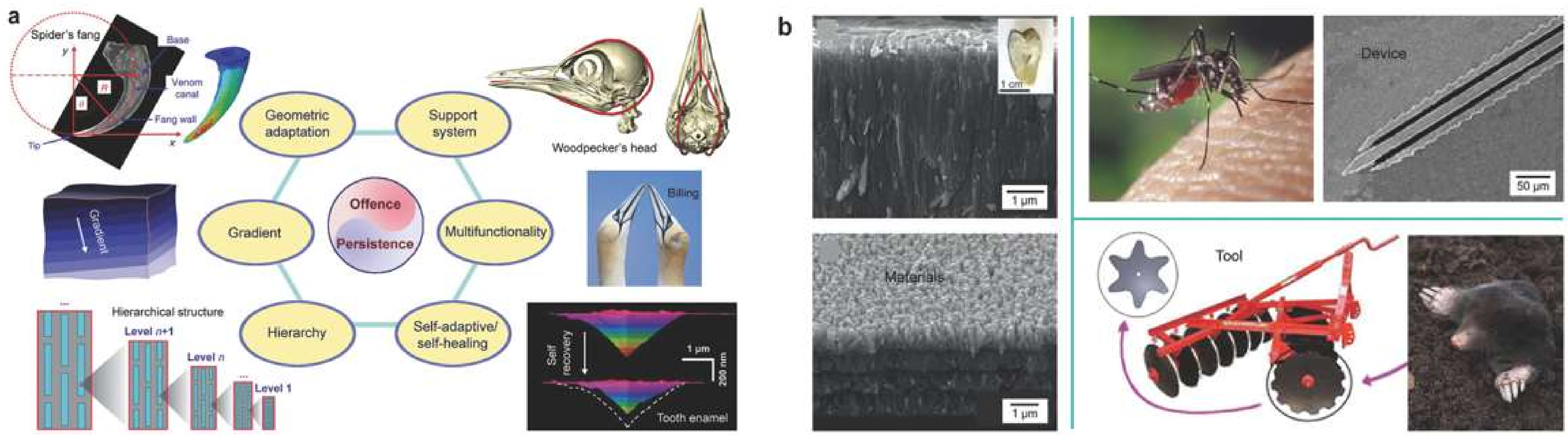

R. Ritchie (2019), Advance Materials

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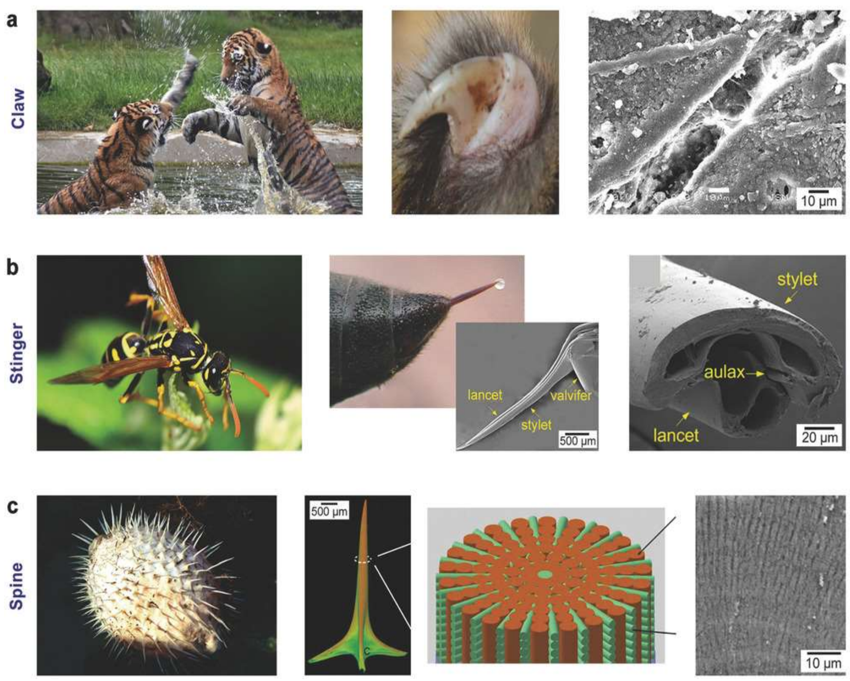

R. Ritchie (2019), Advance Materials

Bioinspired Design in Structural Integrity

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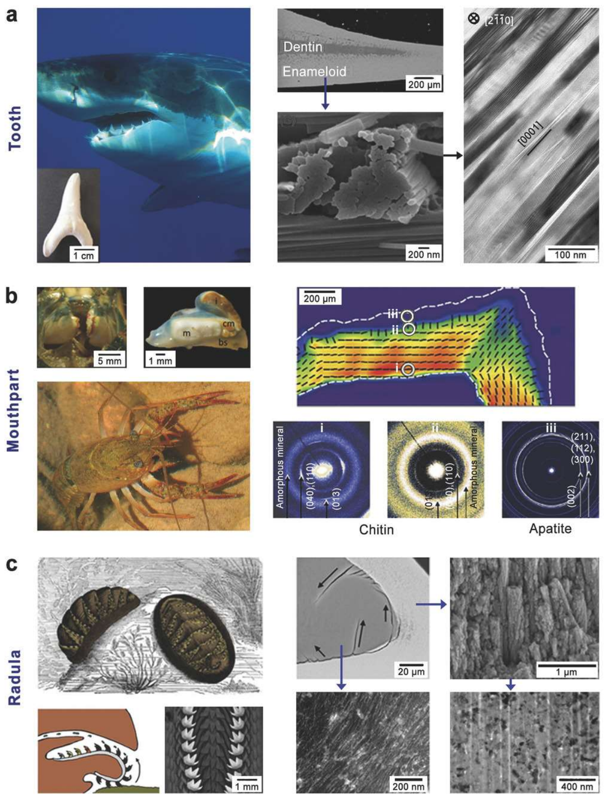
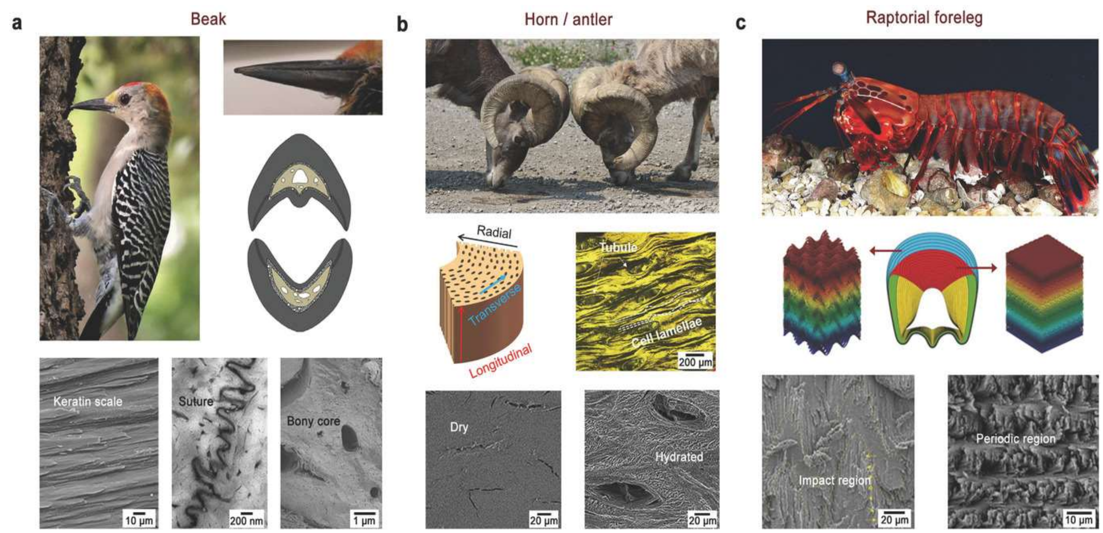
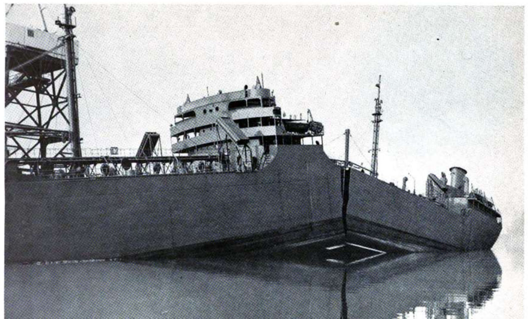




R. Ritchie (2019), Advance Materials


Schenectady ship 1943 (fracture)


Comet airplane 1953 (fracture)

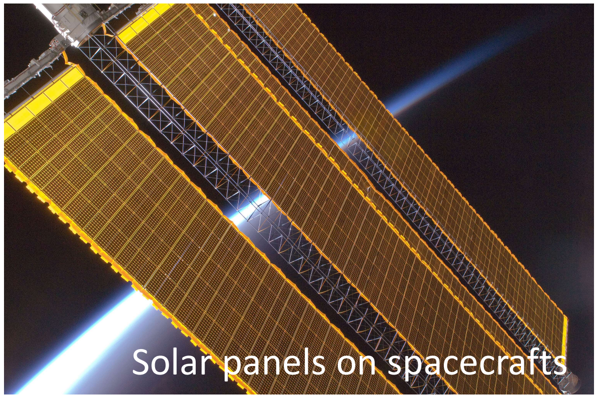
Why ?

Boeing 747 crash 1984 (fatigue fracture)

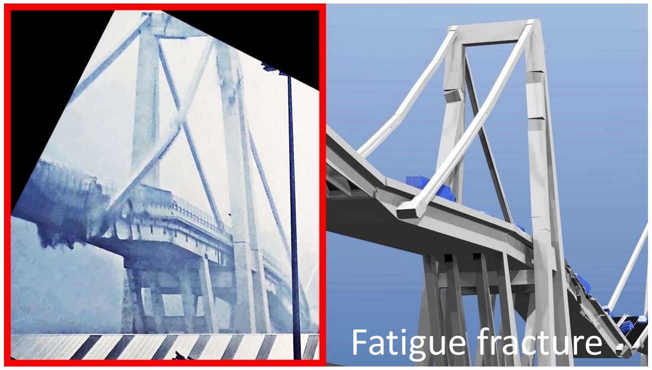

Viareggio rail 2009 (fatigue fracture)


Morandi Bridge 2018 (fatigue fracture)

Dental implant


Solar panels on spacecrafts

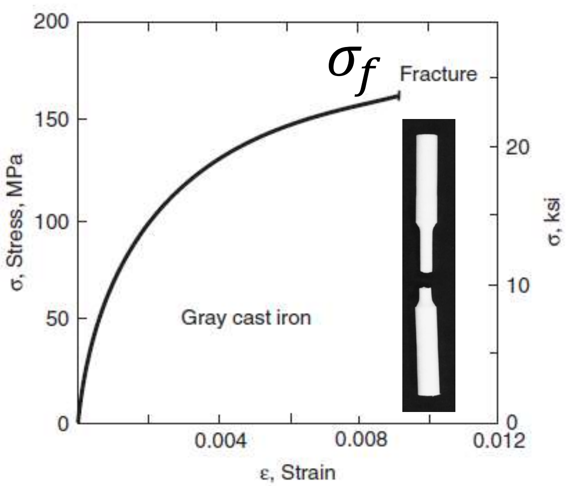
Why ?

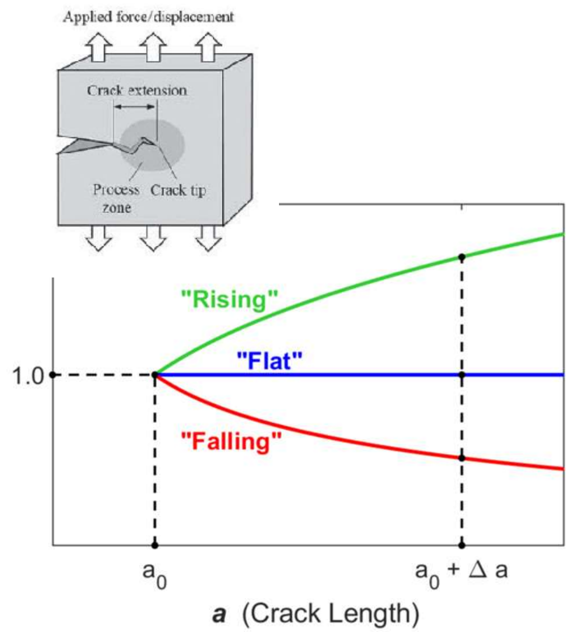

Fatigue fracture

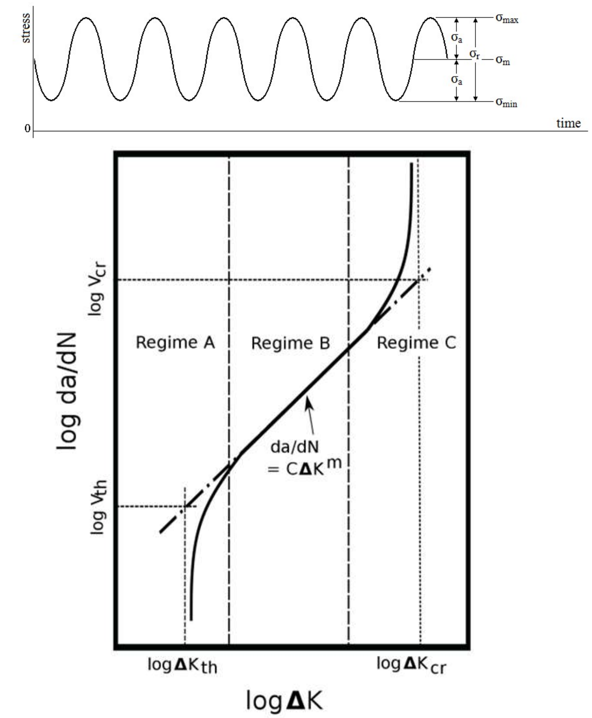

Hip replacement

Strength, fracture toughness and durability (1)

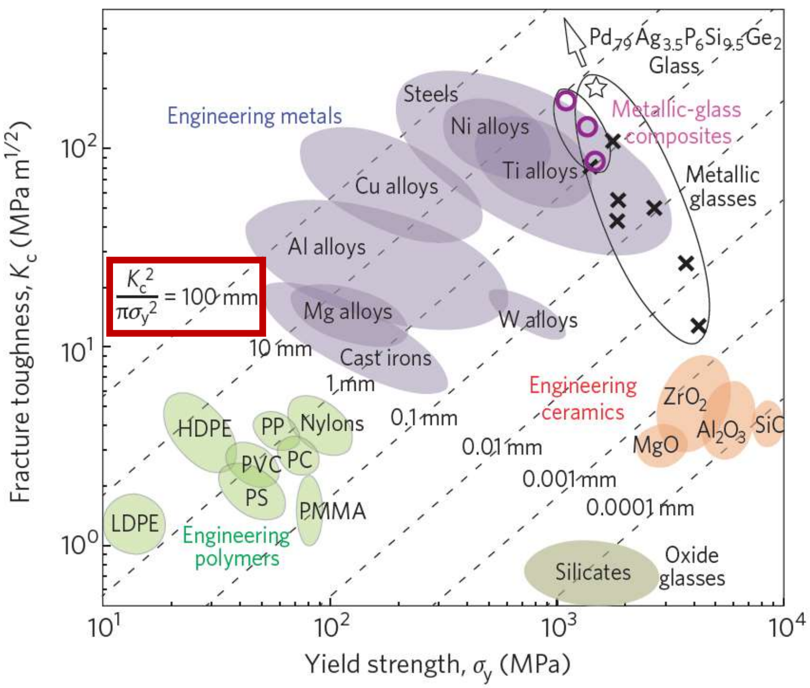
Tensile strength







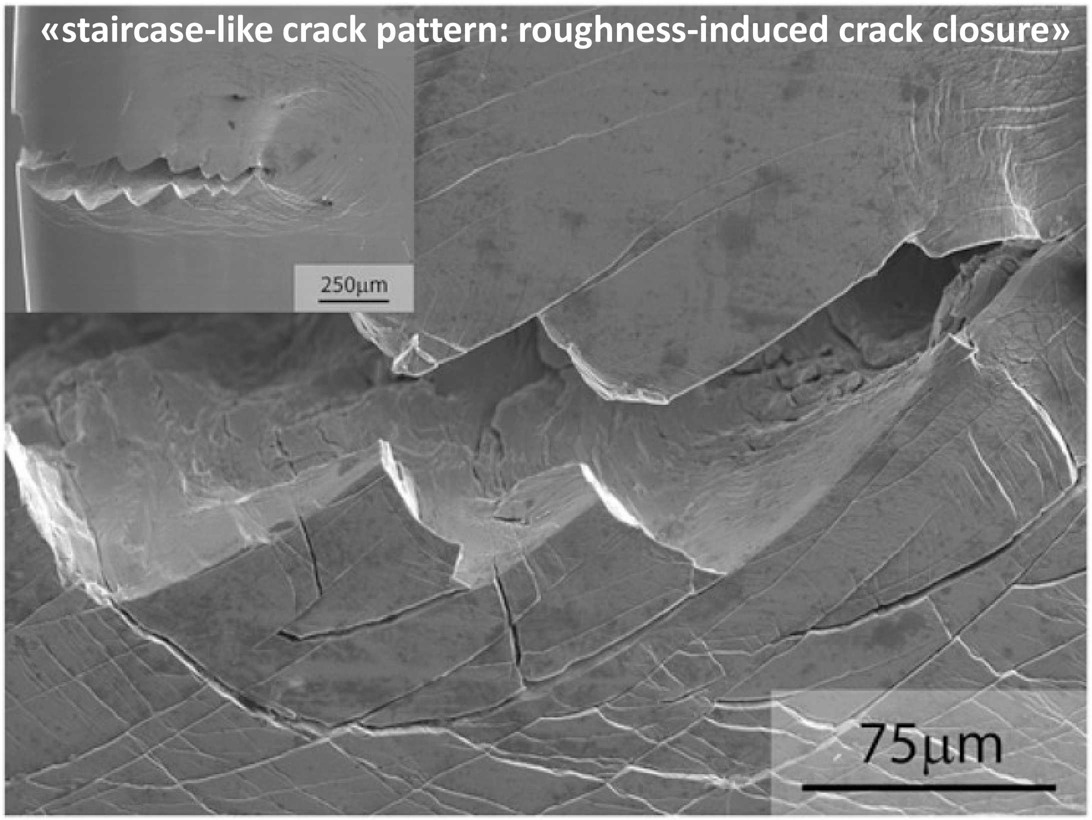
Strength vs. toughness (2)

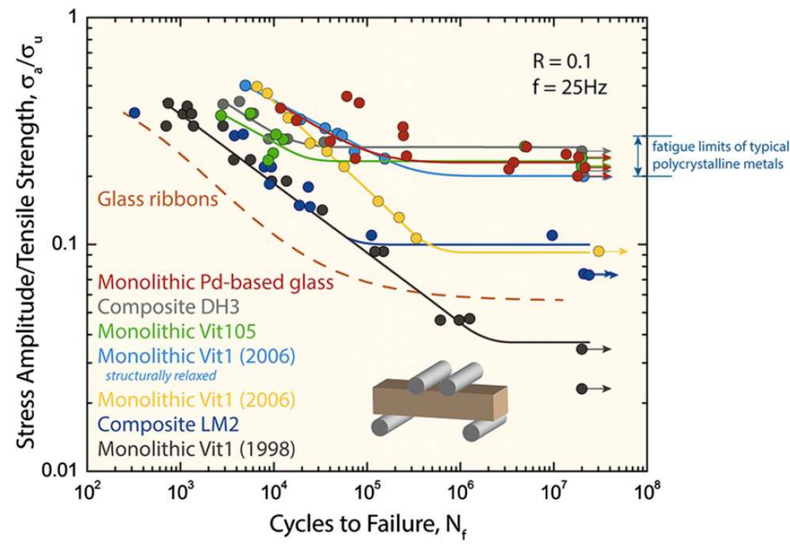


Weak materials tend to be tougher due to ductility, and viceversa !

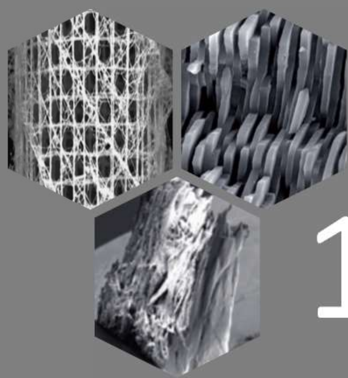
However, toughness can be generated also without ductility (i.e., plastic deformations) !

Fatigue resistance vs. strength (3-4)





Formation and proliferation of shear bands from the crack tip of a propagating fatigue crack during 4-point bending S-N test.

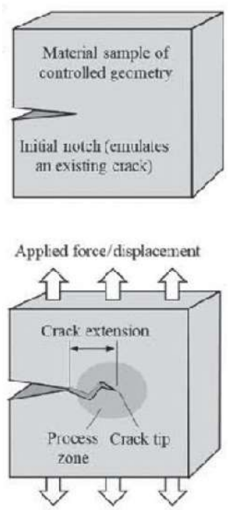


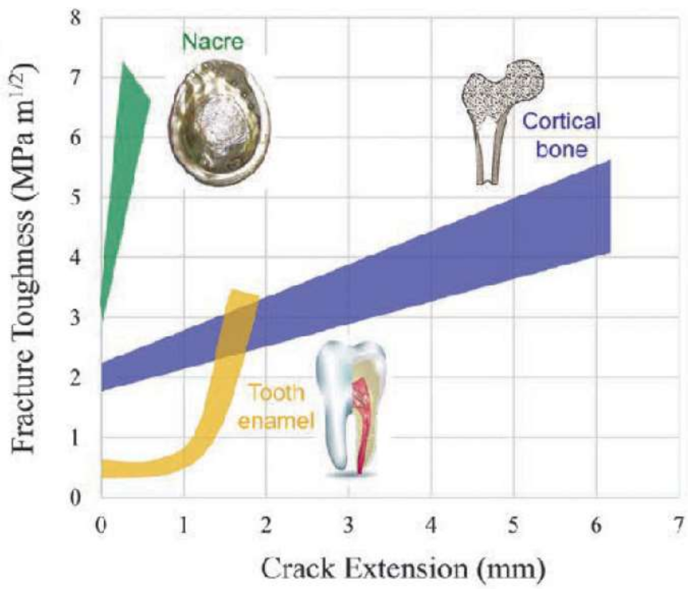
1

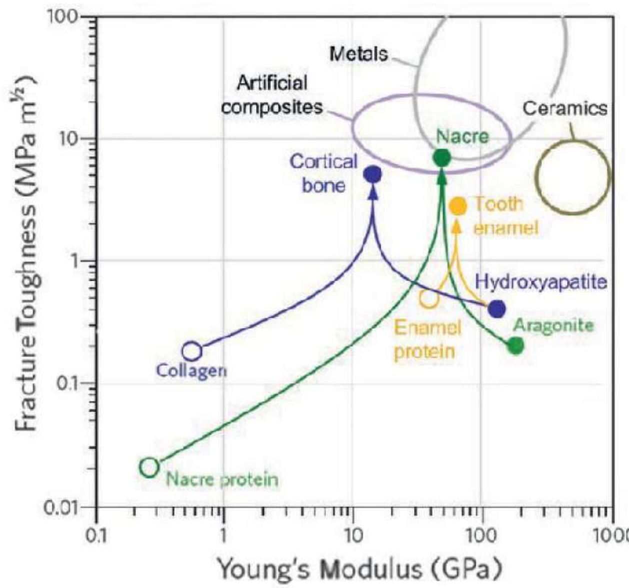
Toughening mechanisms in biological materials

Toughening in natural materials (5)

Rising R-curves



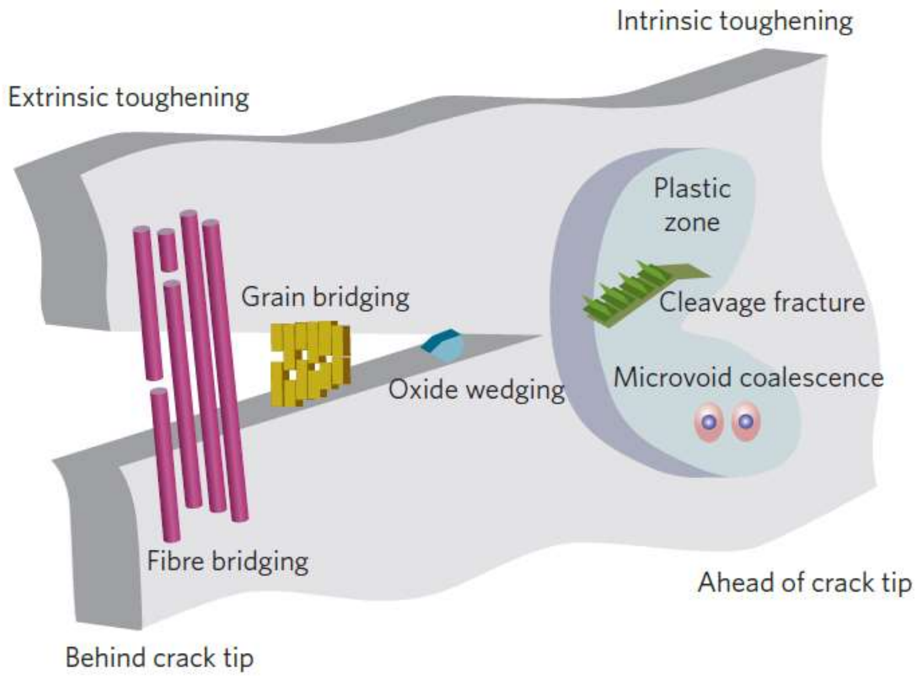




2 – 6 times initial toughness !

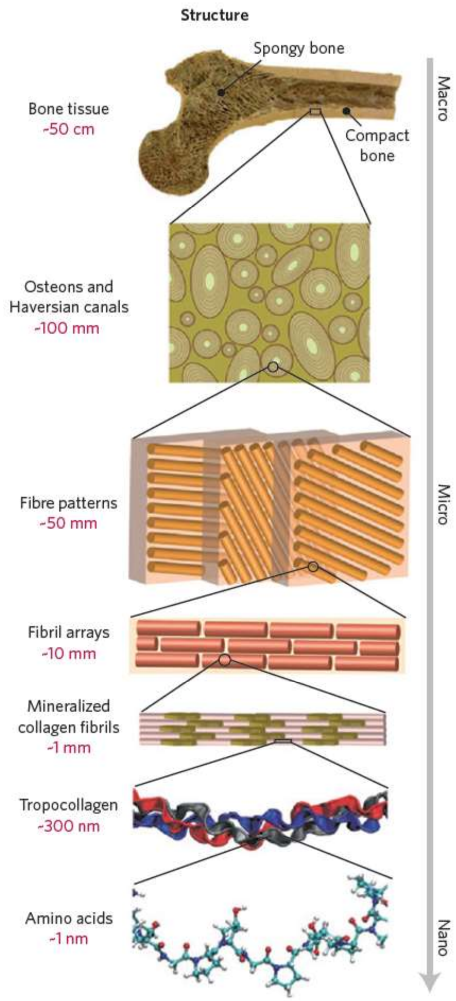
Toughening mechanisms (2)

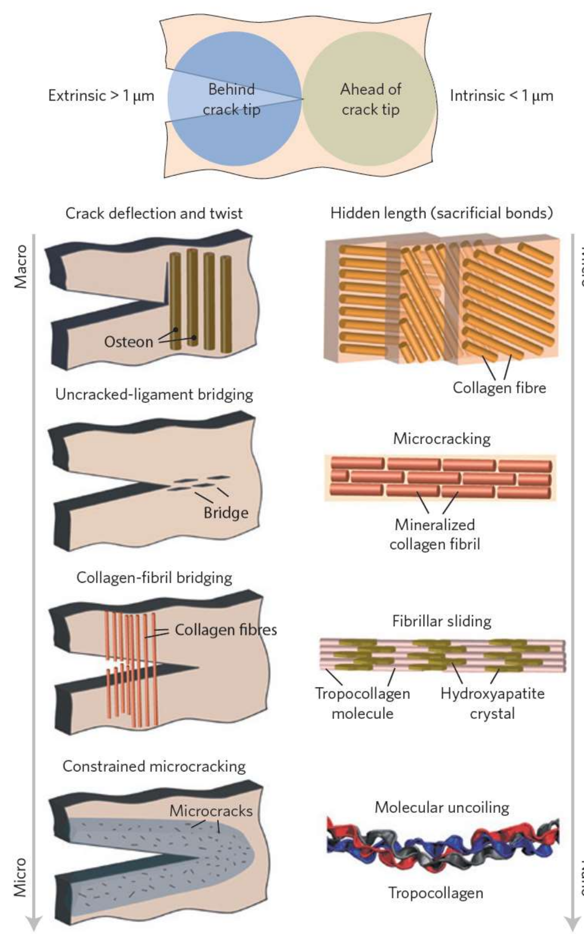
Dominant in **brittle** materials

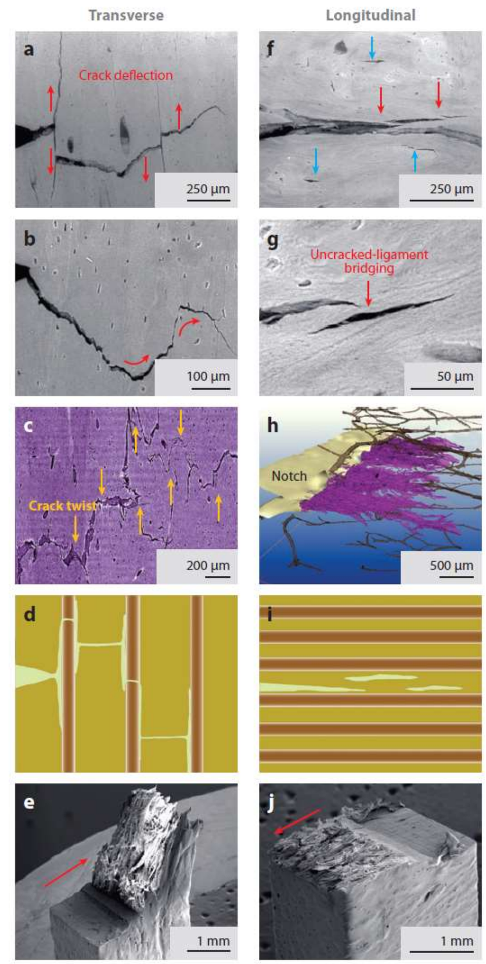


Dominant in **ductile** materials

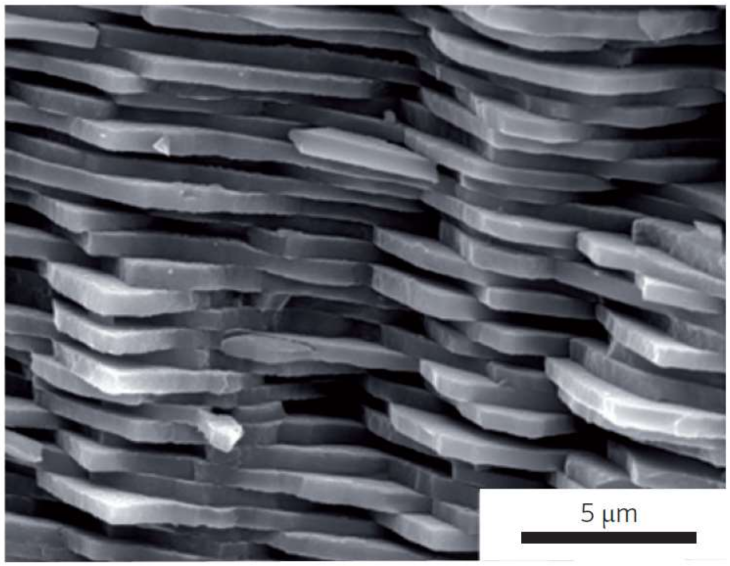
Cortical bone (2,6)



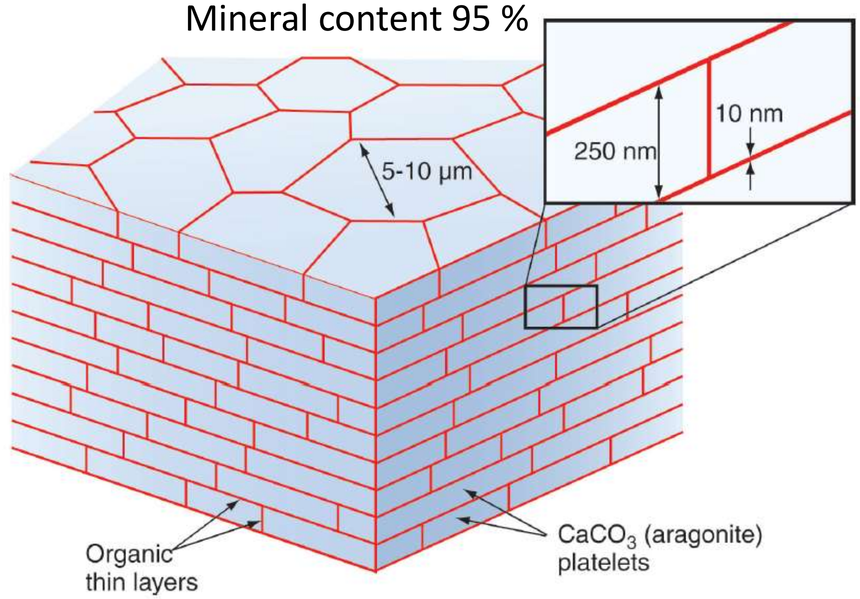




Seashells: nacre (7)



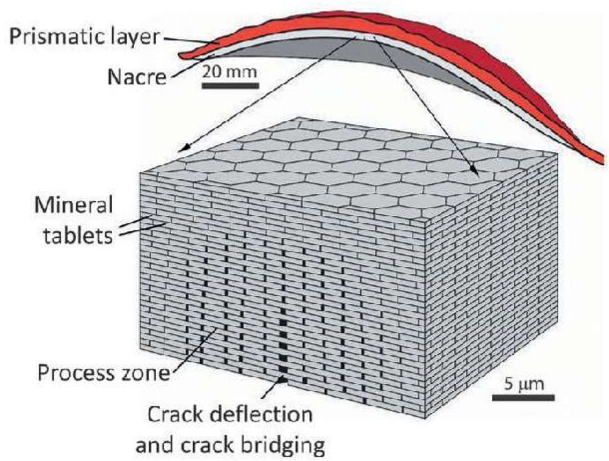
Mineral content 95 %

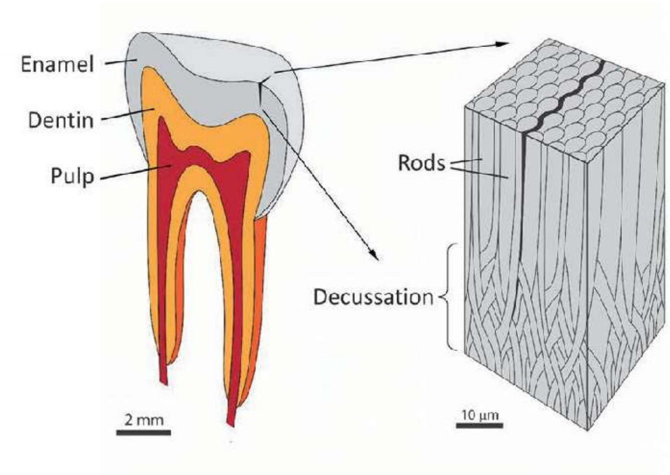


- Delamination
- Multiple microcracking
- Crack deflection
- Crack bridging by organic ligament phase
- Pull-out of the ceramic phase (asperities)
- Frictional sliding of the tablets

Higher fracture resistance and energy absorption at the cost of **lower stiffness and strength** (10 times) compared to the main mineral constituent

Ingredients for toughness (5)





Architecture

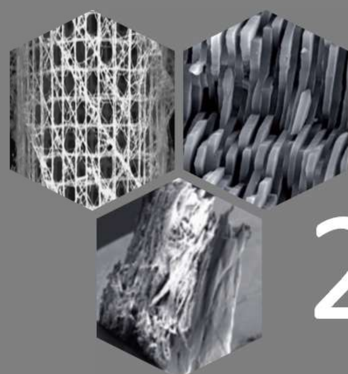
Geometry and topology of hard building blocks joined together via weak interfaces

Weak/soft interfaces

Low volume fraction of weaker and more compliant interfaces. When the crack deflects into the interface, a cascade of toughening mechanisms are initiated

Collective mechanisms for toughness

- Crack bridging
- Crack twisting
- Crack deflection
- Sliding of the hard building blocks
- …



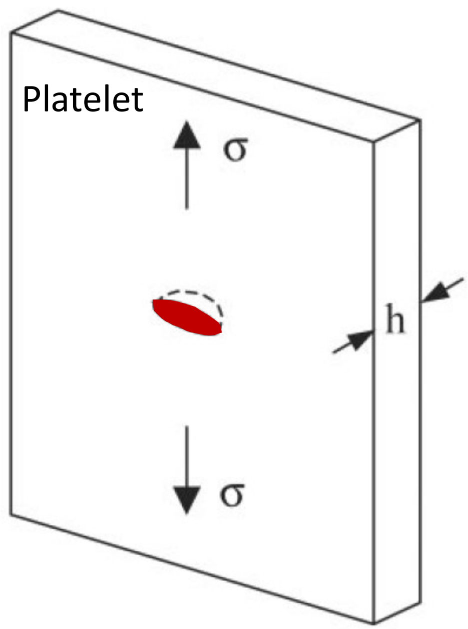
2

Flaw insensitivity at nanoscale

Flaw tolerance: lessons from nature [8]

«The **fracture toughness** of the bio-composite thus hinges on the **tensile strength of mineral platelets**»

Schematization of a mineral platelet



From the Griffith criterion:

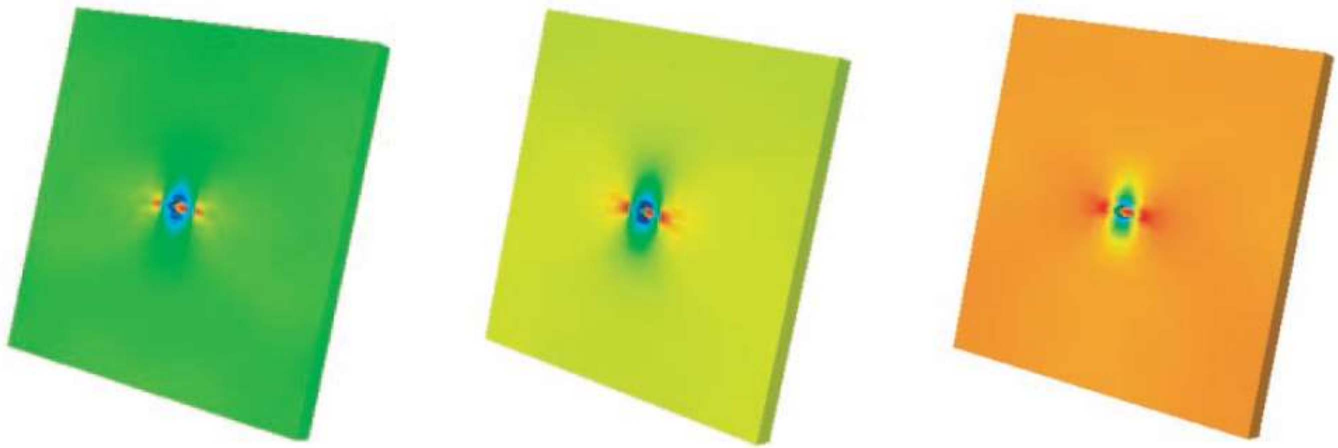
$$h^* \approx \alpha^2 \frac{\gamma E_m}{\sigma_{th}^2}$$

With $\gamma = 1 \frac{J}{m^2}, E_m = 100\ GPa, \sigma_{th} = \frac{E_m}{30}$

$$\boldsymbol{h^* \approx 30\ nm}$$

Protein (soft) inclusion, as an embedded crack

Flaw tolerance: lessons from nature (8)



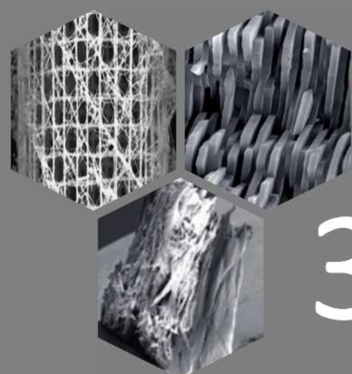
$\frac{\sigma_m^f}{\sigma_{th}} = 0.50, \quad \frac{h}{h^*} = 200$

$\frac{\sigma_m^f}{\sigma_{th}} = 0.66, \quad \frac{h}{h^*} = 20$

$\frac{\sigma_m^f}{\sigma_{th}} = 0.95, \quad \frac{h}{h^*} \approx 1$

σ/σ_{th}

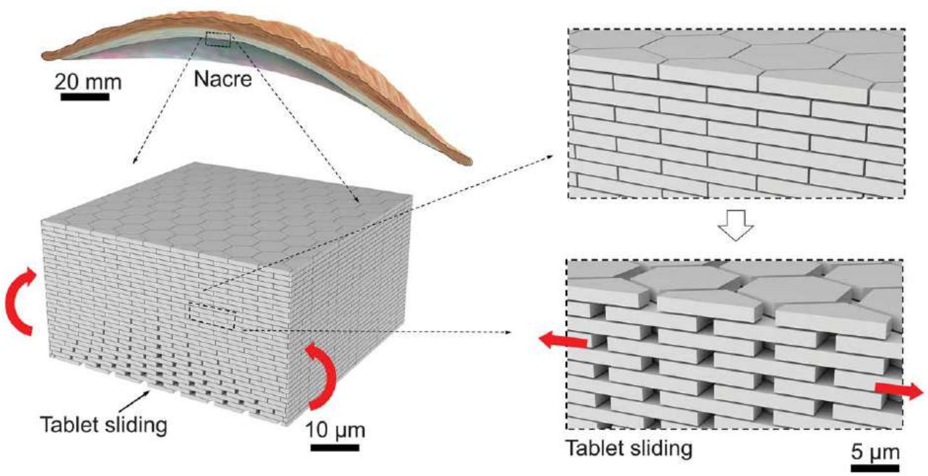
1.000e+000
7.450e-001
4.899e-001
2.348e-001
-2.023e-002



3

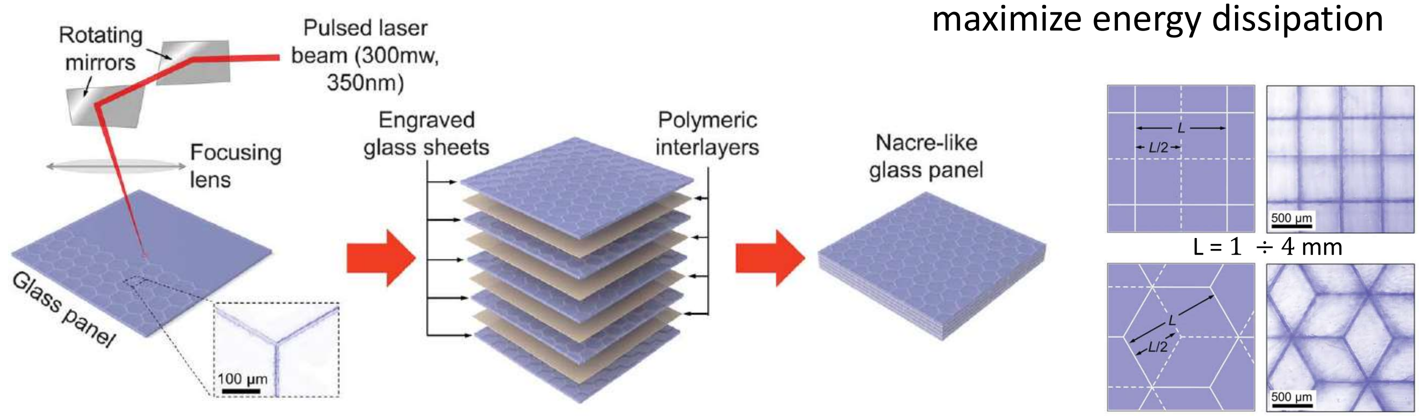
Nacre-like materials

Exploiting the tablet sliding (9)

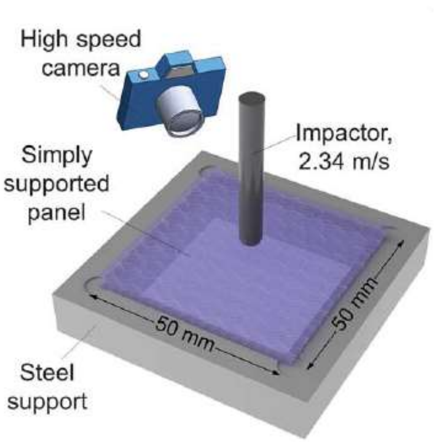


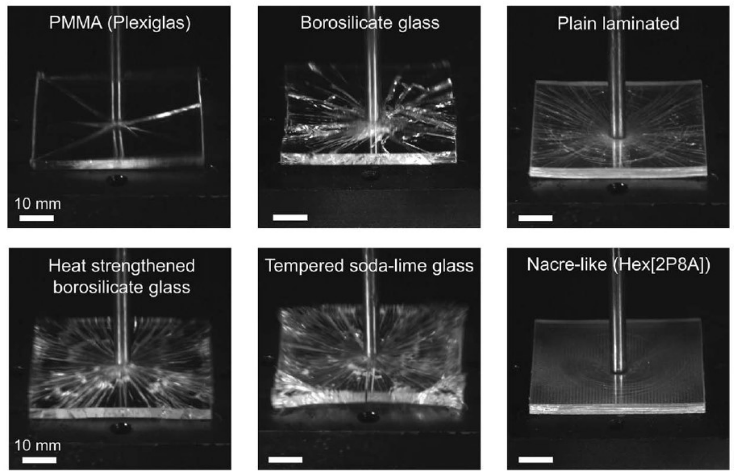
- High aspect ratio to transfer shear stresses but not too high to avoid tablet fracture
- Strong interface-to-mineral adhesion
- Interfaces much more compliant than the tablets to achieve a near-uniform shear stress transfer
- Highly deformable interface
- Size and arrangement of the tablets as uniform as possible to maximize energy dissipation

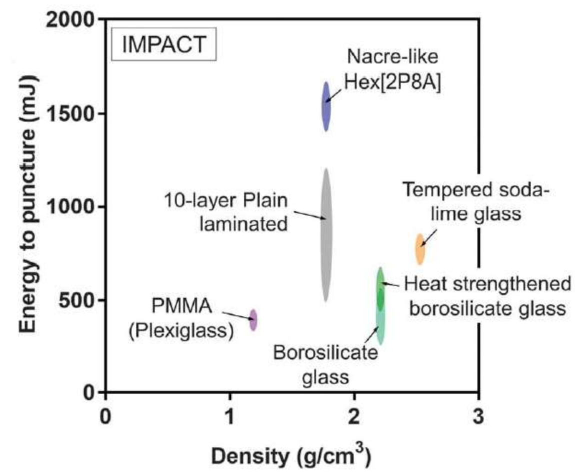
Fabrication

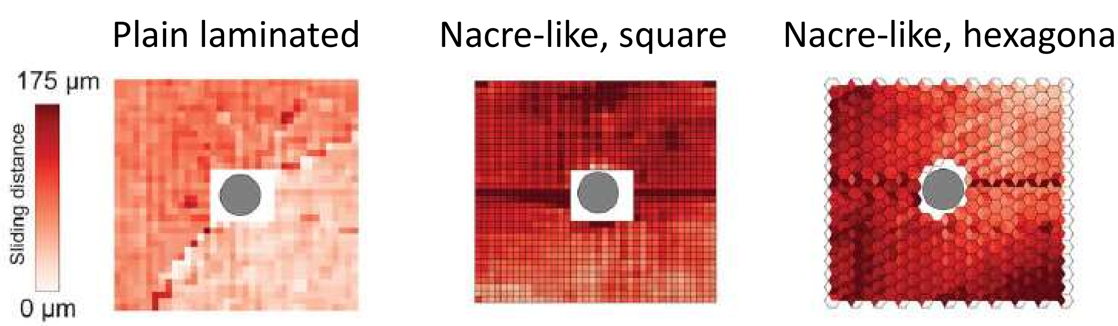


Impact-resistant nacre-like material (9)

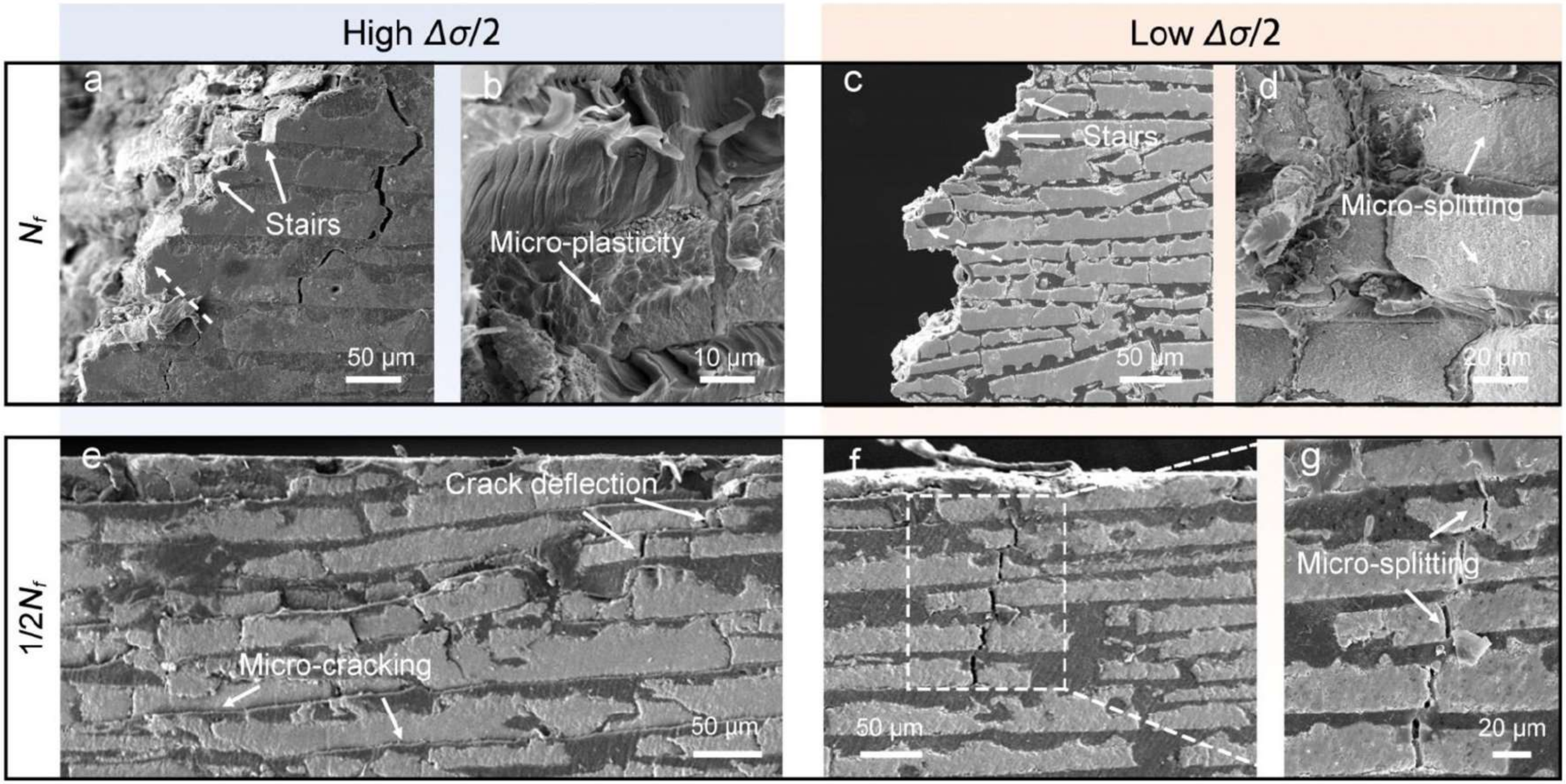


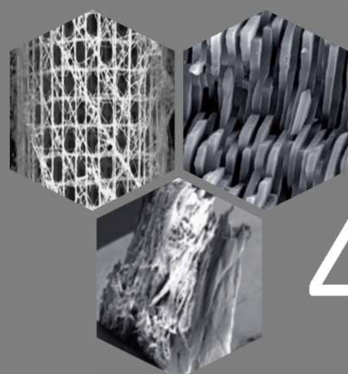






Fatigue-resistant nacre-like material (10)

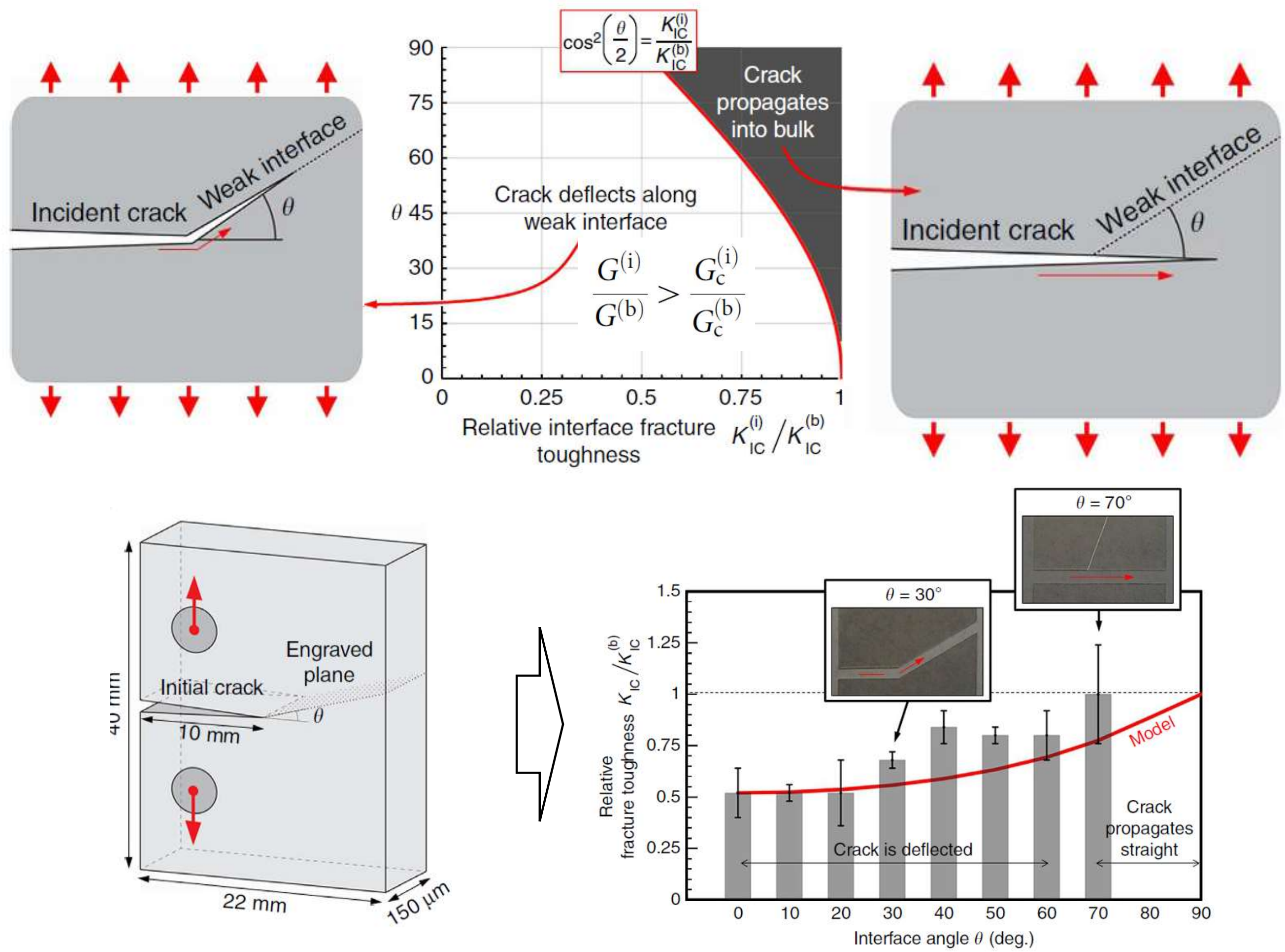




4

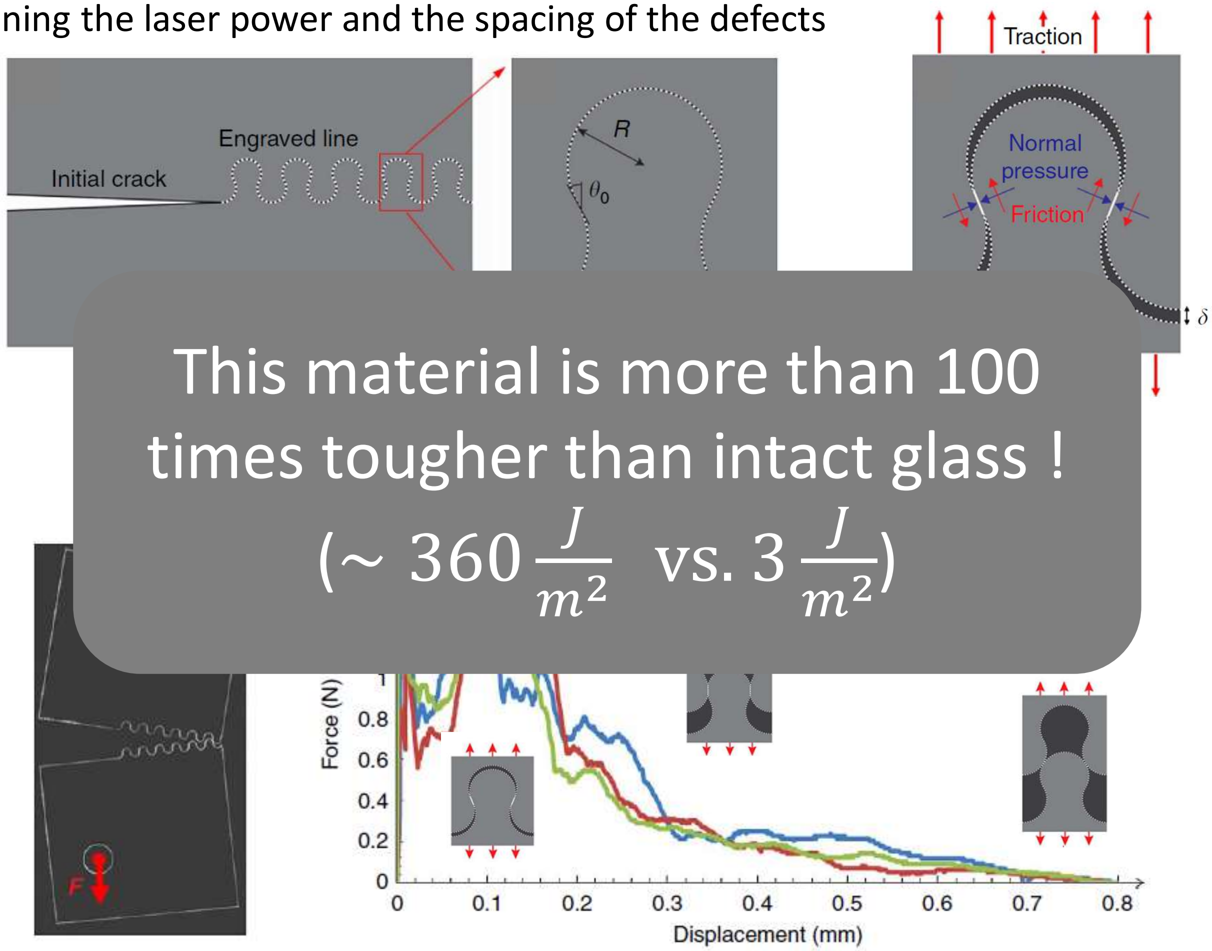
Interlocking features

Exploiting weak interfaces (11)



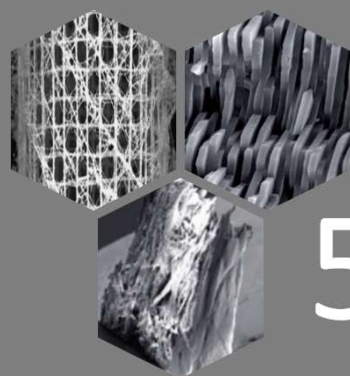
Channeling cracks and interlocking (11)

Tuning the laser power and the spacing of the defects



This material is more than 100 times tougher than intact glass !

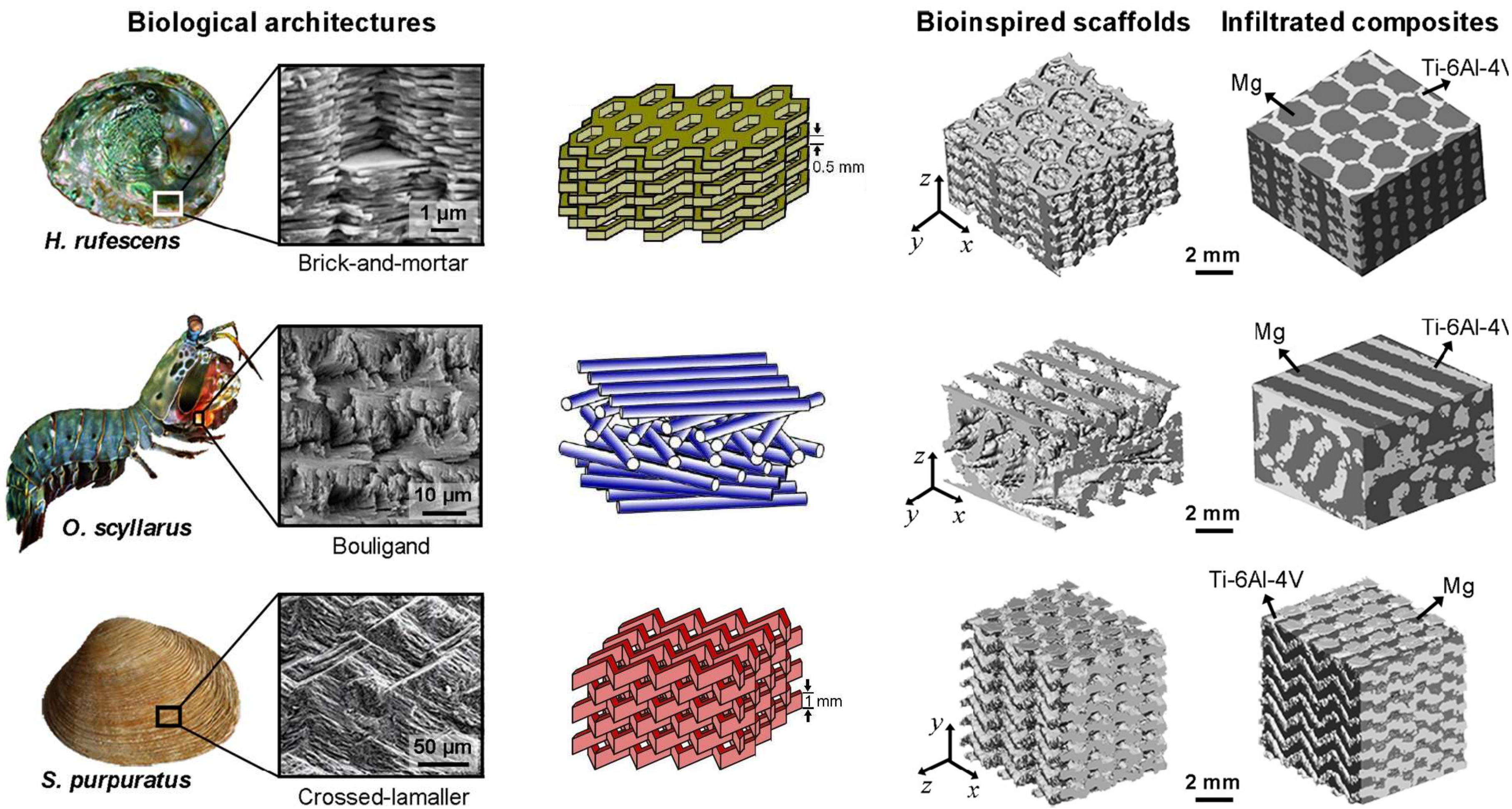
$(\sim 360\,\frac{J}{m^2}\ \text{vs.}\ 3\,\frac{J}{m^2})$



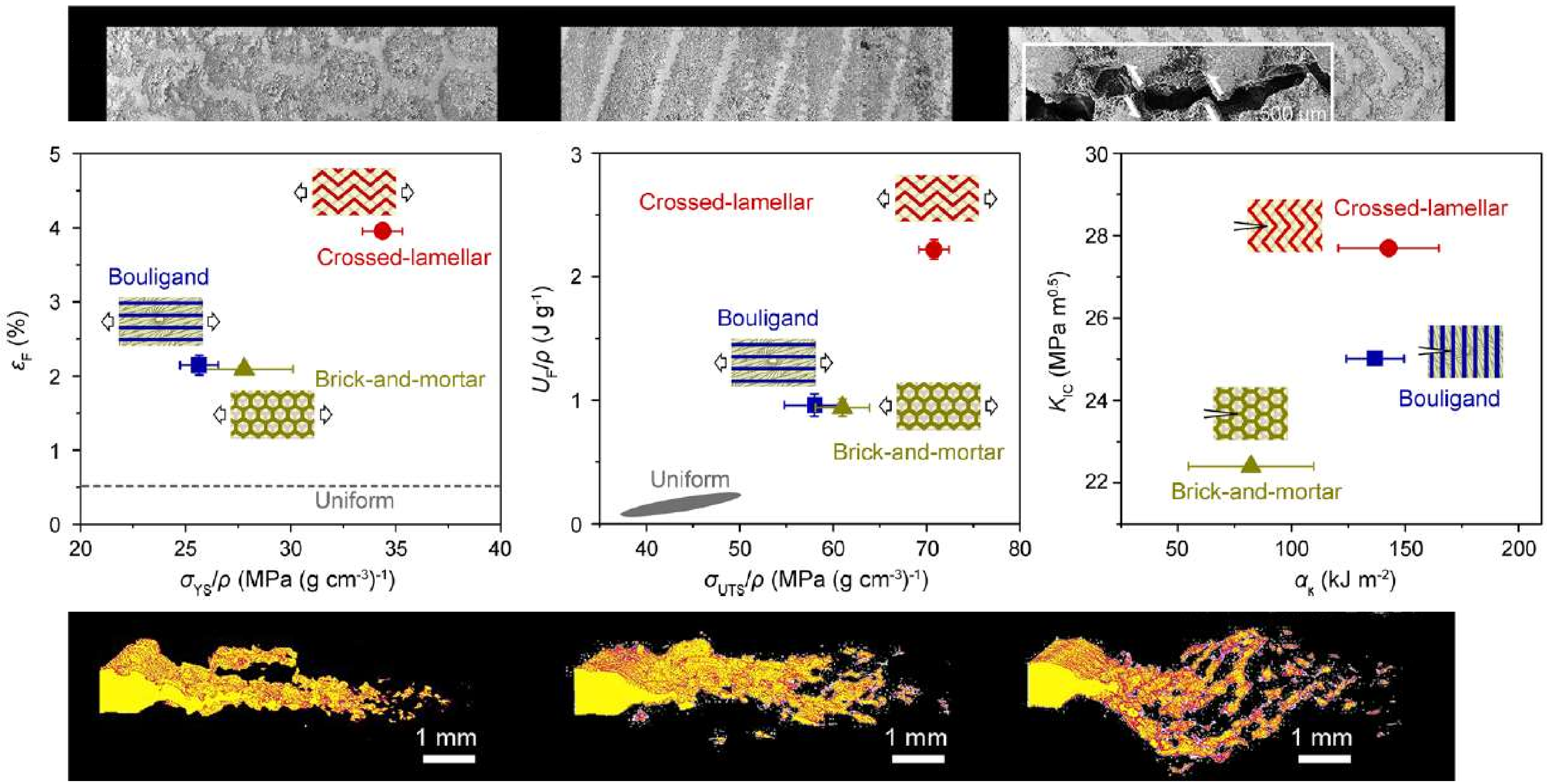
5

Metallic interpenetrating-phase bio-inspired composites

Mg-Ti bio-inspired composites (12)

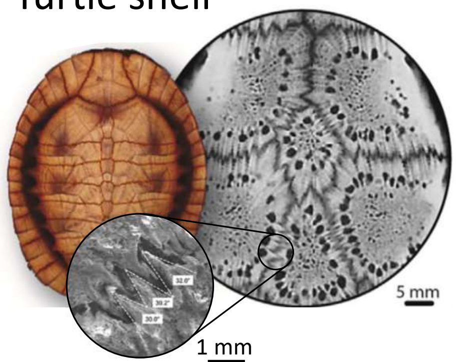


Toughening mechanisms (12)

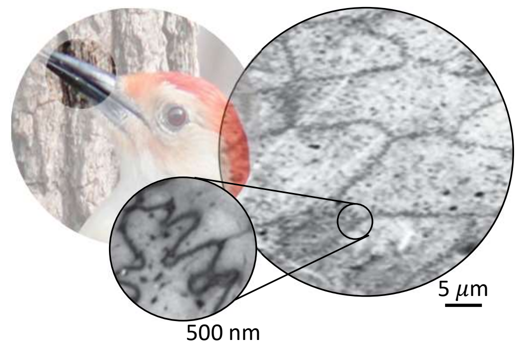


Suture joints

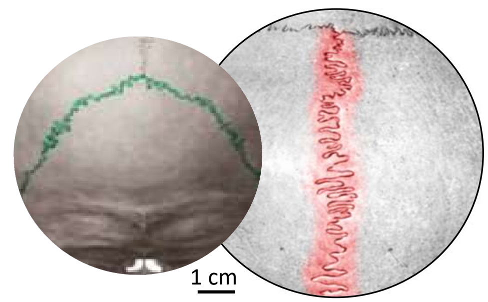
Turtle shell



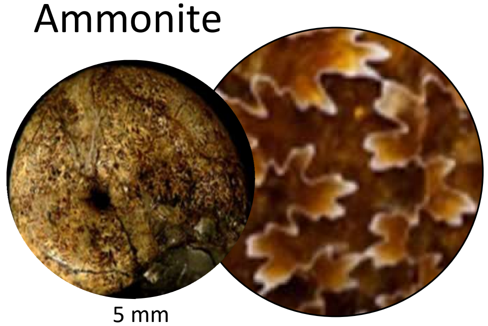
Woodpecker beak



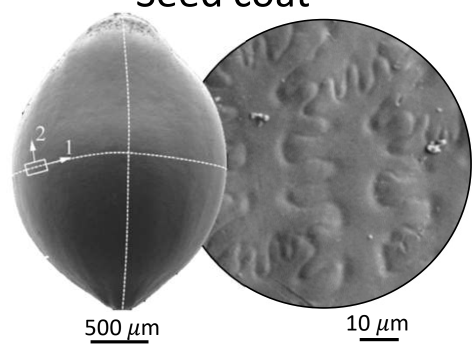
Human skull



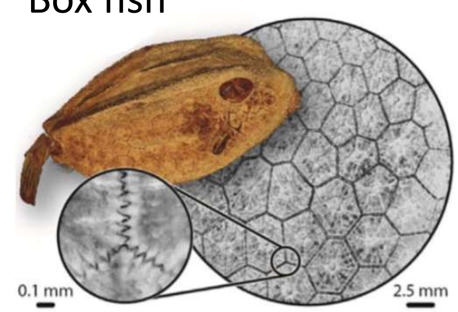
Ammonite



Seed coat

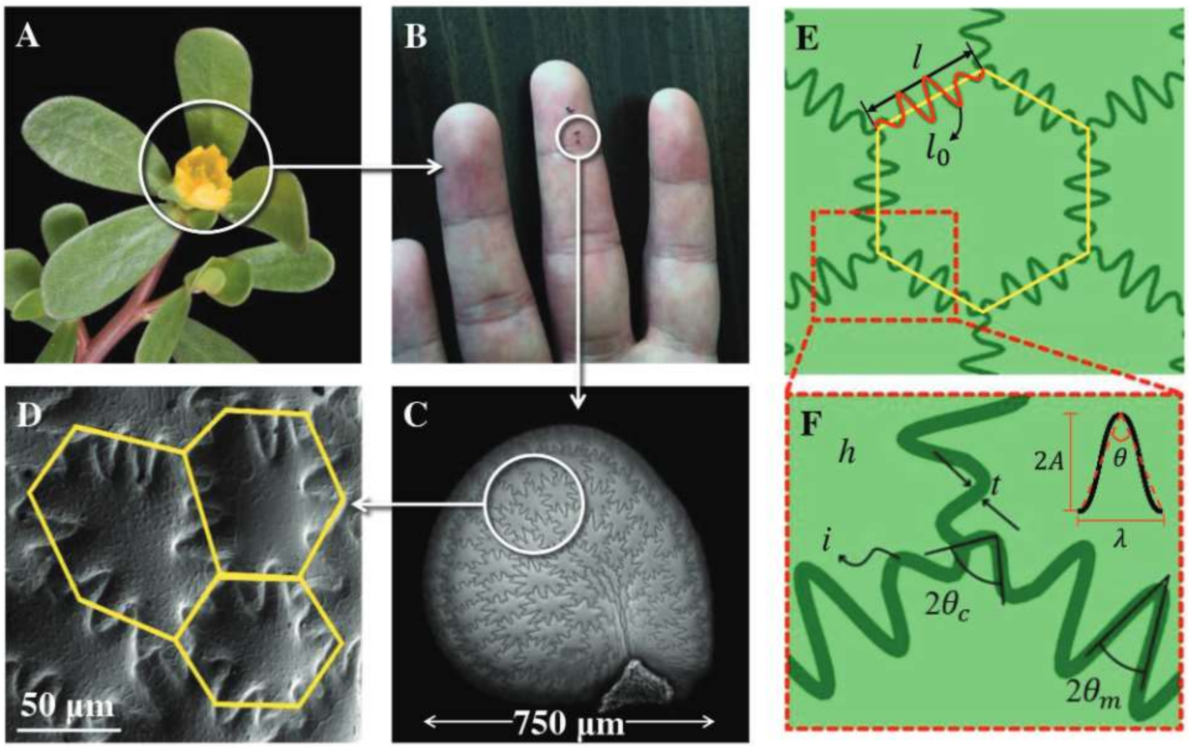


Box fish

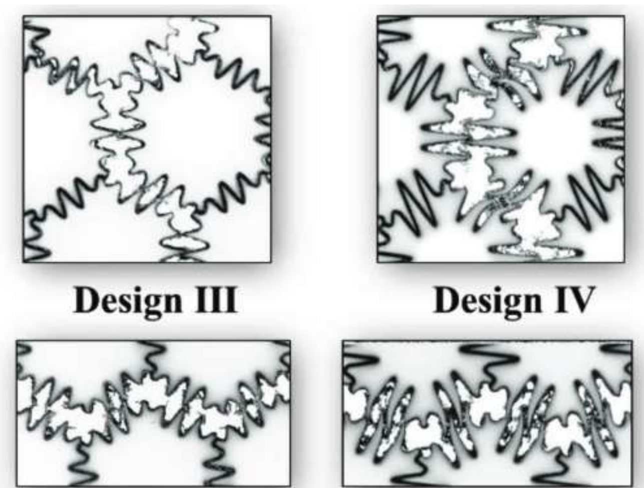


Redistributing stress through the interface profile (12)

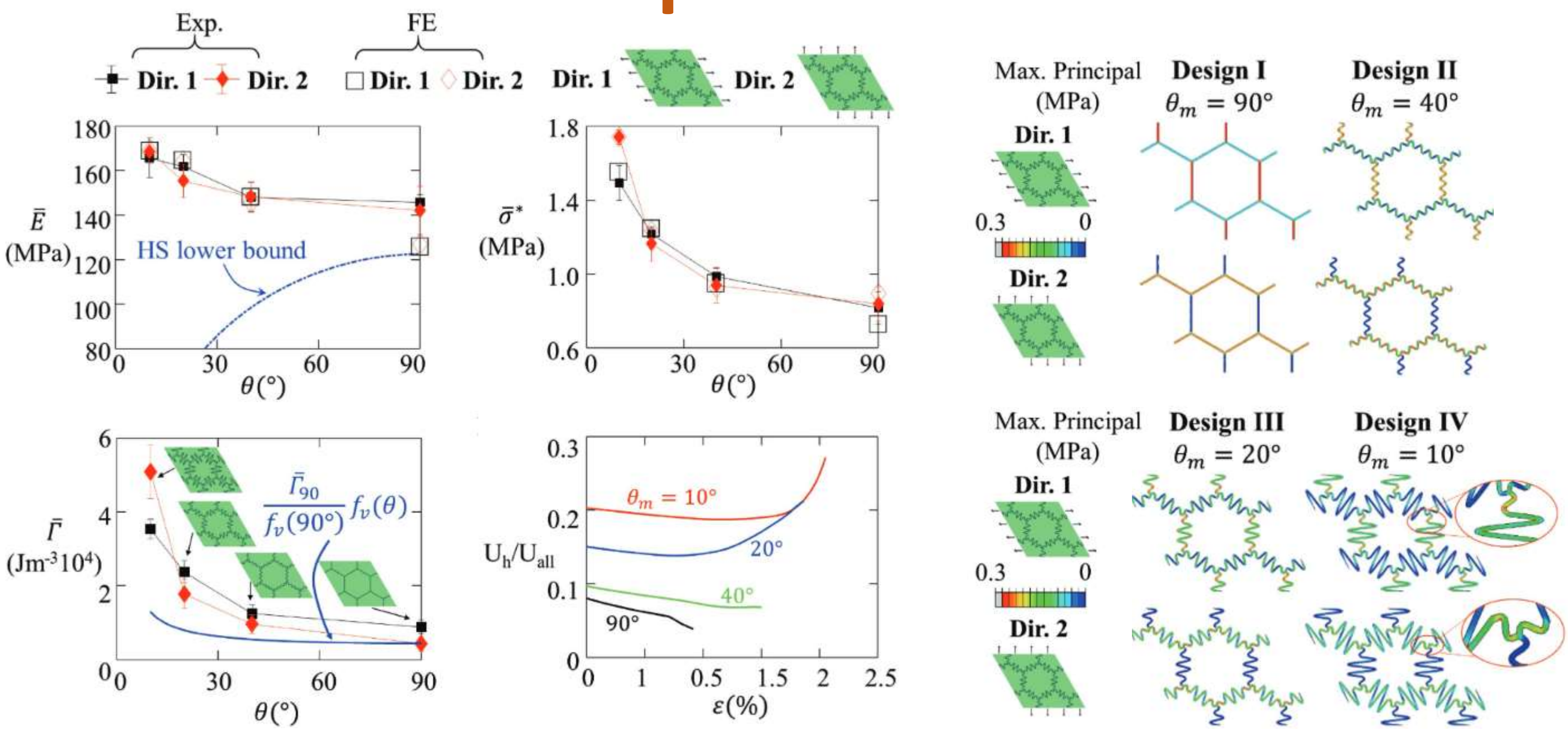
Inspired by the *Portulaca oleracea* ‘s seedcoat

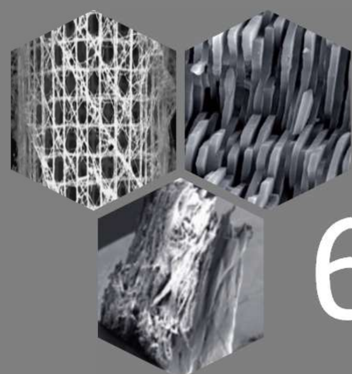


3D-printing and testing



Redistributing stress through the interface profile (12)

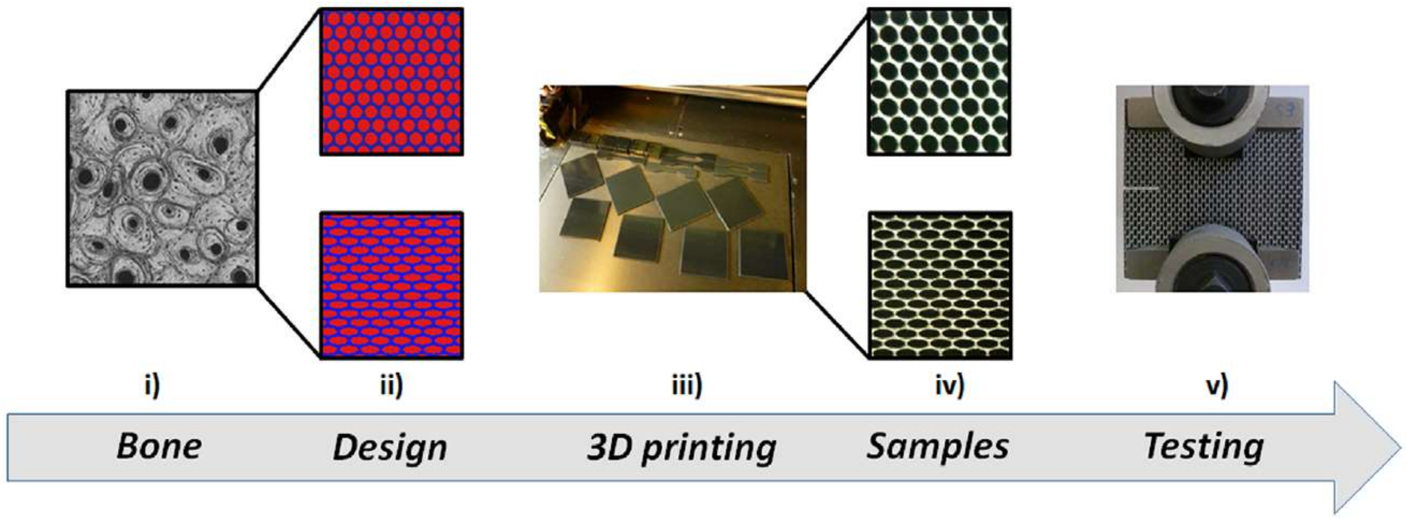


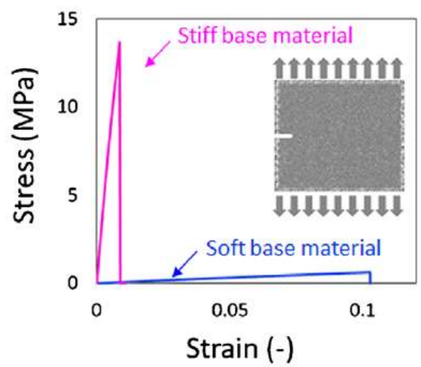


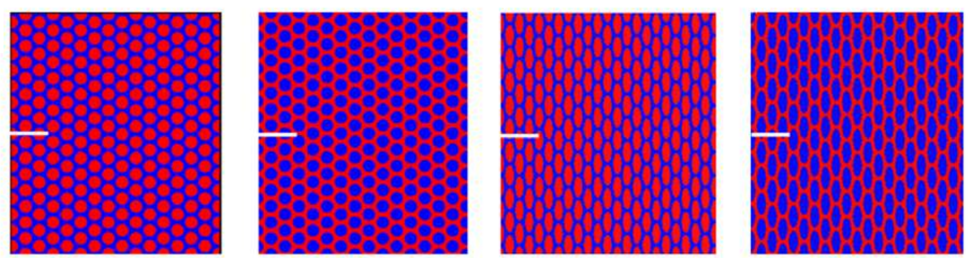
6

Strong-yet-tough cortical bone-inspired materials

Osteon-like composite materials (13)

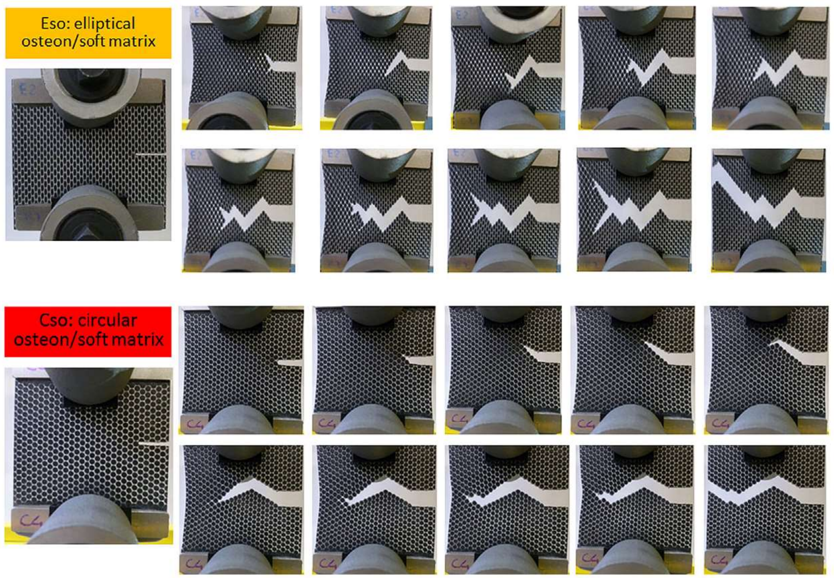




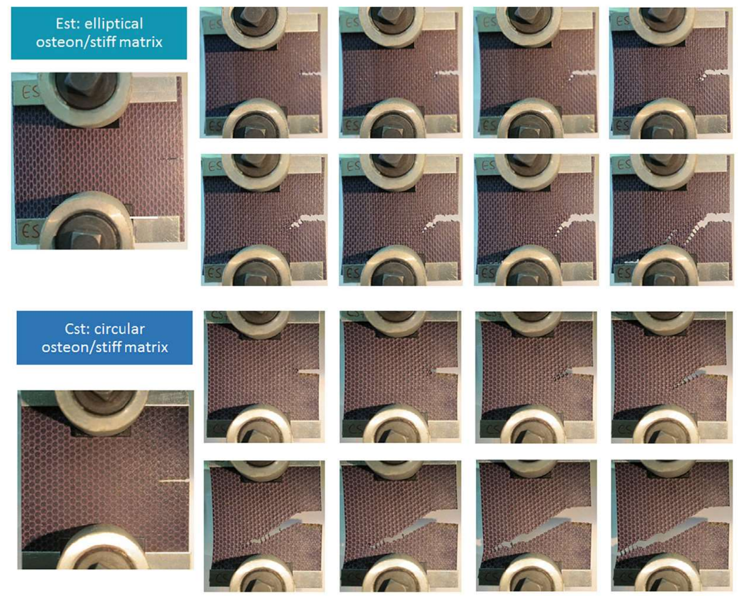


Cso	Cst	Eso	Est
Circular osteons Soft matrix	Circular osteons Stiff matrix	Elliptical osteons Soft matrix	Elliptical osteons Stiff matrix

Geometry and base materials (13)

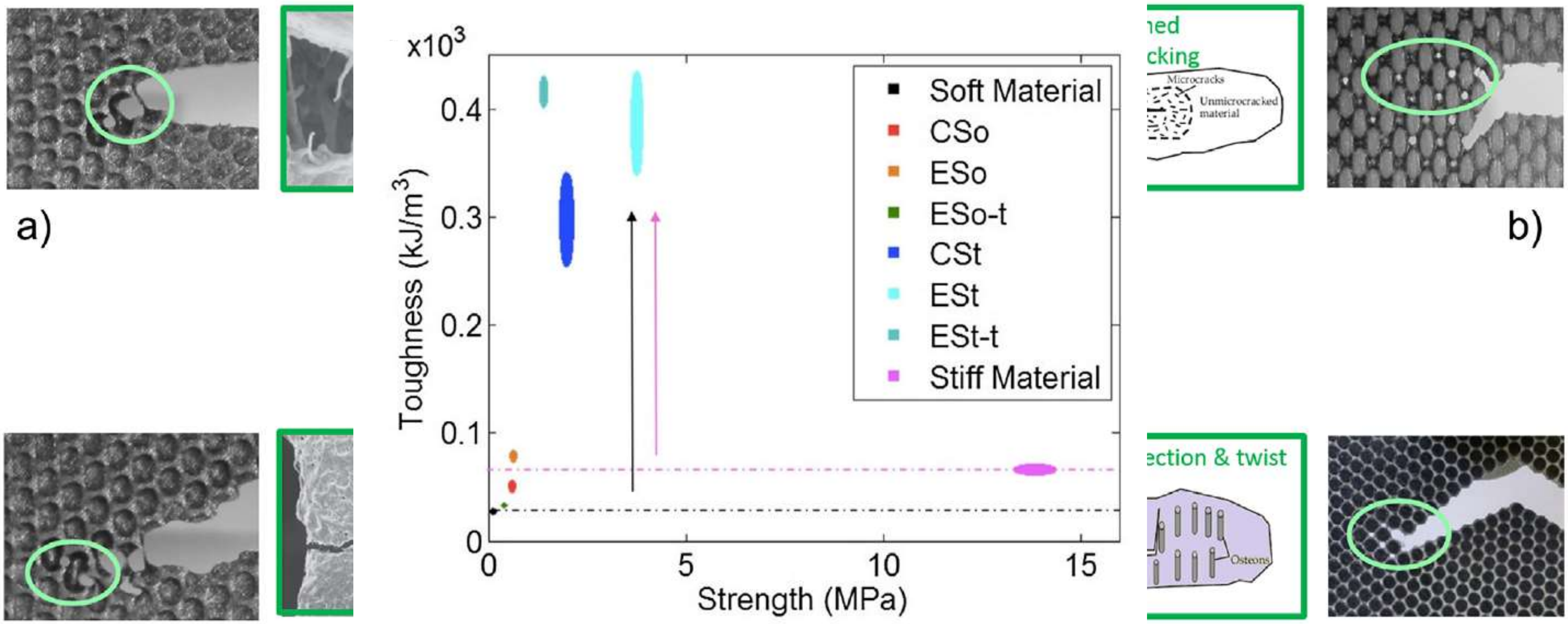


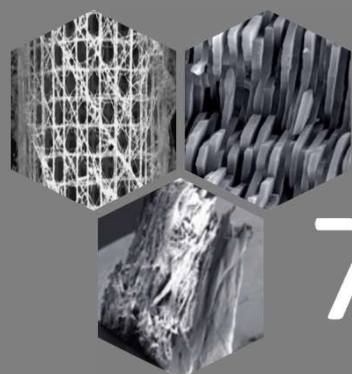
Crack branching and crack deflection



Uncracked ligament bridging (in the stiff matrix) and fibril bridging (in the soft inclusions)

Toughening mechanisms in osteon-inspired composites (13)

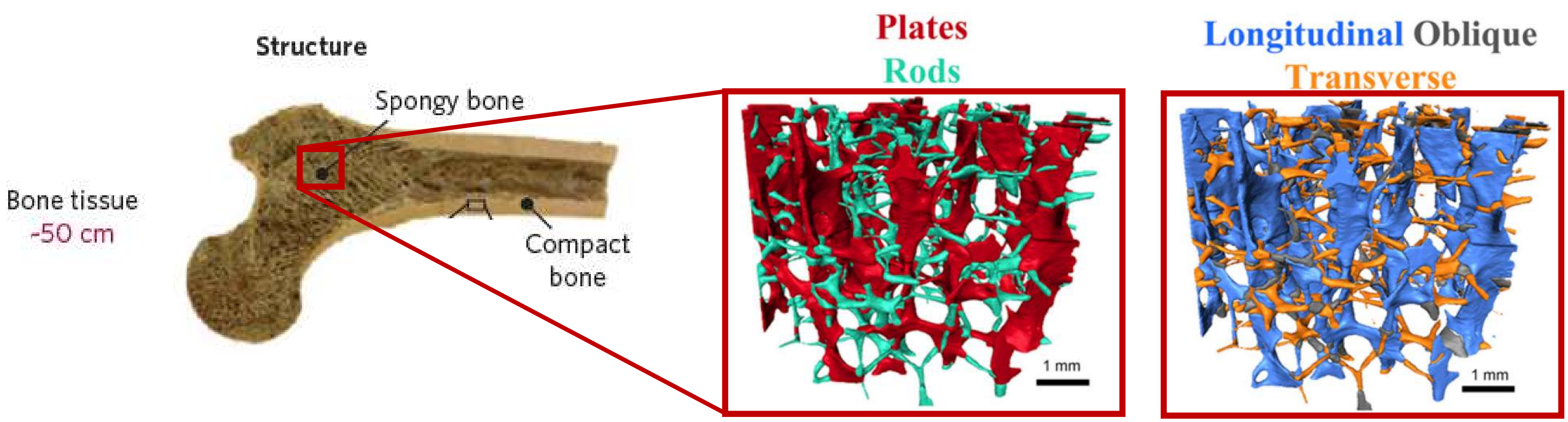


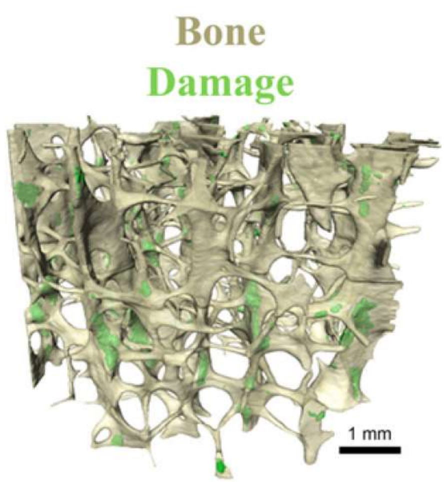


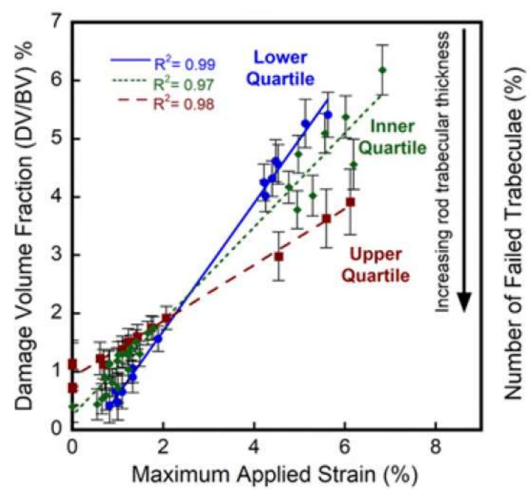
7

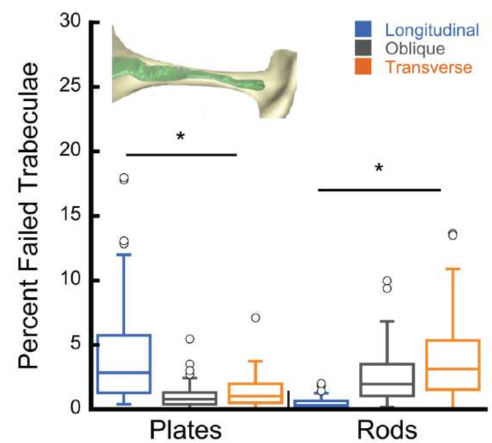
Enhanced fatigue life of bone-inspired materials

Cancelleous bone (14)

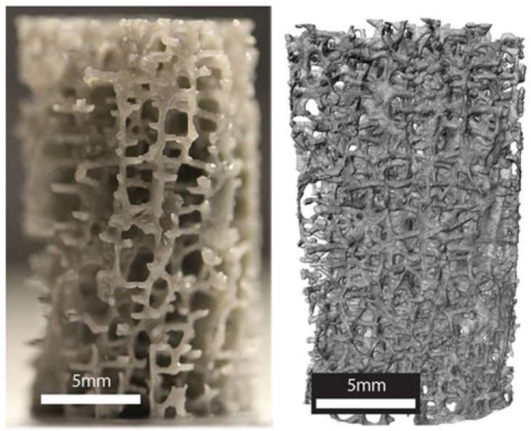


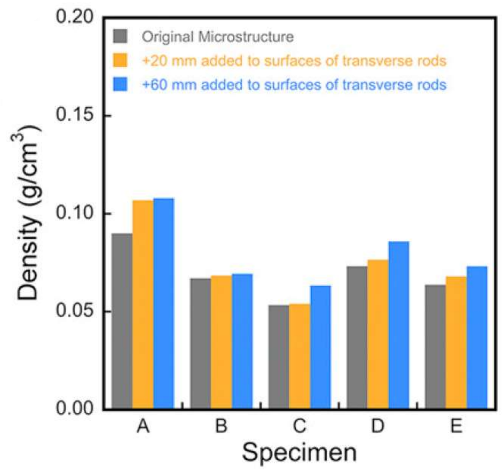


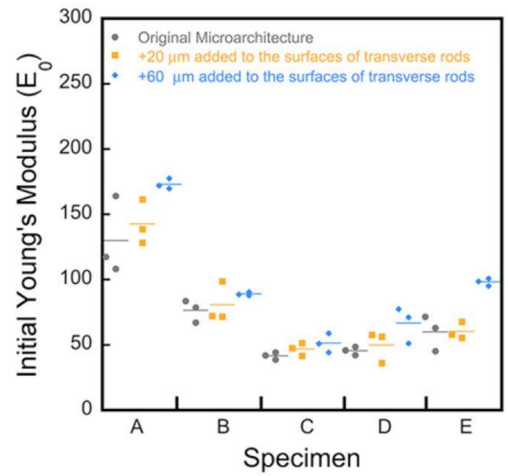


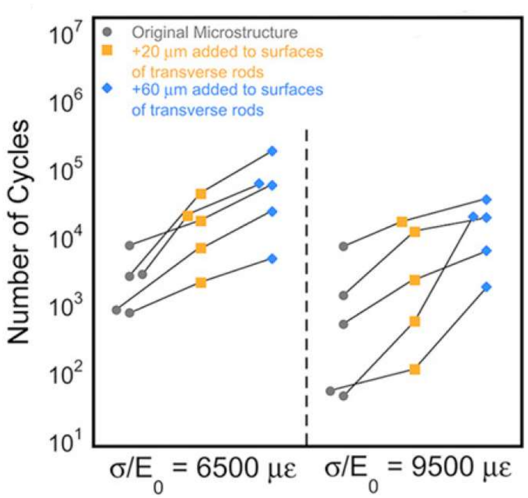


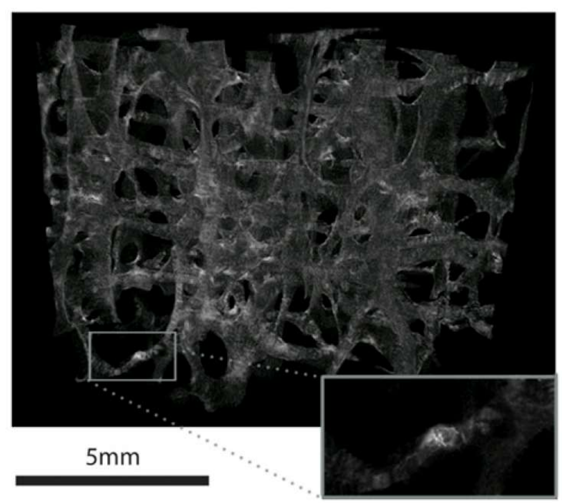
Transverse struts: higher fatigue life (14)

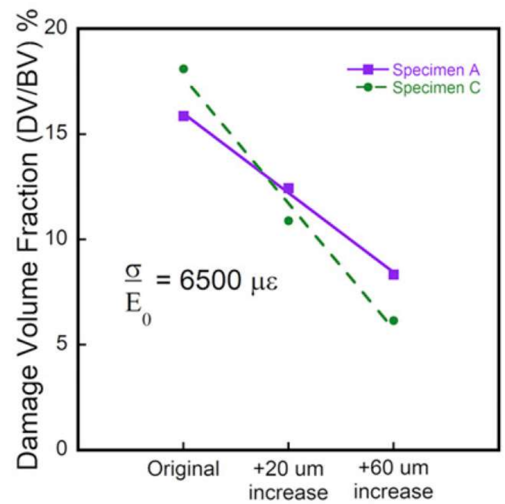




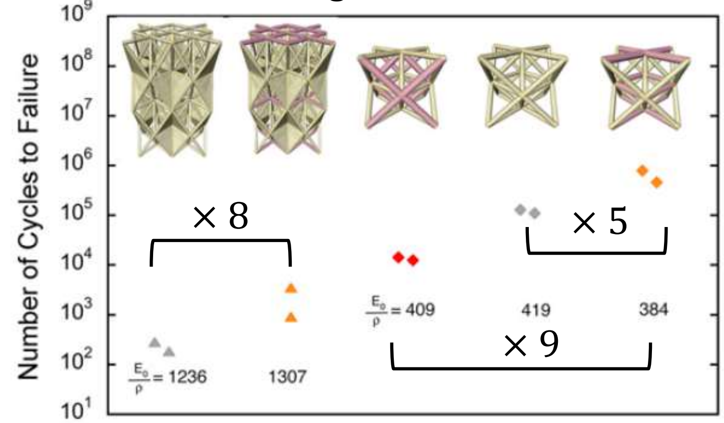


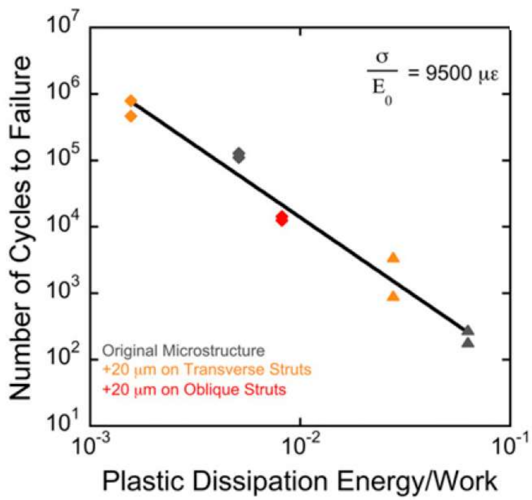




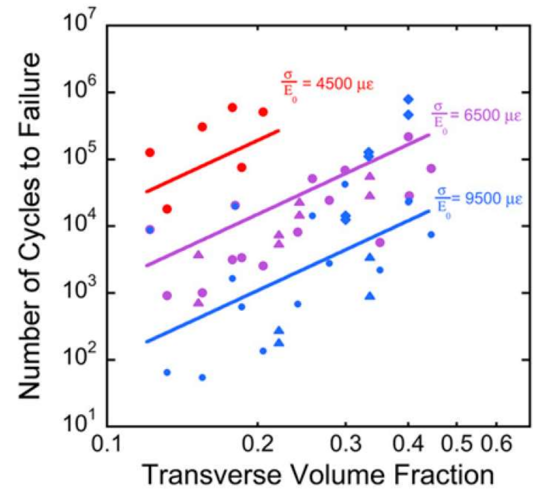


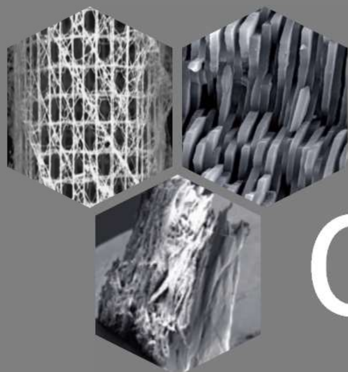
Cancellous bone-like architecture (14)





$$\frac{\sigma}{E_0}\frac{1}{\sqrt{\psi}} = AN_f^B$$





Conclusions and challenges

- Natural structural materials have evolved in millions of years efficiently exploiting the scarce available resources achieving high fracture and fatigue performance.
- Reproducing the toughening mechanisms exhibited by biological materials allows us to manufacture lightweight and strong yet tough and durable materials.
- Architecting materials at multiple length scales (to harness hierarchical toughening) is still an open technological challenge (for additive manufacturing and other techniques).

Thanks for your time !

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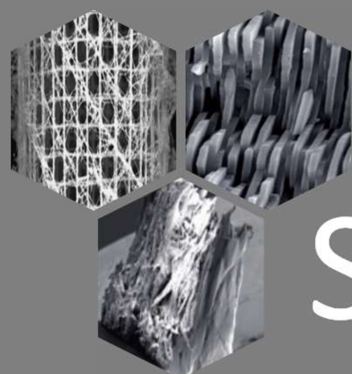
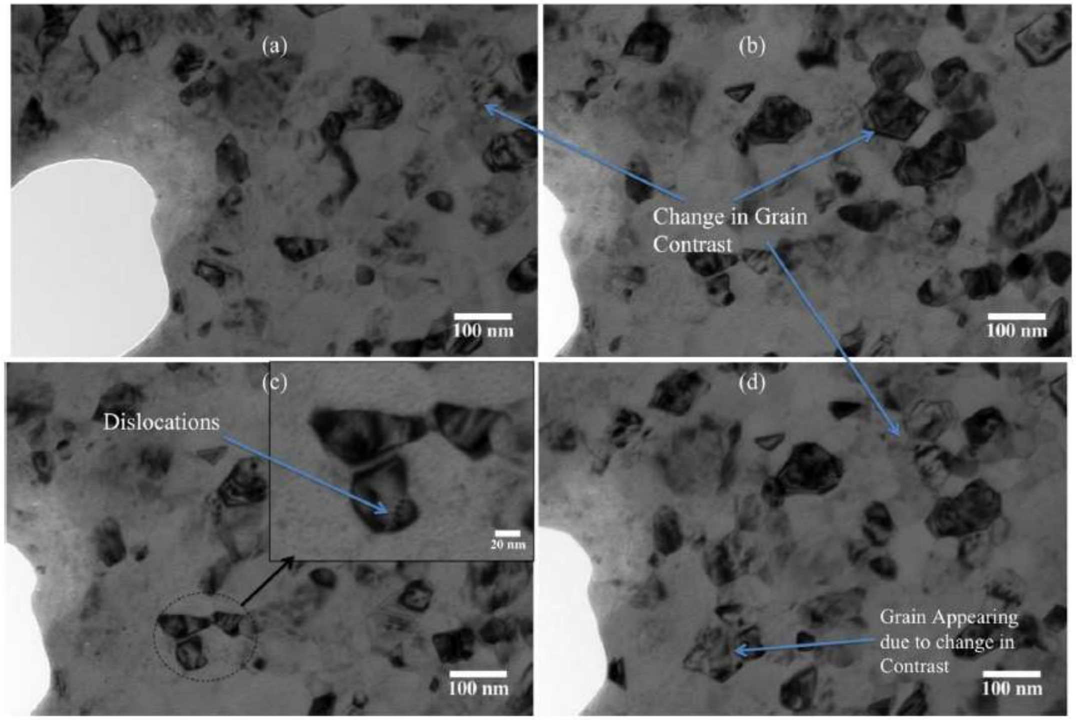


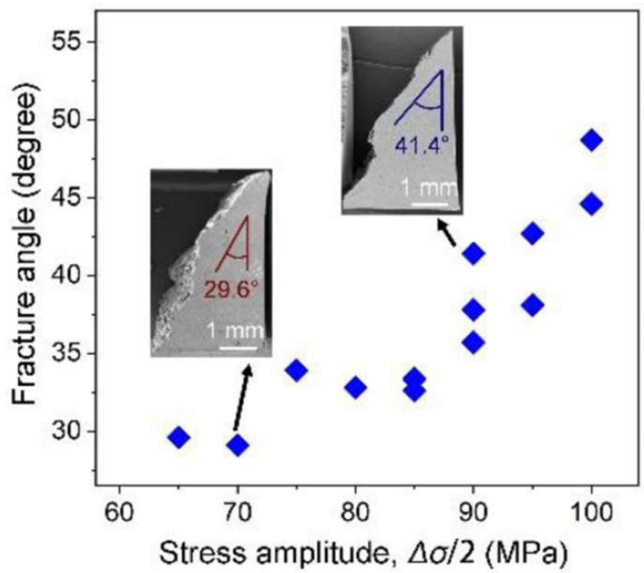
Supplementary Information

Fatigue insensitivity of nanoscale aluminum 200-nm-thick free-standing films

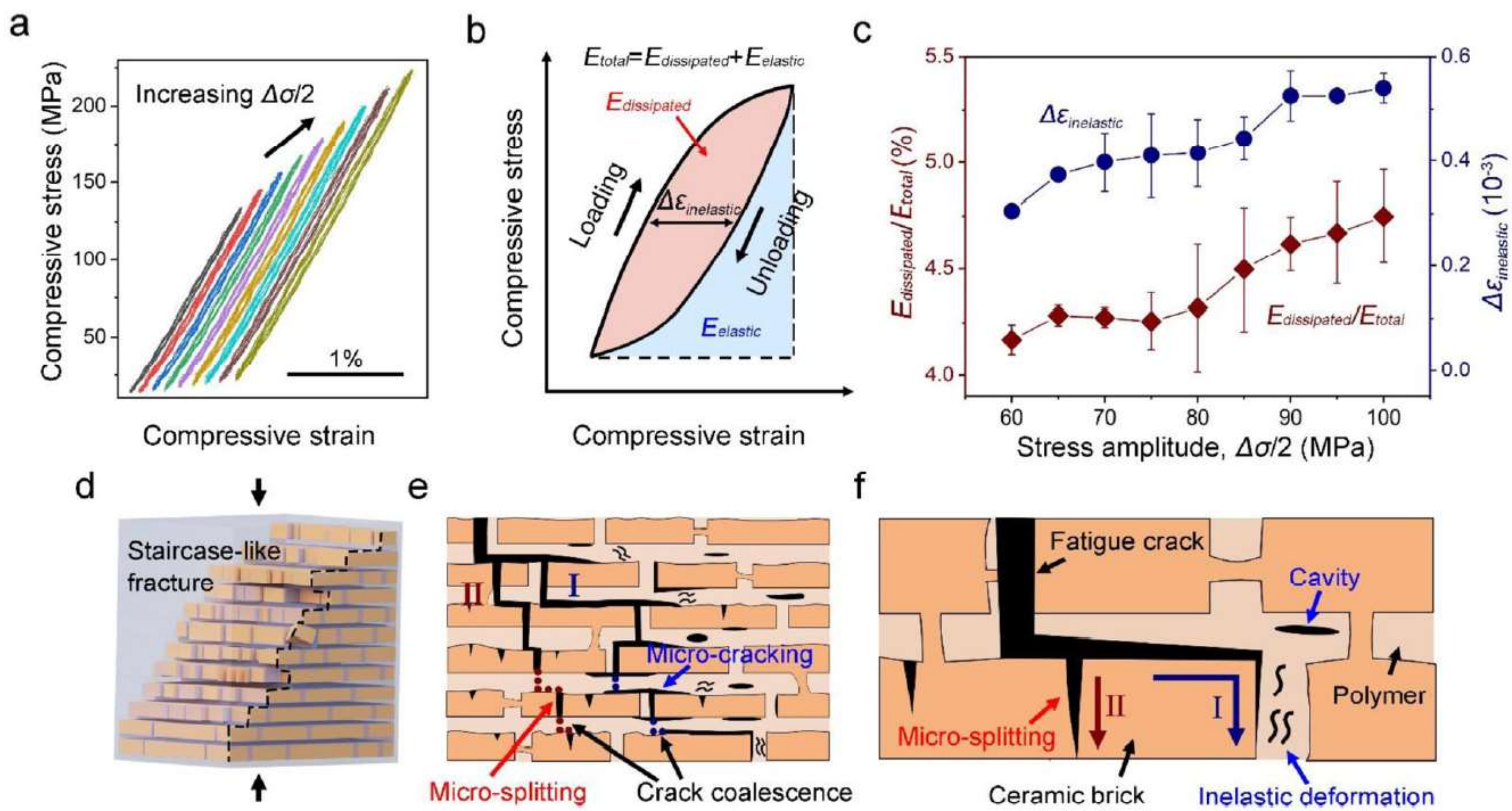


- «Grain rotation is observed to be the dominant deformation mechanism at this length scale»
- Appearance and disappearance of discrete dislocations.
- Not so many dislocations: dislocation starved compared to bulk materials. Indeed, dislocations generate and then quickly disappear at the surface or the grain boundaries.
- No conventional «plastic zone» at the notch tip as seen for bulk metals. Grain rotation allows to relax the stress concentration, redistributing it.

Compressive fatigue properties of nacre-like ceramic-polymer composite



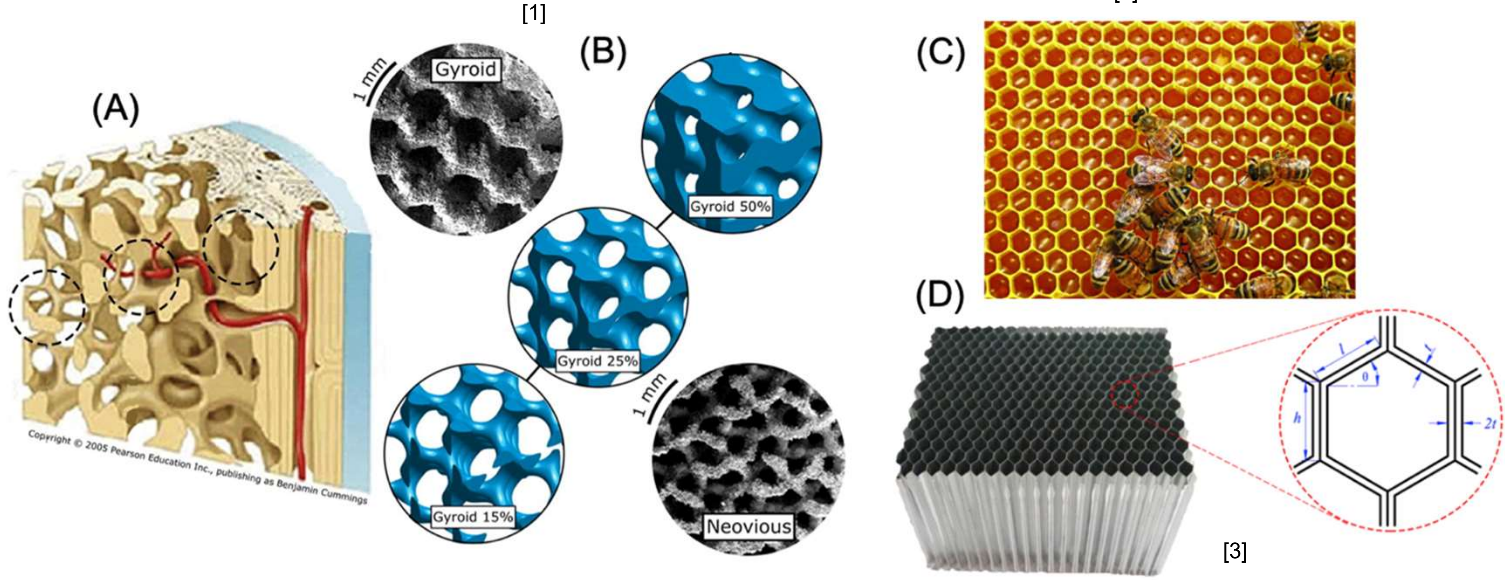
Compressive fatigue properties of nacre-like ceramic-polymer composite



Introduction

Architected cellular materials: learning from nature

[1] [2]



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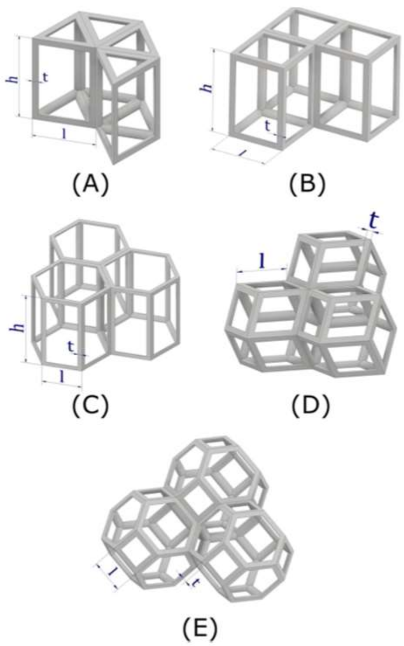
Introduction

Architected cellular materials: filling space unit cells

[4]



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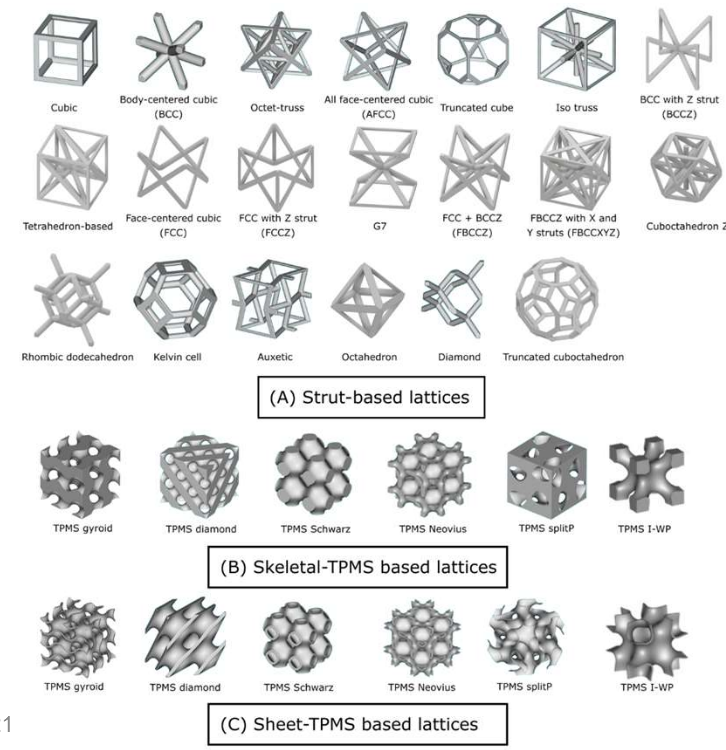

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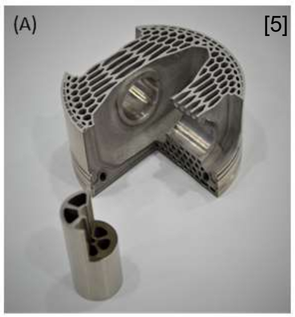
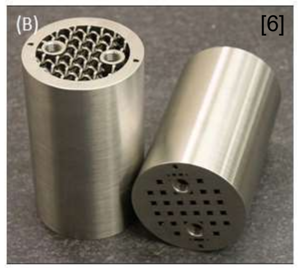
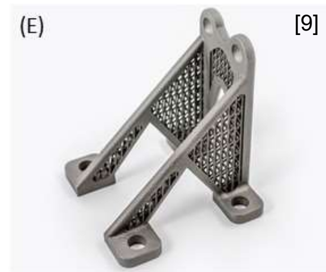
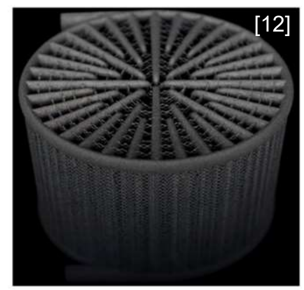
Introduction

Architected cellular materials: applications









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[10] https://resources.renishaw.com/gen/details/spider-bracket--78295
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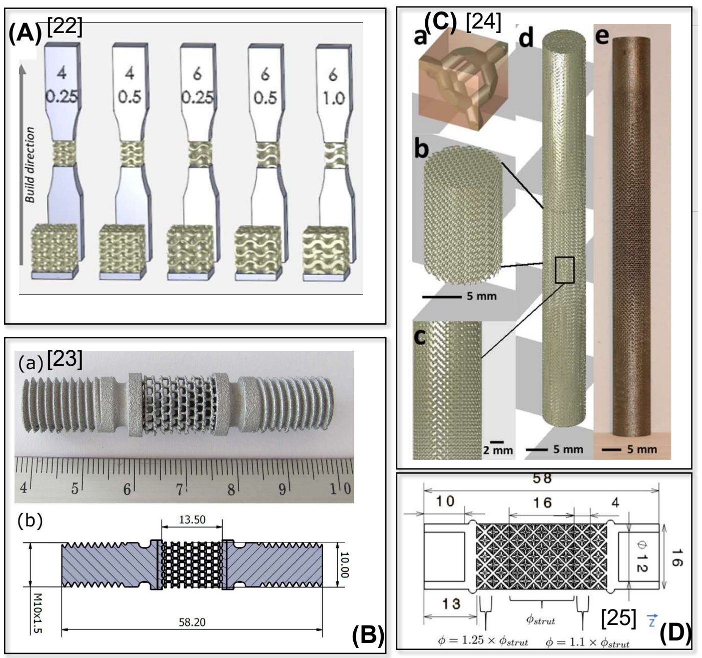
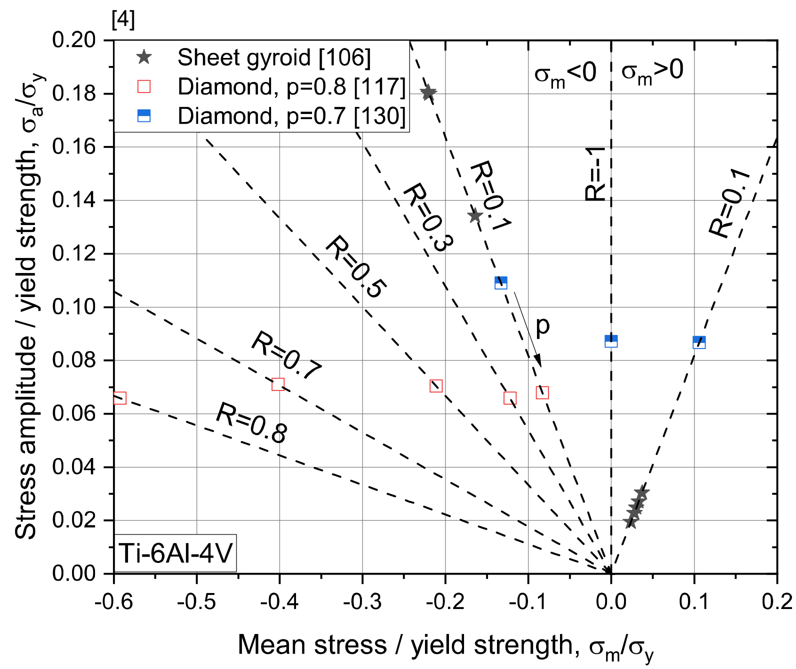
Fatigue experiments on cellular lattice materials

Fatigue strength under tensile loadings





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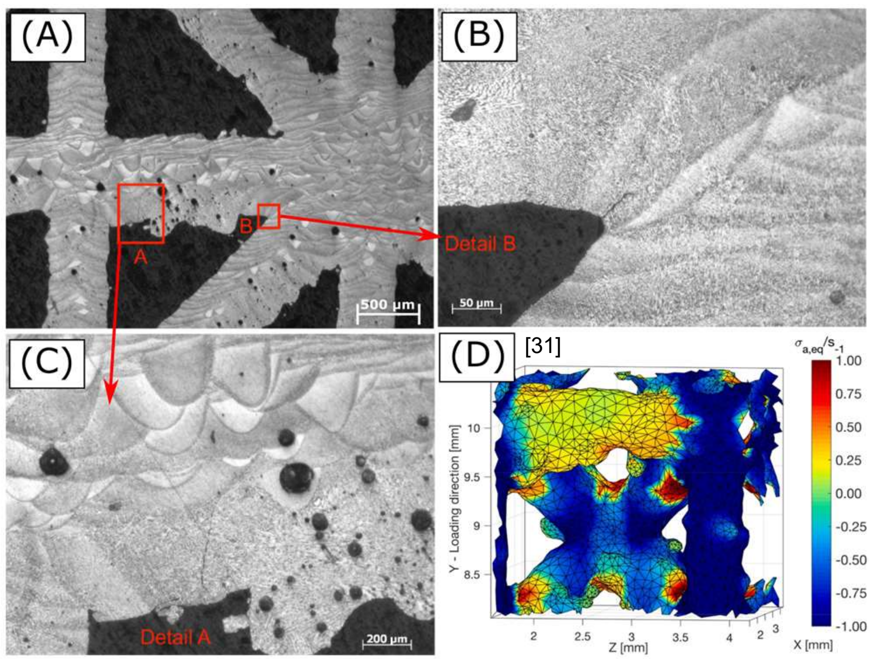
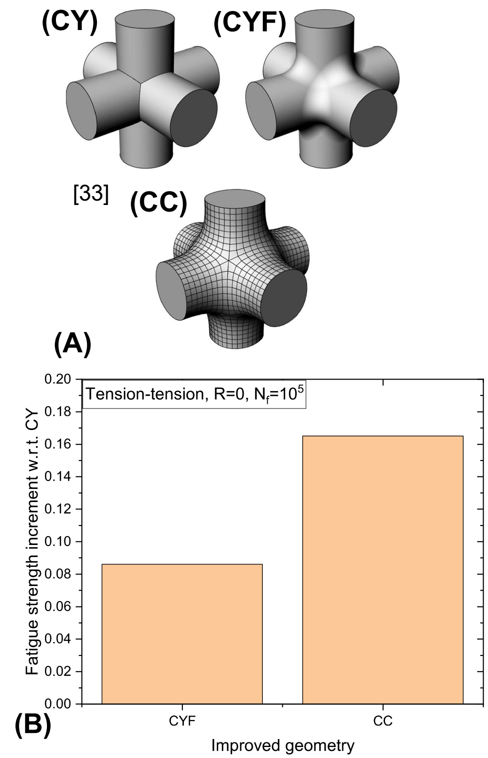
Design measures to improve the fatigue behaviour

Stress concentration at nodes and fillets





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https://doi.org/10.1016/j.matdes.2021.110008

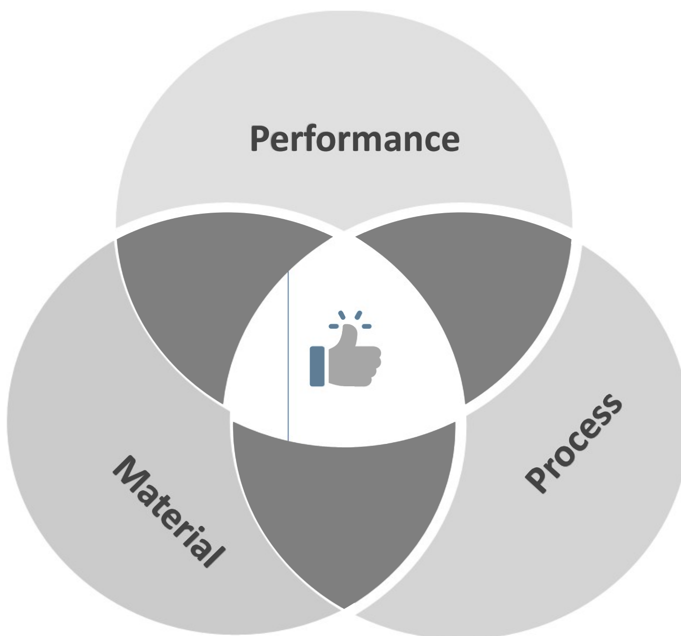
Popular alloys for metal AM *

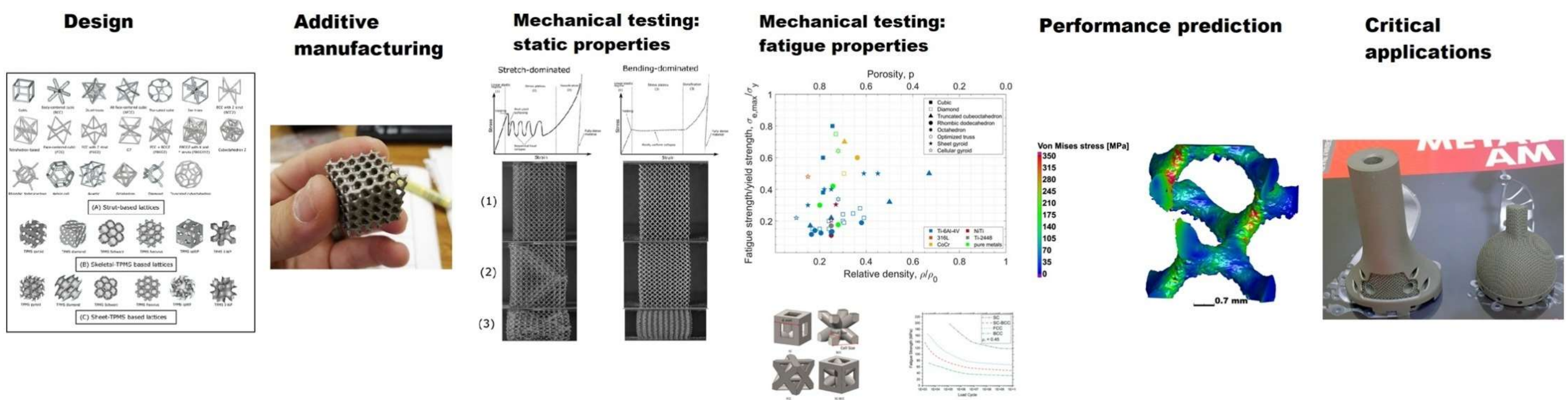
Table 1
Popular commercial alloys available for additive manufacturing [81]

Ni-base	Fe-base	Cu-base	Al-base	Refractory	Ti-base	Co-base	Bimetallic
Inconel 625	SS 17-4PH	GRCop-84	AlSi10Mg	W	Ti6Al4V	CoCr	GRCop-84/IN625
Inconel 718	SS 15–5 GP1	GRCop-42	A205	W-25Re	γ-TiAl	Stellite 6	C18150/IN625
Hastelloy-X	SS 304L	C18150	F357	Mo	Ti-6–2-4–2	Stellite 21	
Haynes 230	SS 316L	C18200	2024	Mo-41Re		Haynes 188	
Haynes 214	SS 420	Glidcop	4047	Mo-47.5Re			
Haynes 282	Tool Steel (4140/4340)	CU110	6061	C-103			
Monel K-500	Invar 36		7050	Ta			
C-276	SS347						
Rene 80	JBK-75						
Waspalloy	NASA HR-1						

* Metal additive manufacturing in aerospace: a review. *Materials & Design*, p.110008. Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F. and du Plessis, A., 2021. https://doi.org/10.1016/j.matdes.2021.110008

Process-material-performance links





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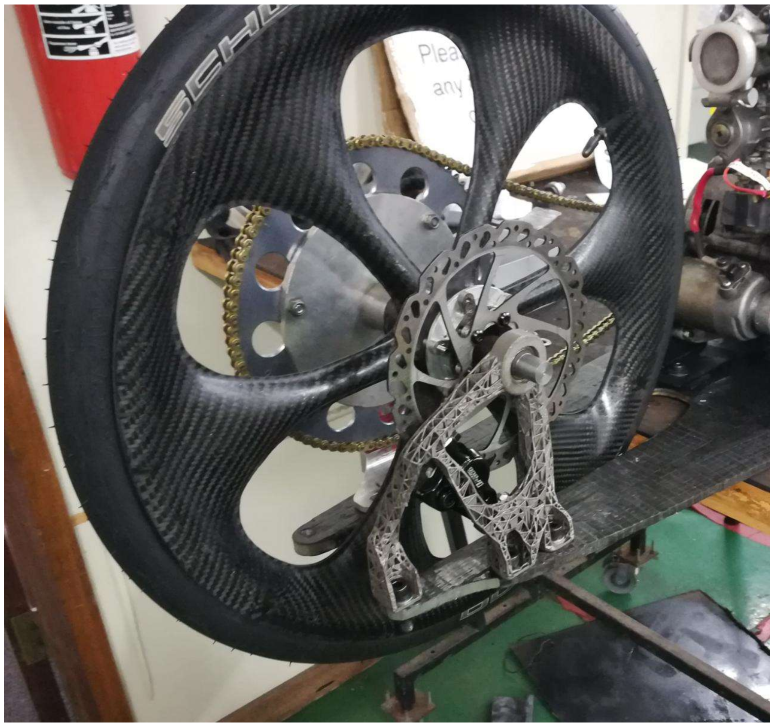

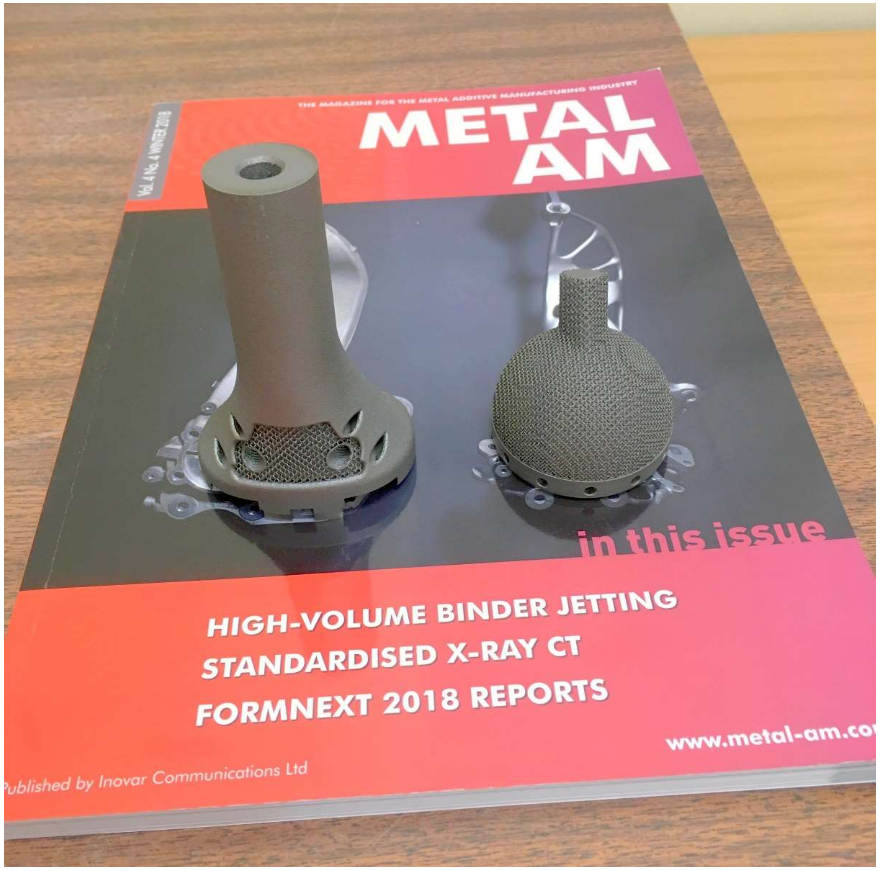
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Effect of defects

Materials and Design 194 (2020) 108899

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The effects of microporosity in struts of gyroid lattice structures produced by laser powder bed fusion

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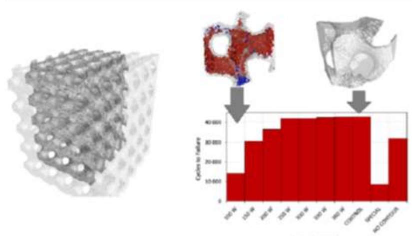
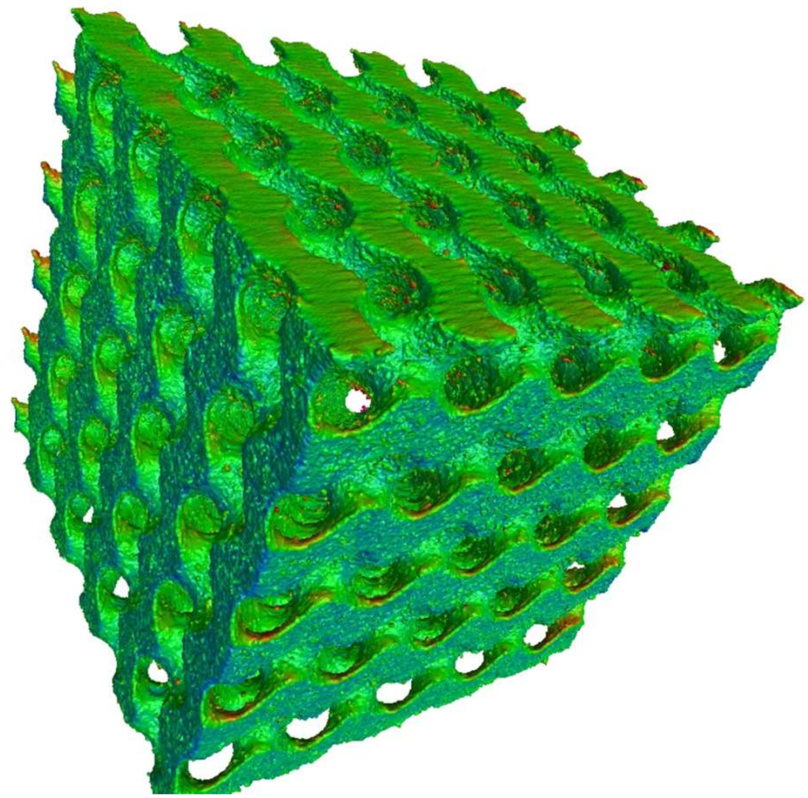
[b] Department of Mechanical Engineering, Nelson Mandela University, Port Elizabeth 6001, South Africa
[c] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU), Trondheim 7491, Norway

HIGHLIGHTS

- Microporosity induced in gyroid lattice structures by process parameters
- X-ray tomography used to confirm and quantify porosity content
- Static and fatigue compression tests performed
- Both stress-relieved and hot isostatic pressed states investigated
- Effect of porosity found to be more detrimental for lack of fusion defects

GRAPHICAL ABSTRACT





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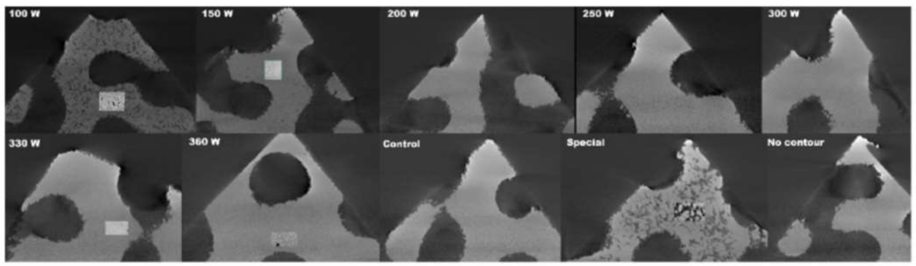

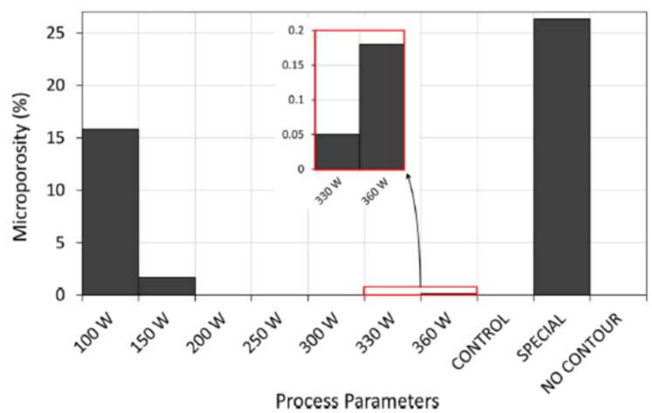

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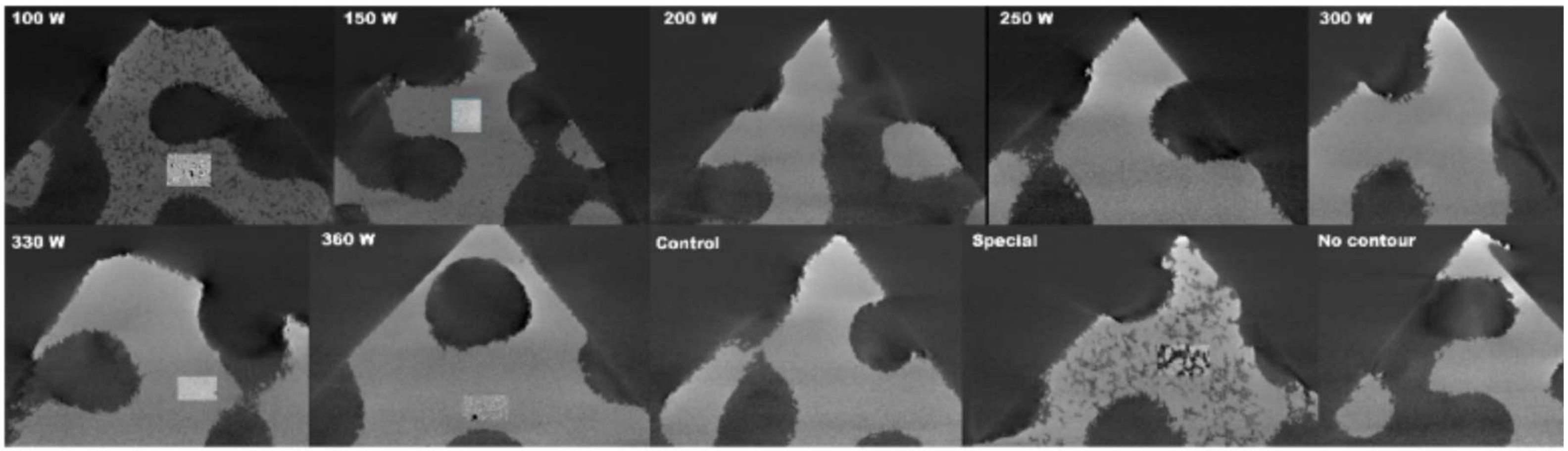

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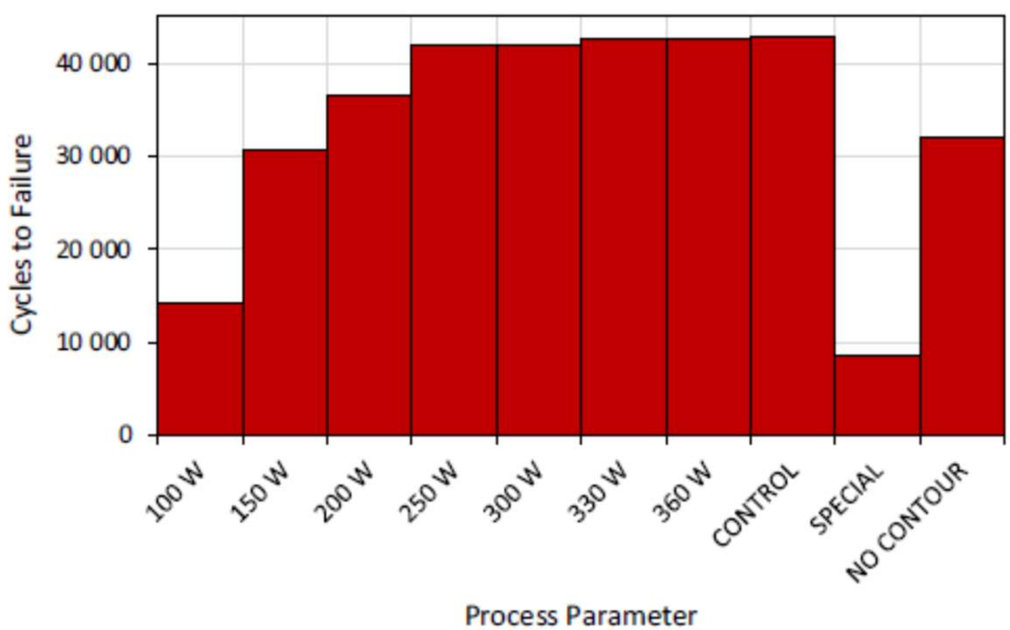
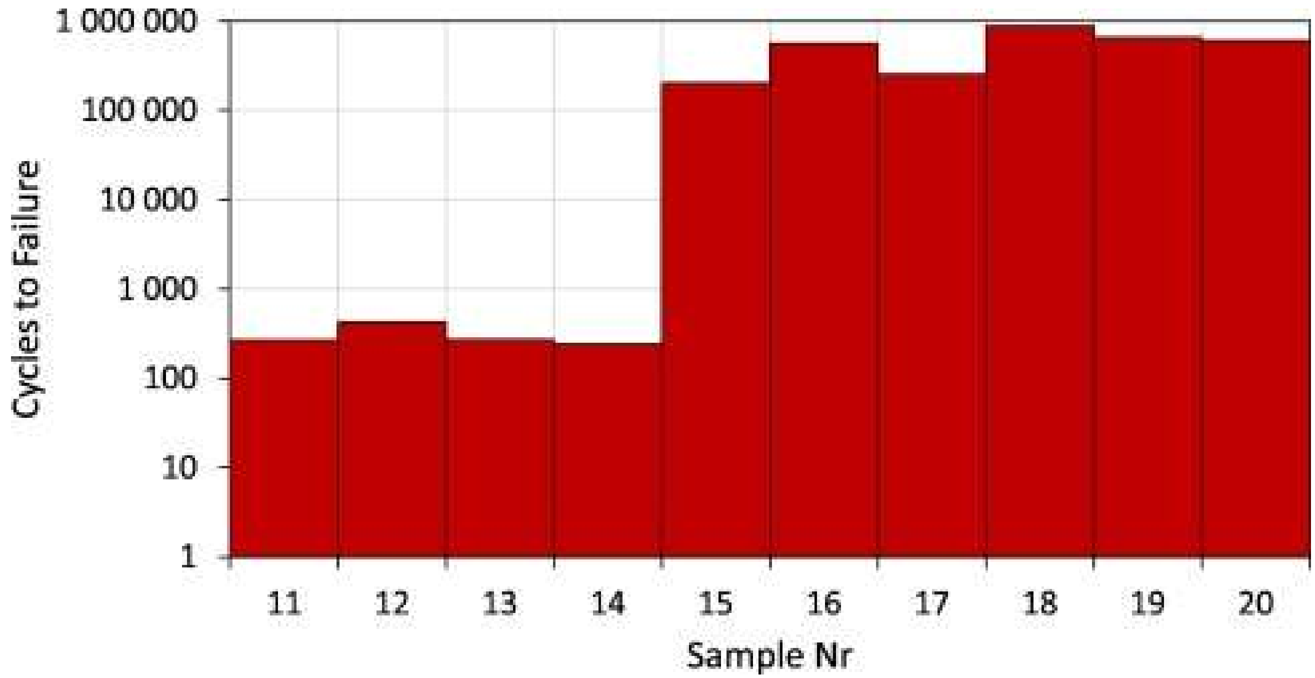
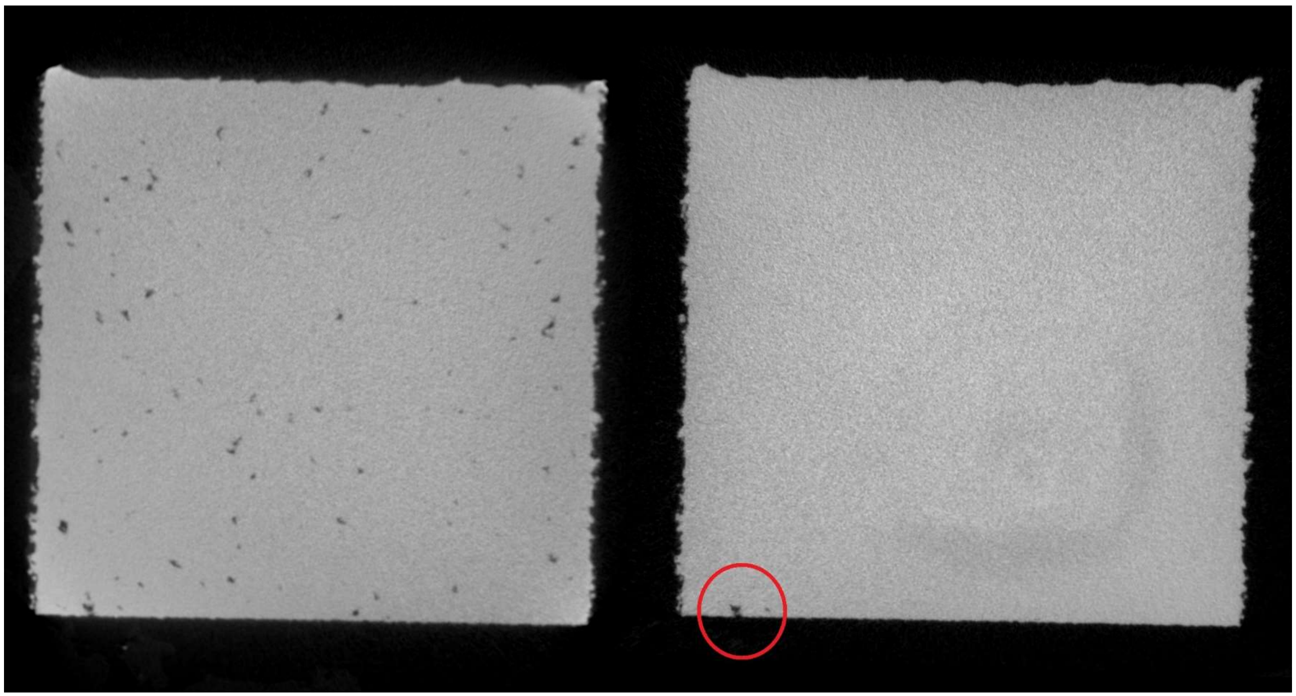


Effect of defects – HIP samples

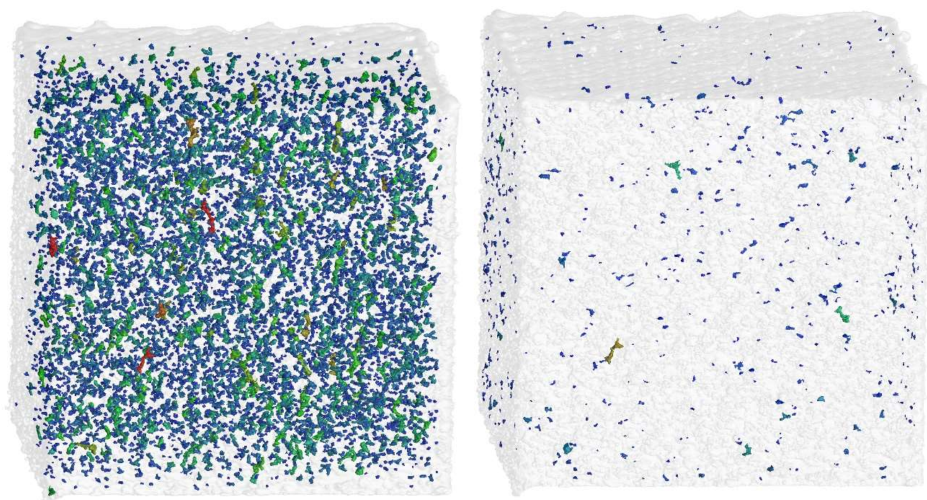


HIP of AM parts



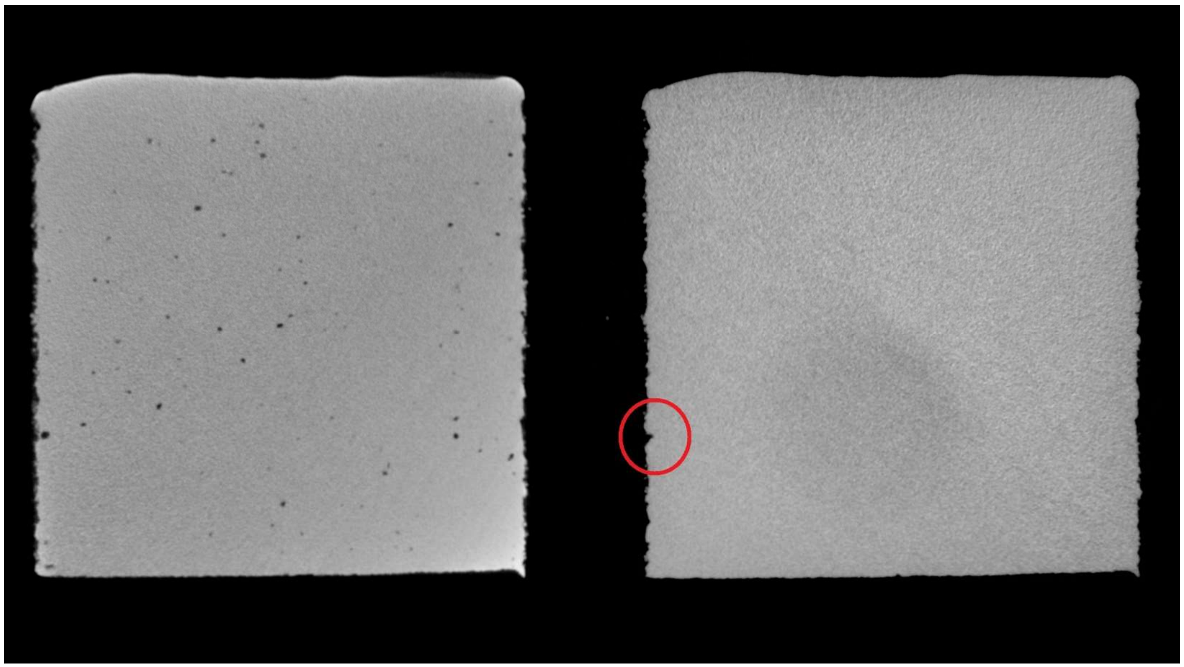
Du Plessis, A. and Macdonald, E., 2020. **Hot isostatic pressing in metal additive manufacturing: X-ray tomography reveals details of pore closure**. *Additive Manufacturing*, *34*, p.101191.

HIP of AM parts

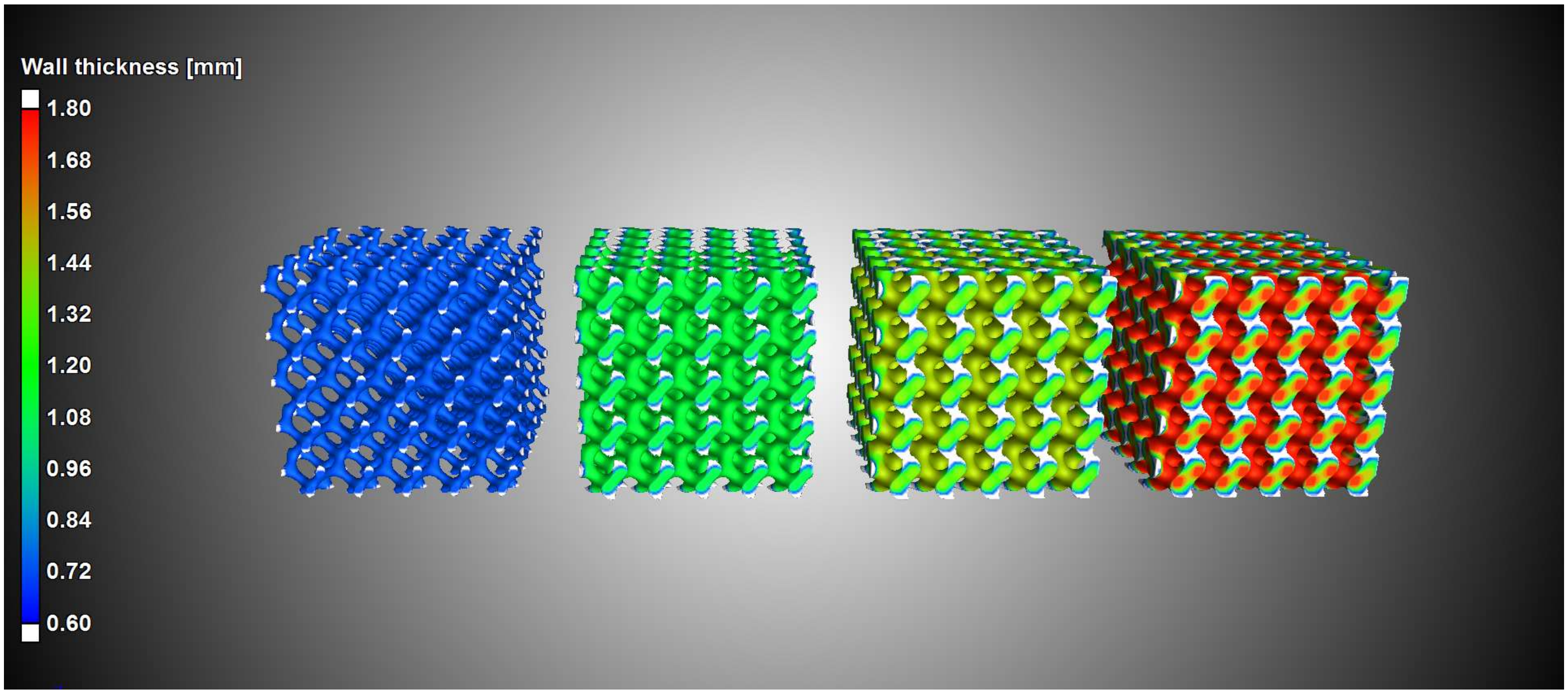


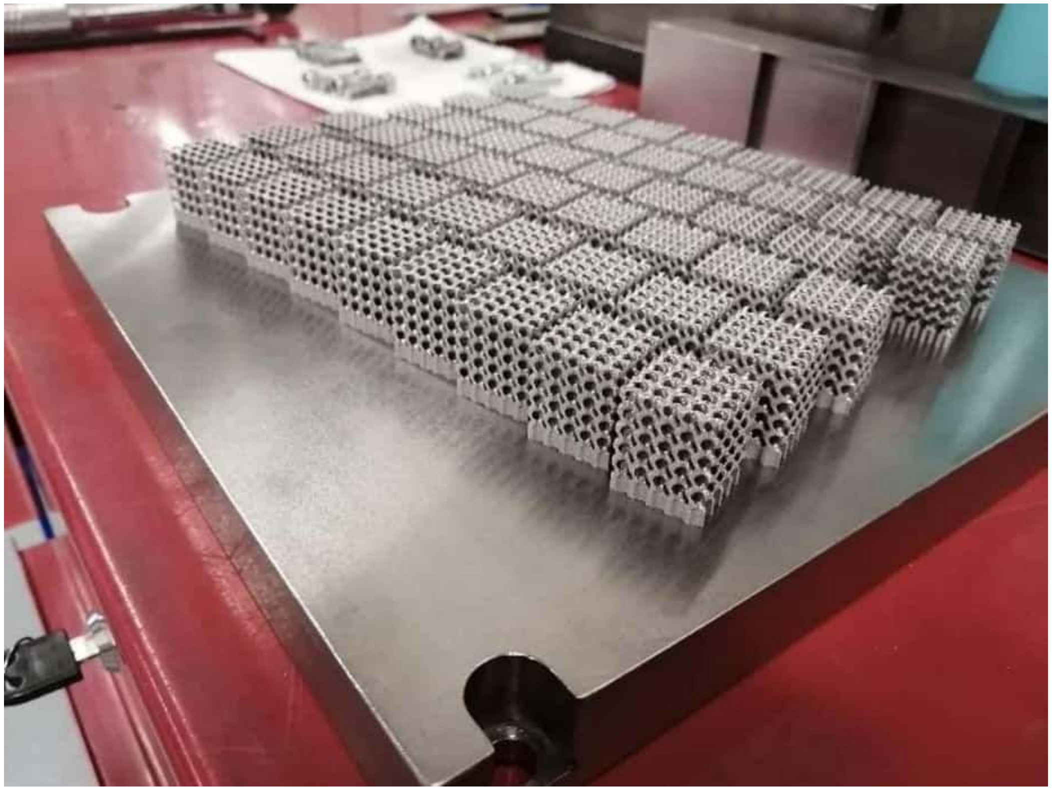
Du Plessis, A. and Macdonald, E., 2020. **Hot isostatic pressing in metal additive manufacturing: X-ray tomography reveals details of pore closure**. *Additive Manufacturing*, *34*, p.101191.

HIP of AM parts

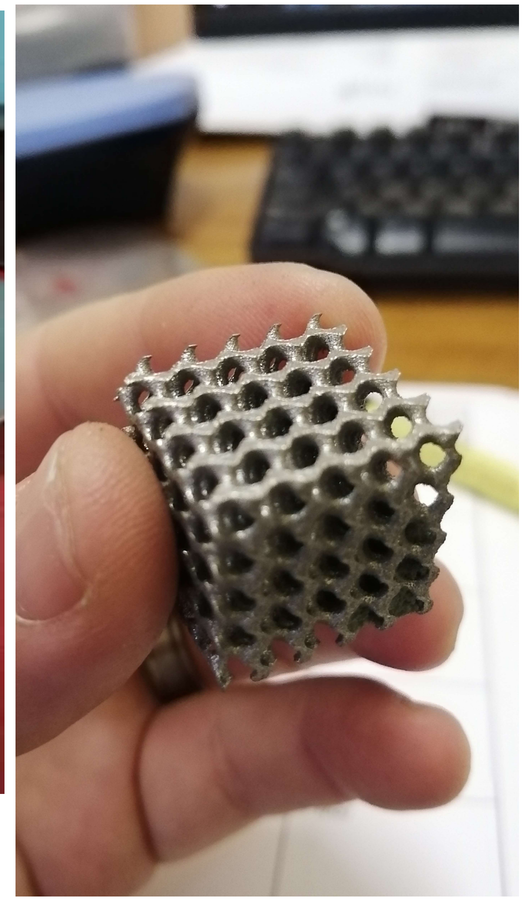


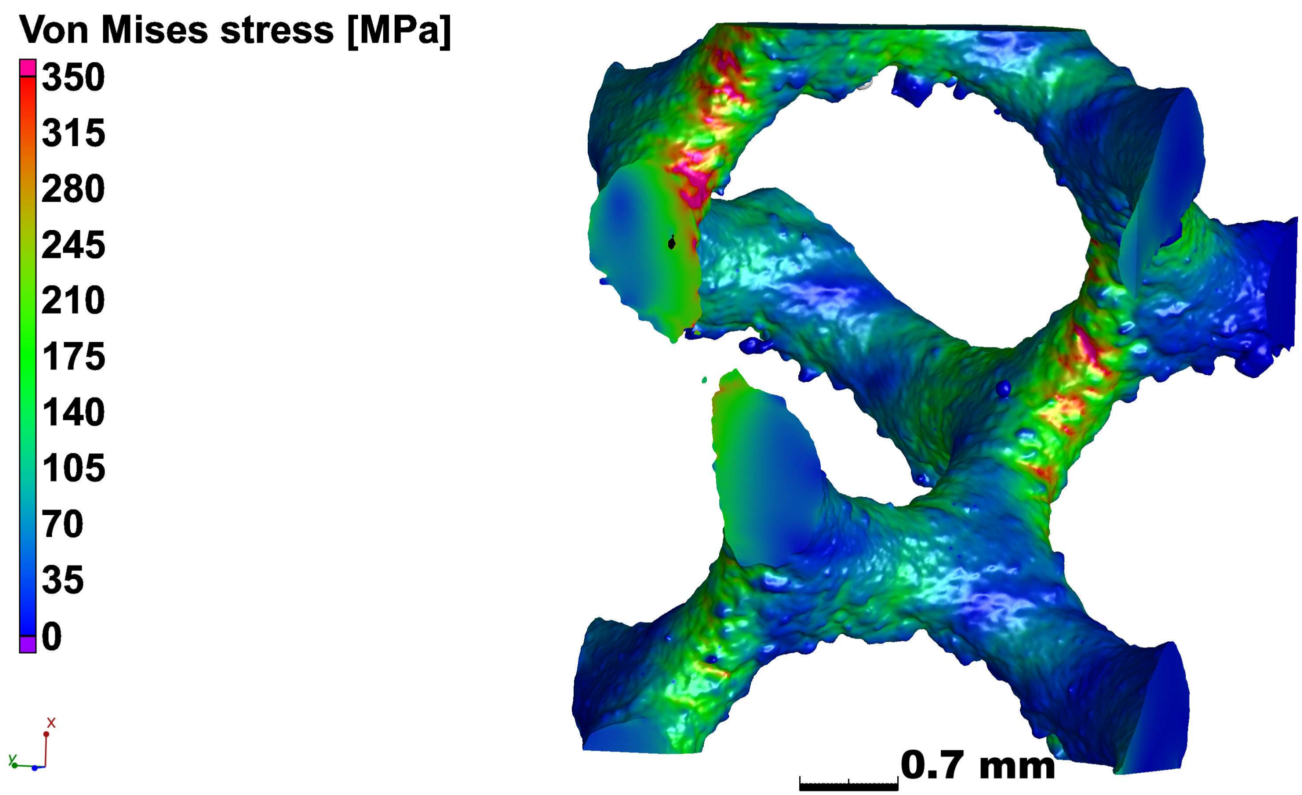
Du Plessis, A. and Macdonald, E., 2020. **Hot isostatic pressing in metal additive manufacturing: X-ray tomography reveals details of pore closure**. *Additive Manufacturing*, *34*, p.101191.

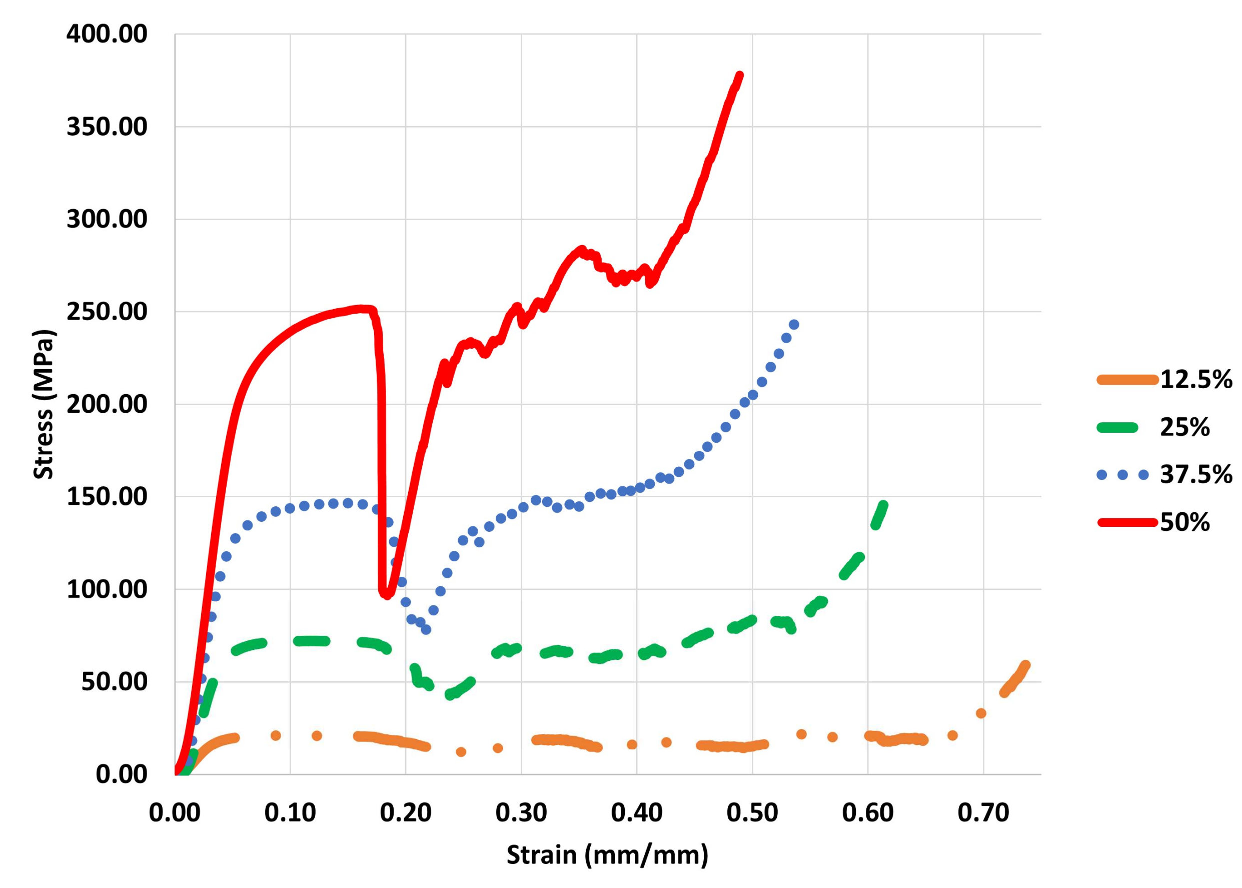

Wall thickness [mm]
1.80
1.68
1.56
1.44
1.32
1.20
1.08
0.96
0.84
0.72
0.60



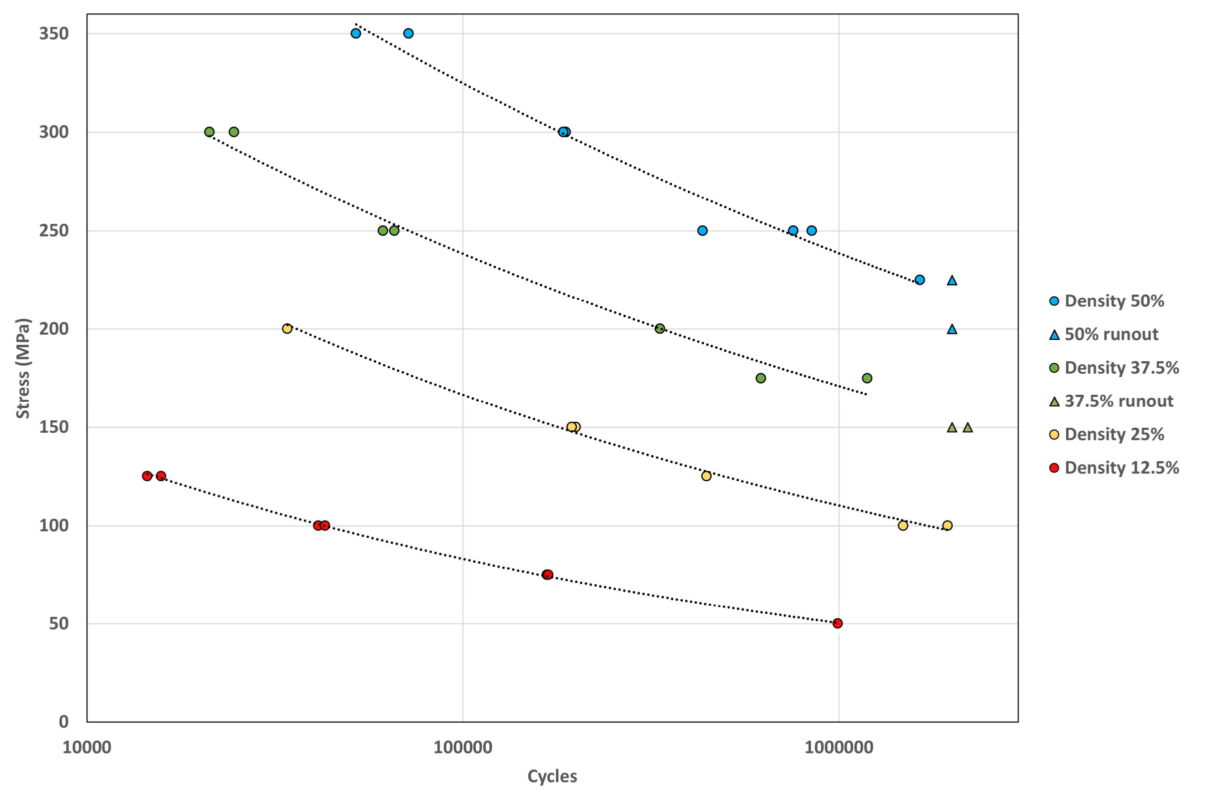
Stress relief: 650 degrees C, 3 hrs
Anneal: 940 degrees C, 2 hrs




Von Mises stress [MPa]
350
315
280
245
210
175
140
105
70
35
0
x
y
0.7 mm



400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Stress (MPa)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
Strain (mm/mm)
12.5%
25%
37.5%
50%


Stress (MPa)
350
300
250
200
150
100
50
0
10000
100000
1000000
Cycles
Density 50%
50% runout
Density 37.5%
37.5% runout
Density 25%
Density 12.5%