Contents

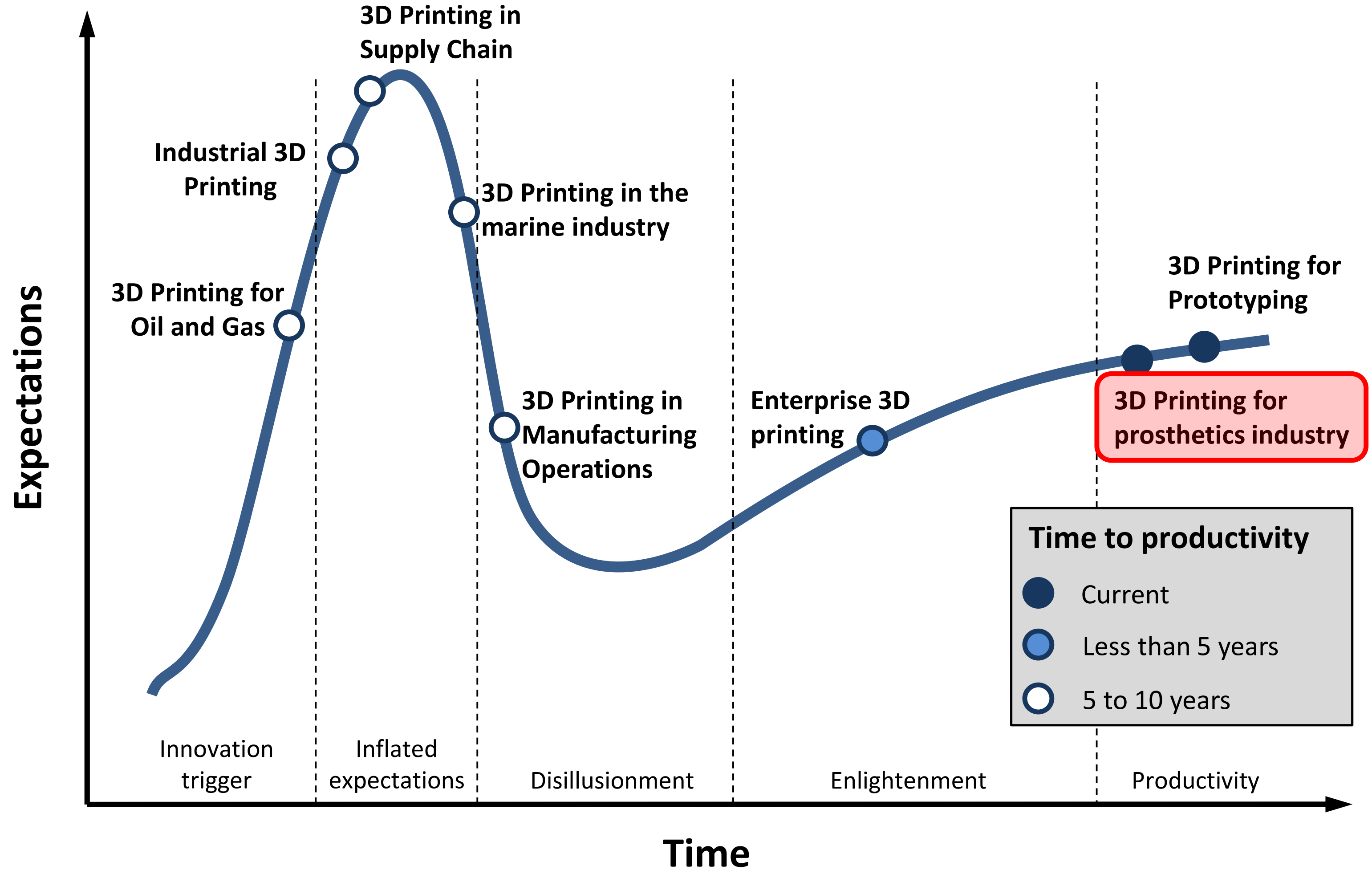
- Introduction: business case, AM evolution, examples of industries using AM at different stages of maturity (biomedical, aerospace, naval)
- Schematics of materials that can be printed with the different techniques
- Microstructural control of AM metals; epitaxy and microstructure evolution in metal AM
- Mechanical properties of metallic materials produced by AM manufacturing
  - Overview, ASTM/ISO rules, anisotropicity, defect dominated vs microstructure-dominated properties: quasi static, fatigue
  - Summary of properties for key metallic materials
  - Examples of special materials: Al alloys, high temp metals Ni superalloys, shape-memory NiTi, TiAlV
- Ceramic materials via AM
- Laser cladding
- Notes on Topology opitmization
- Architected cellular materials, new concepts (deformation curves, vibrations)
- Qualification and certification

Introduction

The business case for AM

Lower costs	Better design	Customisation	Sustainability	New business models
No tooling or cheaper tooling	Complexity for free	Ergonomics	Less waste	Prototyping
Less transportation	Added features (cooling, isola-tion, structure, porosity, con-ductivity, etc)	Interfaces with other products	Light weight	Shorten time-to-market
Less warehousing	Hybrid materials	Body contours (external and internal)	Less fuel consumption	Small series
Less working capital required	Light-weight	Aesthetics	Efficient supply chains	Supply chains (on demand, on location)
Fast	Less assembly by integrated design	Use specific variations	Life Cycle Analysis	Distributed manufacturing
				Services
				Co-creation / home creation

AM evolution



AM in the prosthetics industry

- **Prototyping**
- **Serial production of prosthetics parts with complex shapes**

Lima Corporate, Italy

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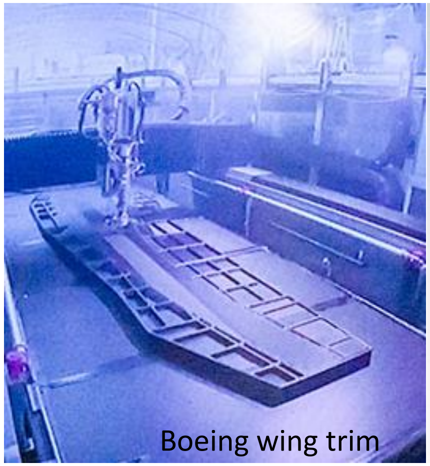
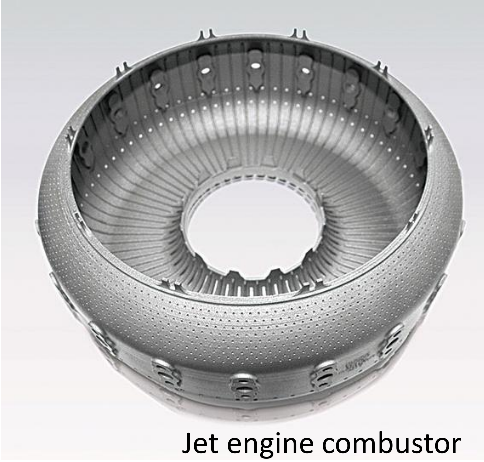
AM in the aerospace industry

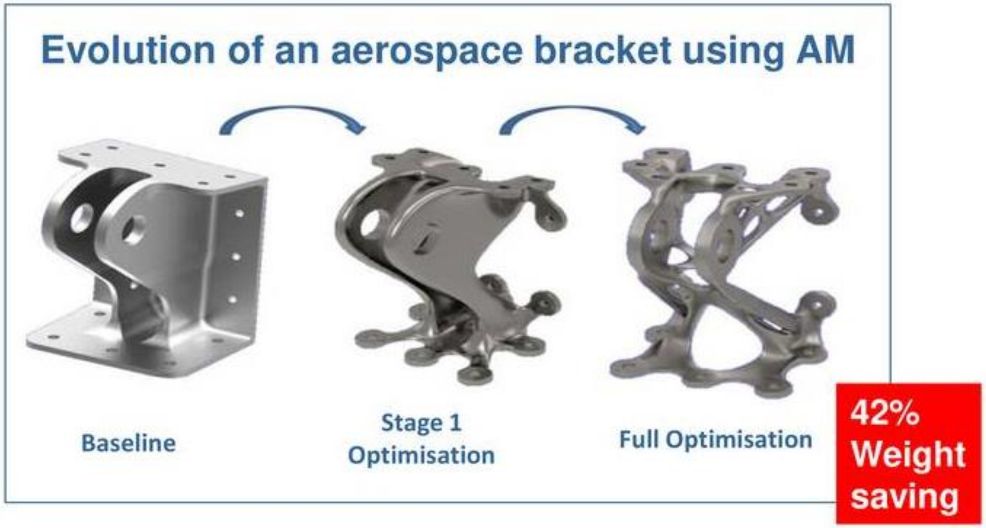
- **Prototyping**
- **Production**
- **Major drivers:**
  - Weight reduction
  - Lead time reduction



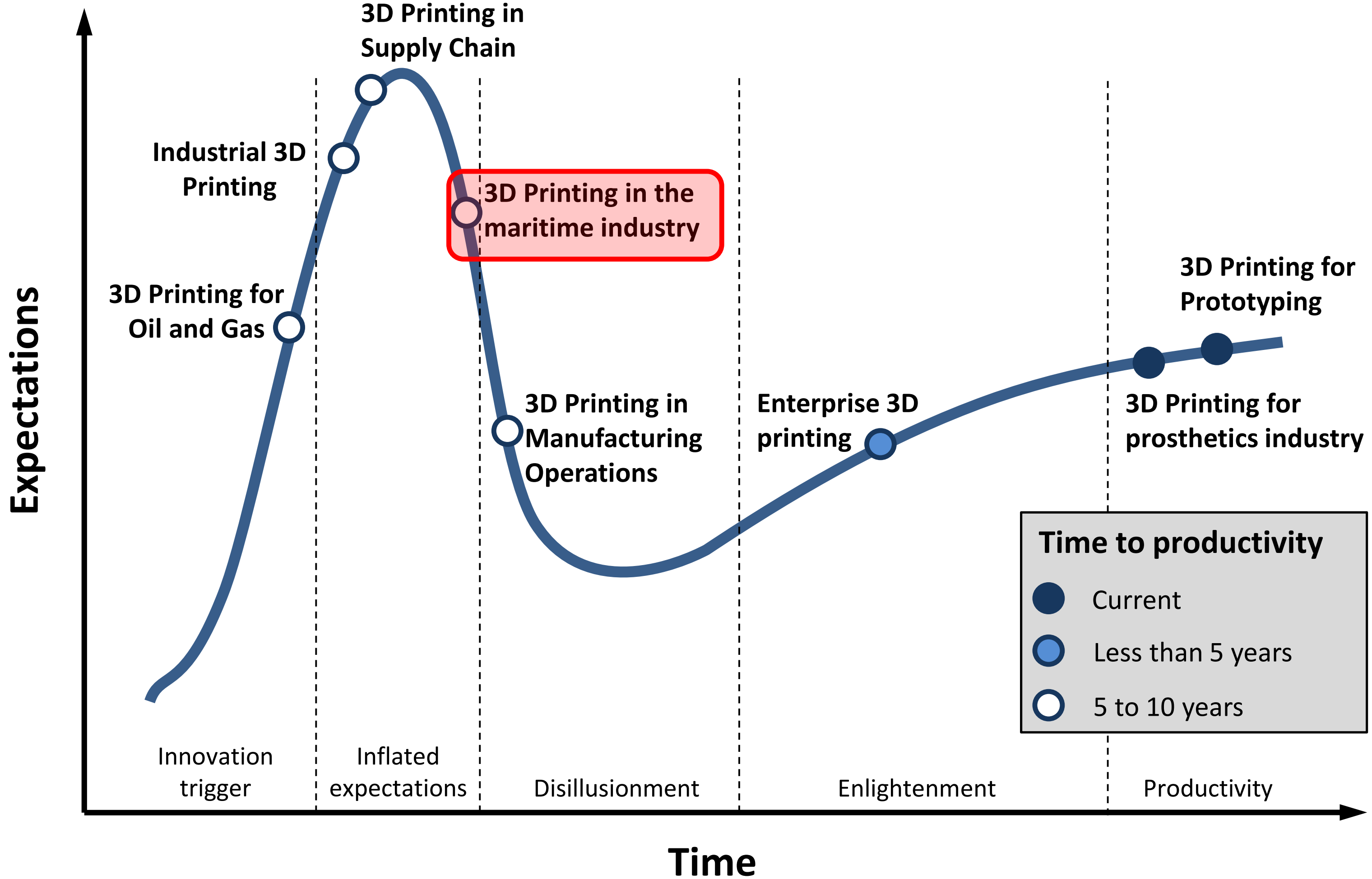
Boeing wing trim



Jet engine combustor



AM evolution



Role of AM in the maritime industry

- **Quick availability of spare parts**
  (on-board or in-port manufacturing capability, avoid large stock)

- **Fast prototyping for hydrodynamic studies**

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Examples of maritime spare parts that could be produced by AM

Which parts should be manufactured by AM?

Selection criterion: maximize AM benefits

Product design benefits

- Possibility of part consolidation
- Weight or volume reductions
- Integrated functionalities
- Less waste

Supply chain benefits

- Low volume production
- Reduced lead times
- Decreased inventory or stock levels
- Less supplier risks
- Lower location based costs

AM benefit score

#	Part	Part Consolidation	Weight/Volume Reductio	Integrated Functionality	Less Waste	Low Volume	Lead Time	Inventory	Supplier Risk	Location based costs	AM Score	
1	Propeller Marin (real/scale)	1	1	1	1	1	1	1	1	0	8	High potential; potential for part consilidation, weight reduction, improve functionality,
2	Cooled valve seat Ruysch	1	0	1	0	0	1	0	0	0	3	Medium potential due to high volume production of part, complexity medium
3	Space ring Huisman	0	0	0	0	1	1	1	1	1	5	High potential due to low volume part, long lead time, high cost to manufacture
4	Hinge Fokker	1	1	1	1	1	1	1	1	0	8	High potential; Weight reduction, less waste, part optimized for AM production
5	T connector Heerema	1	0	0	0	0	1	1	1	0	4	Medium potential; cost reduction in making of cast, surface roughness is issue
6	Jig to glue seals Aegir	0	0	0	0	0	1	1	1	1	4	Medium potential; reduction in logistic costs only if printed locally where part is needed, long lead time
7	Hydraulic manifold Huisman	1	1	1	0	0	0	0	1	0	4	Medium protential; weight reduction, integrated functionality
8	Neck flange	0	0	0	0	0	0	0	0	0	0	Technically and economically not challenging enough compared with conventional manufacturing
9	Swivel connector	0	0	0	0	0	0	0	0	0	0	Threaded rod technically not feasible with DMG, EOS, Ex-One and economically not challenging enough compared with conventional manufacturing
10	Wear rings (non ferro) bronze series of impeller	0	0	1	1	1	1	1	0	0	5	Medium potential; new super alloys could reduce wear and tear, increase livespan impeller
11	Mechanical seal	1	0	1	0	0	1	0	0	0	3	Medium potential; part consolidation, integrated functionality if technically feasible
12	Eccentric reducer	1	0	1	0	0	1	1	1	0	5	Medium potential; depending on size (large size, low volume production)
13	Worm wheel (bronze)	0	0	0	0	0	0	0	0	0	0	Threaded rod technically not feasible with DMG, EOS, Ex-One and economically not challenging enough compared with conventional manufacturing
14	Worm shaft (alloy steel)	0	0	0	0	0	0	0	0	0	0	Threaded rod technically not feasible with DMG, EOS, Ex-One and economically not challenging enough compared with conventional manufacturing
15	Piston for air compressor (non ferro)	0	0	0	0	0	1	0	0	0	1	Technically feasible, economically not challenging enough compared with conventional manufacturing
16	Structural fastener	0	0	0	0	0	0	0	0	0	0	Technically and economically not challenging enough compared with conventional manufacturing
17	Bearing shell (tri metal)	0	0	1	0	0	0	0	1	1	3	Potential for lasercladding different materials on base material, cost of convential production probably cheaper
18	Box heat exchanger	1	1	1	1	1	1	1	0	0	7	High potential; Part consolidation, weight reduction etc. proven benefits in other markets for instance formula 1
19	Screw pin shackle	0	0	0	0	0	1	1	1	0	3	Medium potential; depending on size (large size, low volume)
20	Open spelter socket	0	0	0	0	0	1	1	1	0	3	Medium potential; depending on size (large size, low volume)
21	Wire rope cable sheave	1	1	1	0	0	1	0	0	0	4	Medium potential; part consolidation, integrate functionality such as hardness of material to reduce wear and tear
22	Twist lock pin	0	0	0	0	0	0	0	0	0	0	Technically and economically not challenging enough compared with conventional manufacturing
23	Alum / Steel transition joint	1	0	0	0	1	1	0	1	0	4	Medium potential; part consolidation,low volume production part, few suppliers. Technically feasible to be determined.
24	Hydraulic hose end fitting	0	0	0	0	0	0	0	0	0	0	Threaded rod technically not feasible with DMG, EOS, Ex-One and economically not challenging enough compared with conventional manufacturing
25	Eyebolt	0	0	0	0	0	0	0	0	0	0	Threaded rod technically not feasible with DMG, EOS, Ex-One and economically not challenging enough compared with conventional manufacturing
26	Exhaust gas manifold	1	1	1	1	1	1	1	1	1	9	High potential; depending on complexity of the manifold, potential weight reduction, production volume
27	Weldolet	1	0	1	0	0	0	1	0	0	3	Medium potential: potential to consolidate parts/improve functionality, however surface finish important factor to take into consideration
28	Turbocharger nozzle ring	1	1	1	1	1	1	1	1	1	9	High potential: improve heat and corrosion resistance, reduce long lead times, see for instance Tru Marine Singapore example
29	Turbocharger gas inlet/outlet casing	1	1	1	1	1	1	1	0	0	7	High potential; potential for part consilidation, weight reduction, improve functionality
30	Valve constituent parts (valve disk)	0	0	1	0	0	1	0	0	0	2	Technically and economically not challenging enough compared with conventional manufacturing

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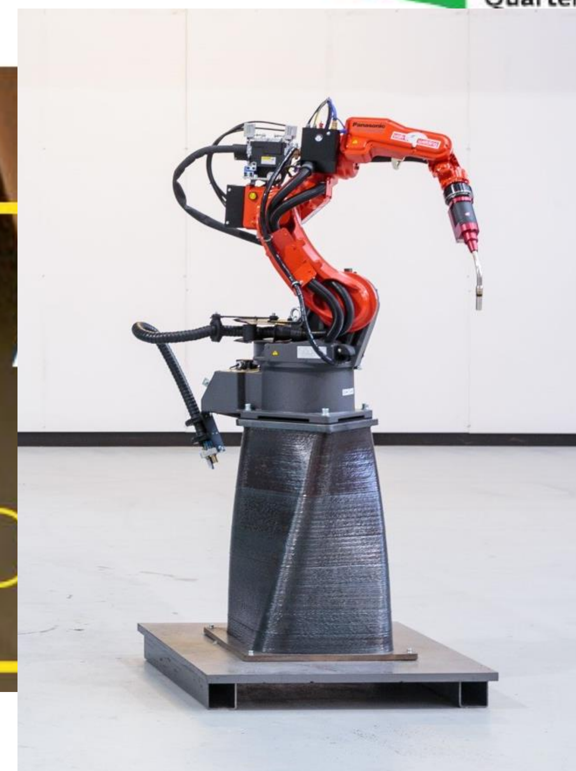
Raising interest for AM in maritime applications



Raising interest for AM in the Valve Manufacturing Industry

VALVE MAGAZINE
THE OFFICIAL MAGAZINE OF THE VALVE MANUFACTURERS ASSOCIATION OF AMERICA

FEATURES

Additive Manufacturing: Will It Change the Valve Industry?

26 May 2015 Written by Arie Bregman and Kate Kunkel

VALVE MAGAZINE
THE OFFICIAL MAGAZINE OF THE VALVE MANUFACTURERS ASSOCIATION OF AMERICA

3D Printing: A New Era for Valve Manufacturing?

05 Jul 2016 Written by Kate Kunkel

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EMERSON OPENS SECOND ADDITIVE MANUFACTURING CENTER

Monday, March 27, 2017

Share

With the goal of spurring innovation to address customers' engineering design challenges and accelerating speed to market for new, rigorously-tested products, Emerson opened an advanced additive manufacturing center at its Singapore campus. More....

Shan-Rod

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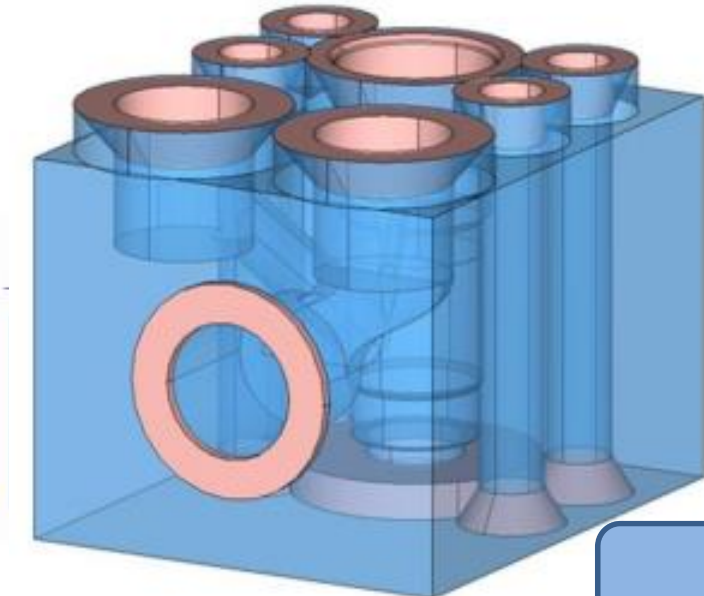
3D PRINTING FOR VALVE MANUFACTURERS

Posted on December 16, 2016 at 2:44 pm.

ADDITIVE MANUFACTURING REVOLUTIONIZES VALVE PRODUCTION

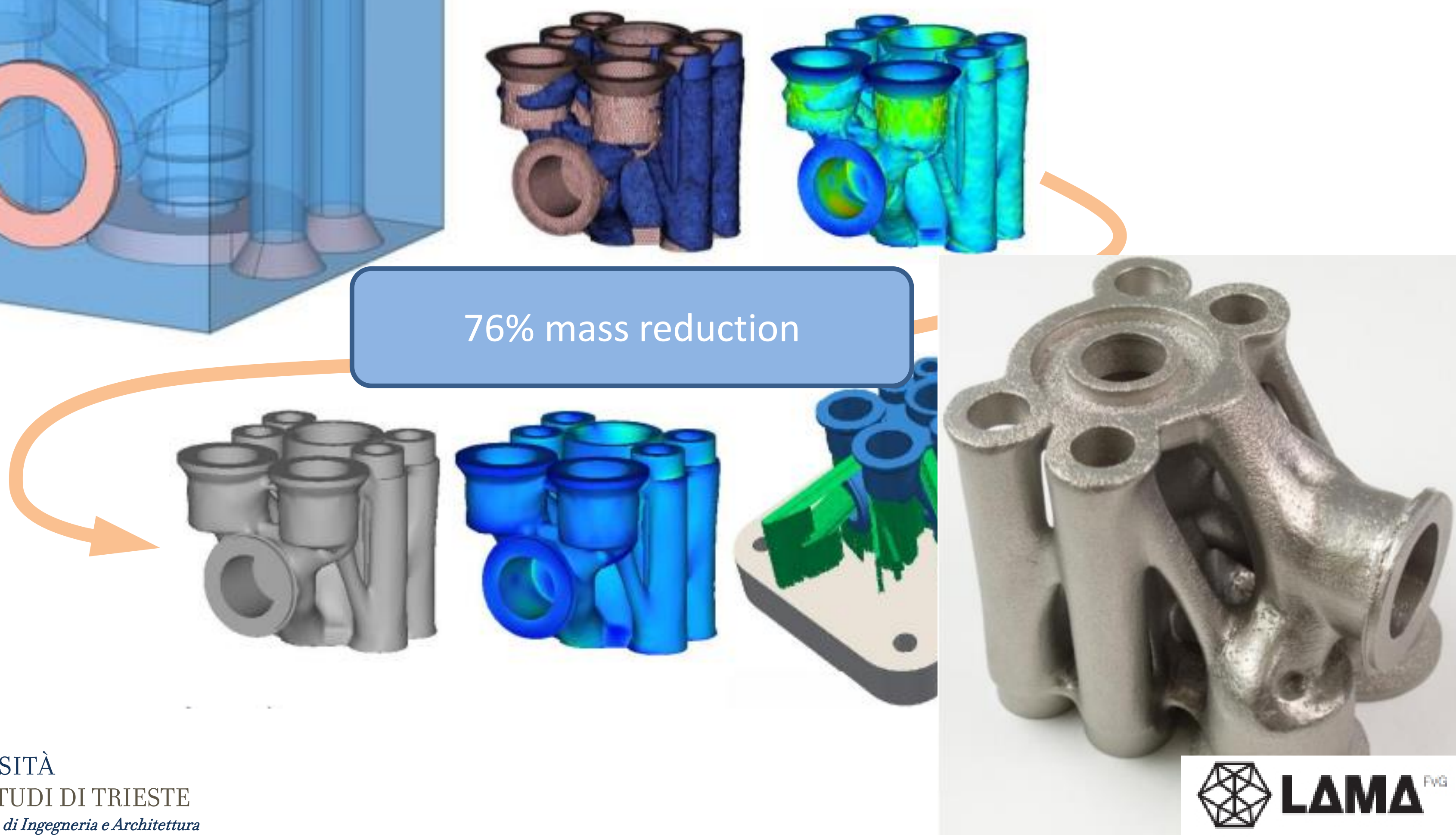
3D printing falls into the category of additive (as opposed to traditional subtractive) manufacturing. A trending technique for scientists, engineers and hobbyists alike, 3D printing has revolutionized everything

AM in the VM industry
The opportunty for better design



Hydraulic Valve Block Re-Design

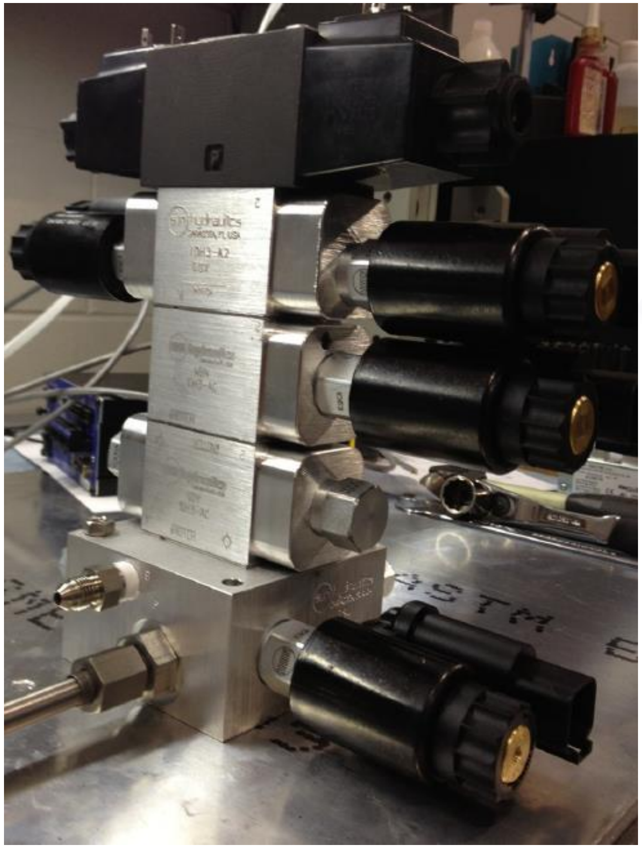
(VTT Finland)

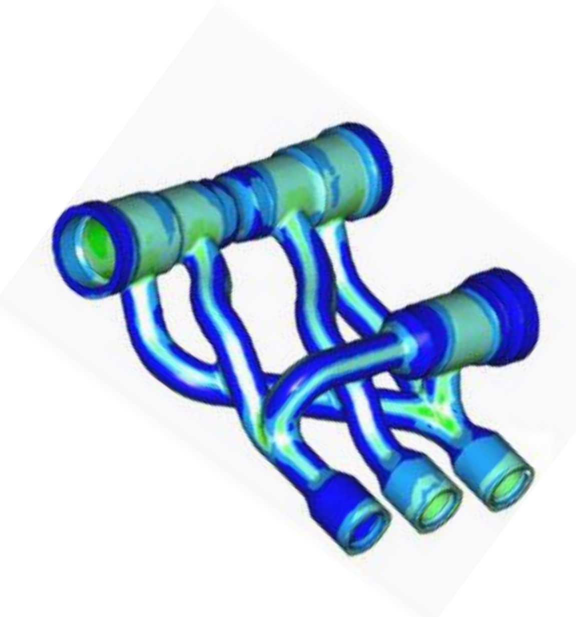


AM in the VM industry
The opportunty for better design

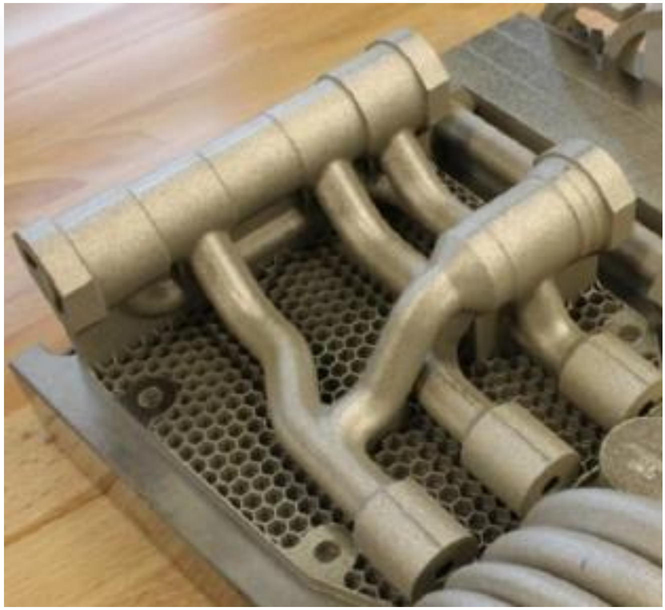
Hydraulic Manyfold Re-Design

J. Mech. Design 137, 111404-1 (2015)



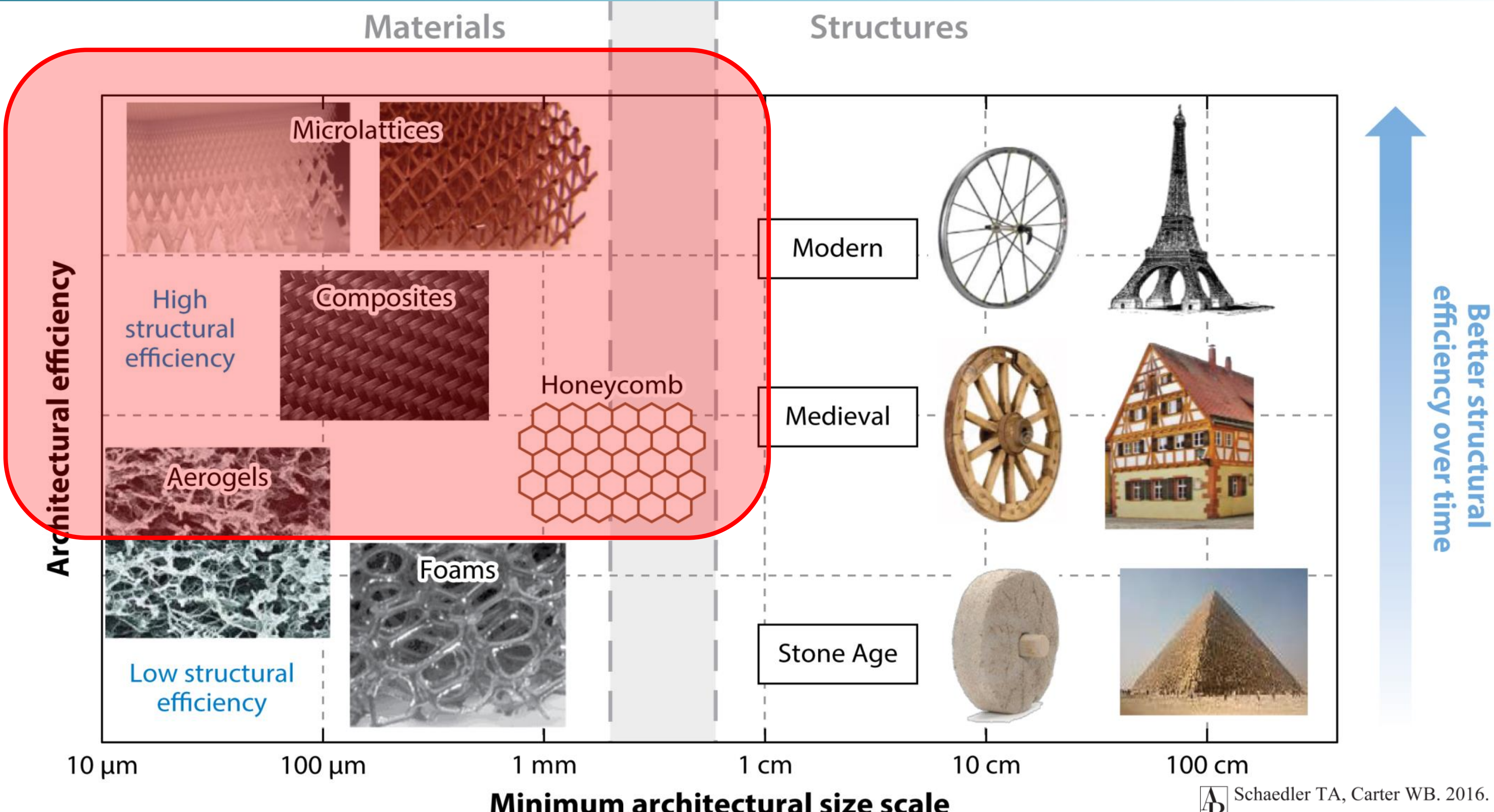


60% weight reduction
53% max heigth reduction



Better desing with Architected materials

- AM as an opportunity for high architectural efficiency and function integration -



Schaedler TA, Carter WB. 2016. Annu. Rev. Mater. Res. 46:187–210

AM: Limits and Challenges

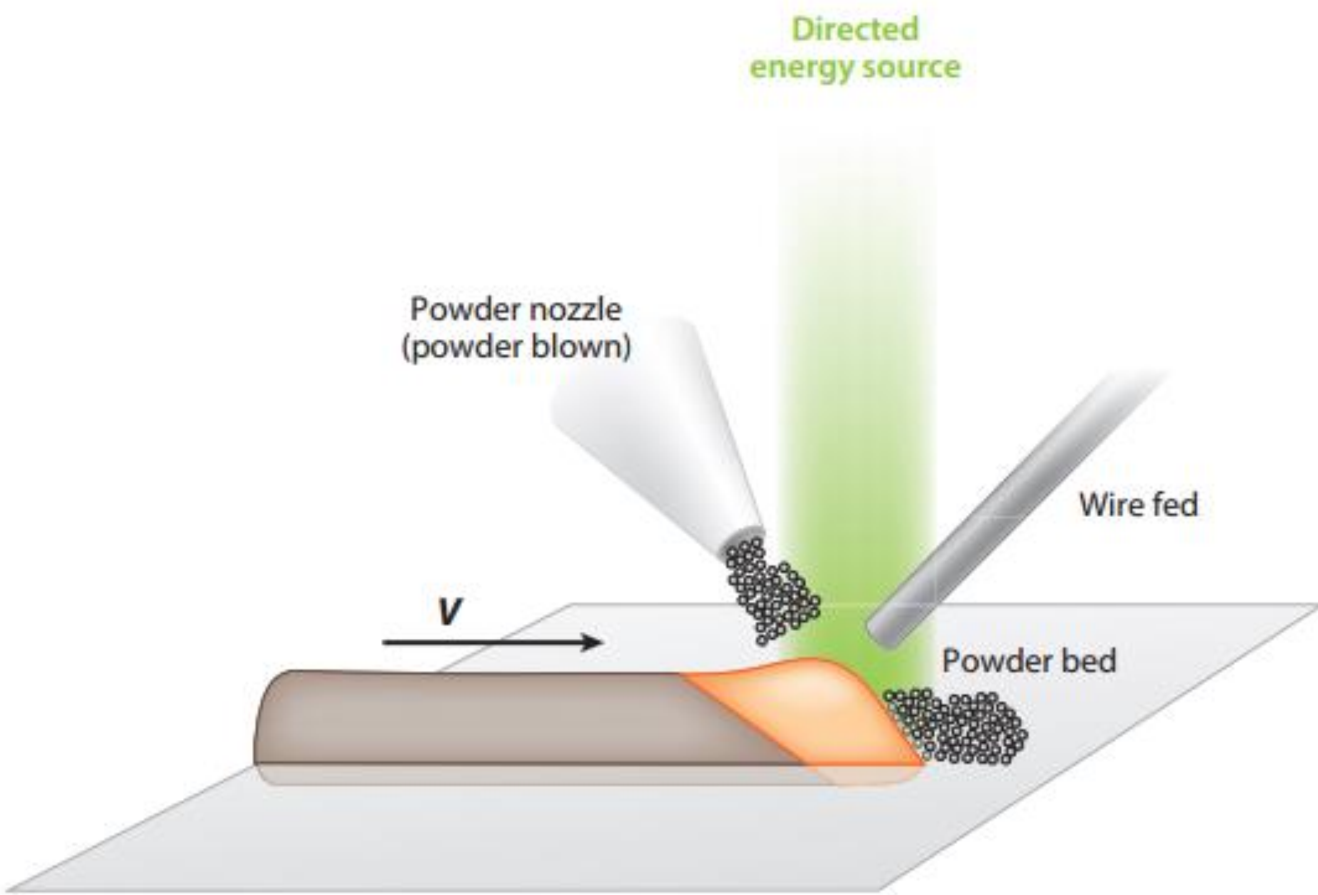
- Size
- Cost (capital, materials)
- Surface finish
- Maturity of design engineers
- Intellectual Property and Liability
- **Materials**
- **Qualification and Certification**

"The single biggest obstacle to widespread use of AM parts for structurally critical components are the cost and time associated with qualification and certification"

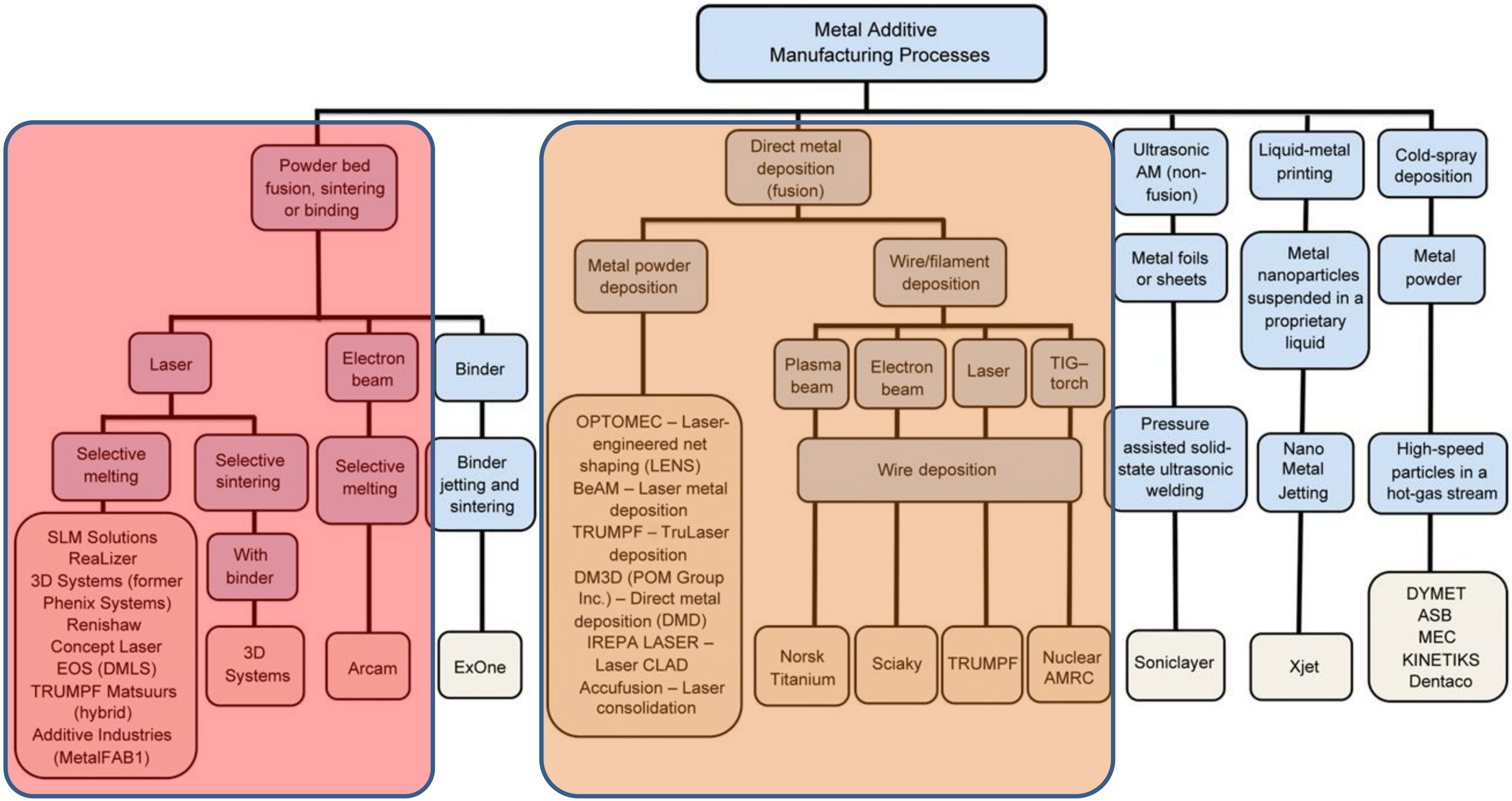
- William E. Frazier, US Naval Air Systems Command -

Materials Issues

Wide range of AM processes

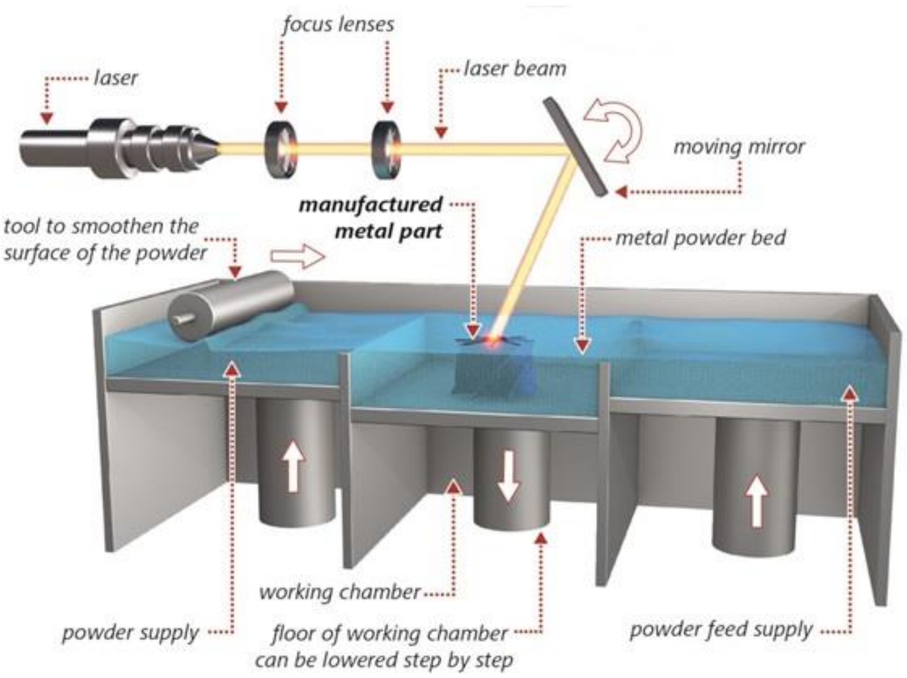


Wide range of AM processes

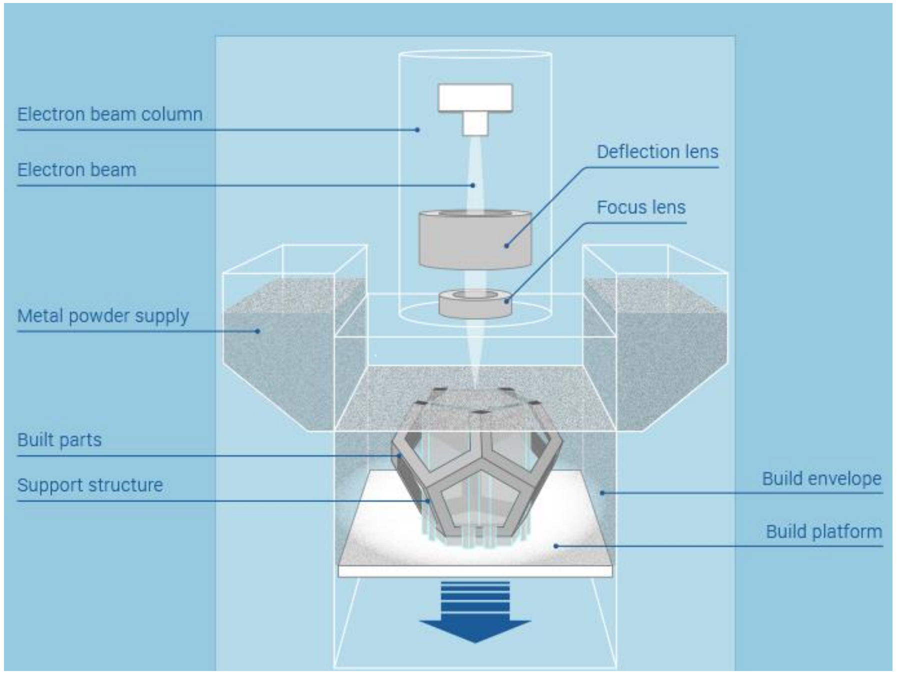


Processess that guarantee reliability and quality today for metallic AM components

Selective Laser Melting



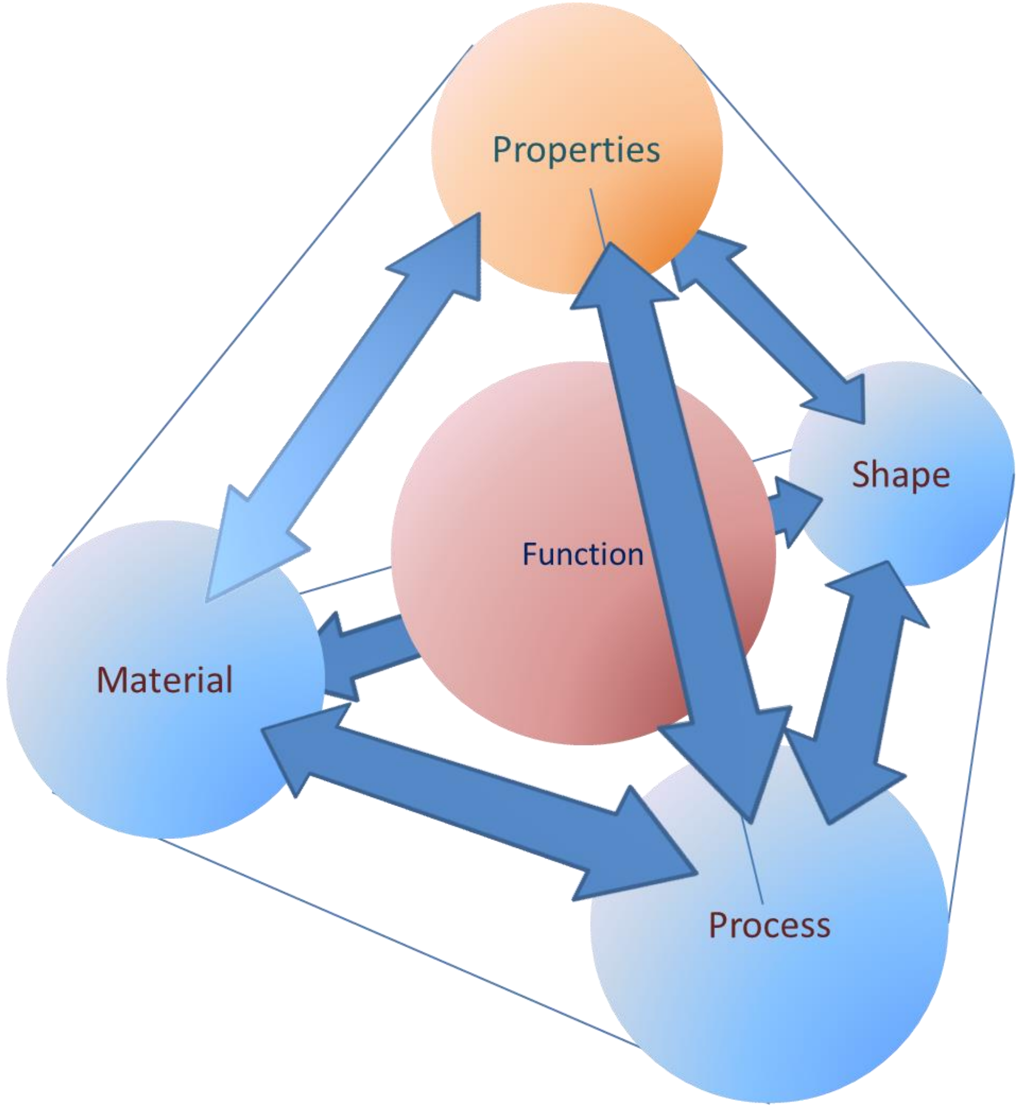
Electron Beam Melting



Wide range of materials for AM

- Titanium (pure, Al-V alloy, …)
- Steels (including stainless)
- Ni-Cr alloys (e.g. Inconel)
- Aluminum and aluminum alloys
- Cobalt-chrome alloys
- Copper and bronze
- Iron
- Precious metals

Materials, process, structure, geometry



Materials, process, structure, geometry in AM

Materials and Process Key Parameters

- Powder morphology, size, distribution
- Power, *P*
- Scan speed, *v*
- Scan pattern
- Track spacing, *h*
- Powder layer thickness, *t*
- Spot diameter, *d*
- Powder feed rate

Process Physical Parameters

- Thermal gradients
- Liquid-solid interface velocity
- Pool melt size

Material Characteristics

- Morphology
- Texture
- Residual stress
- Composition

Material Properties

- Tensile strength
- Elongation
- Toughness
- Hardness
- …

Materials science approach

Engineering Approach

$$E_{SLM} = P/vht$$

$$E_{LMD} = P/vd$$

- Correlations are complex, strongly coupled, still sporadically explored
- The science of fusion welding, solid-state welding, and powder metallurgy help in understanding the mechanisms that control microstructure in AM

Microstructure of AM metals

Microstructure of AM metals

Macro-level microstructural features

- Material and microstructureal discontinuities
- Residual stresses
- Texture

Micro-level microstructural features

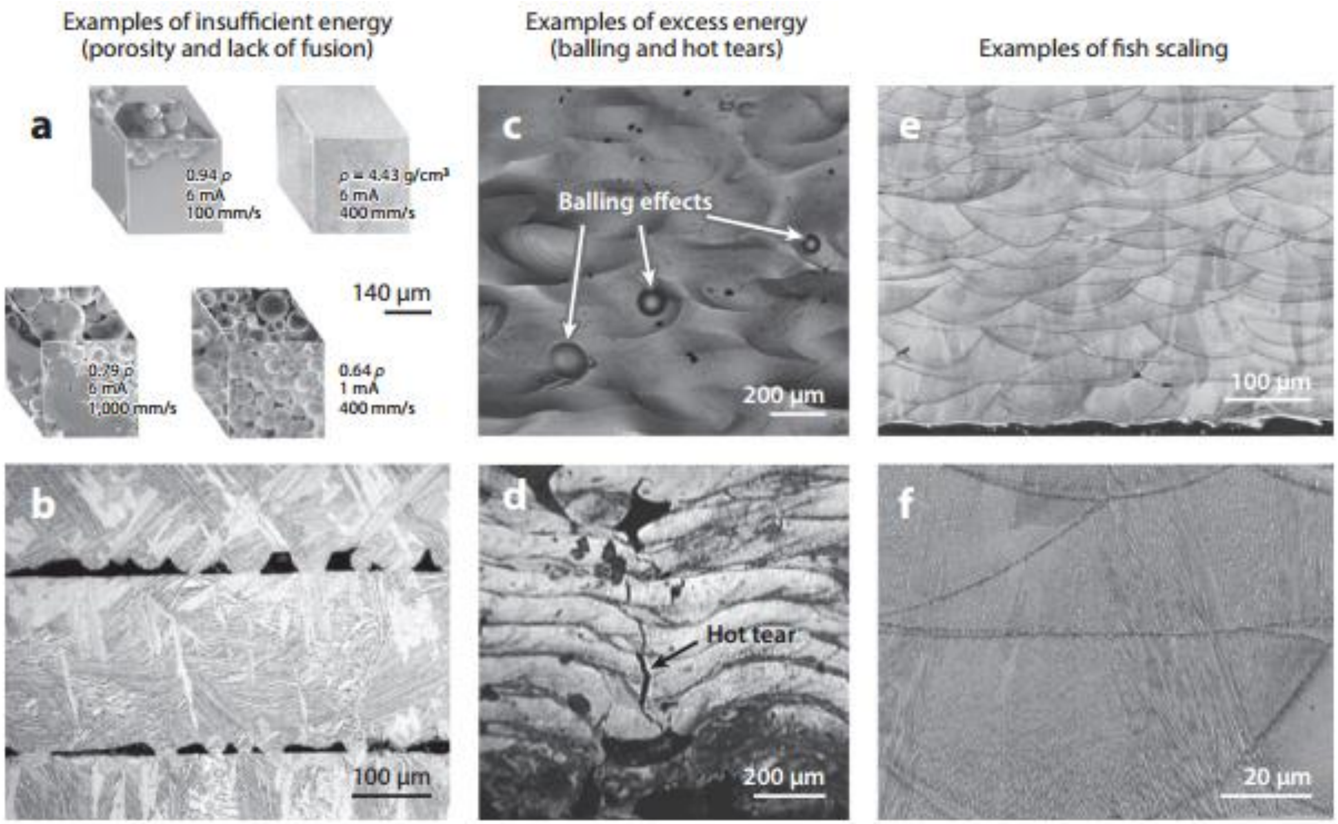
- Grain size and morphology
- Phases

Process-induced effects on composition

- Bulk compositional variation
- Nonequilibrium partitioning

Microstructure of AM metals

Macro-level microstructural features: <u>Material and microstructural discontinuities</u>

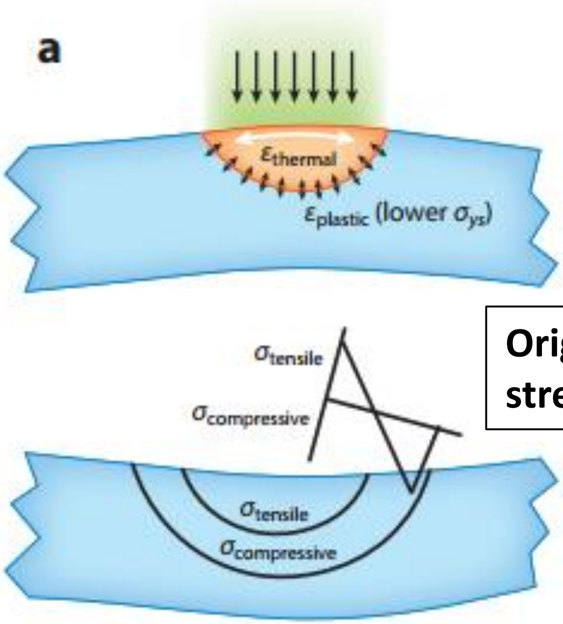


Annu. Rev. Mater. Res. 2016.46:63-91

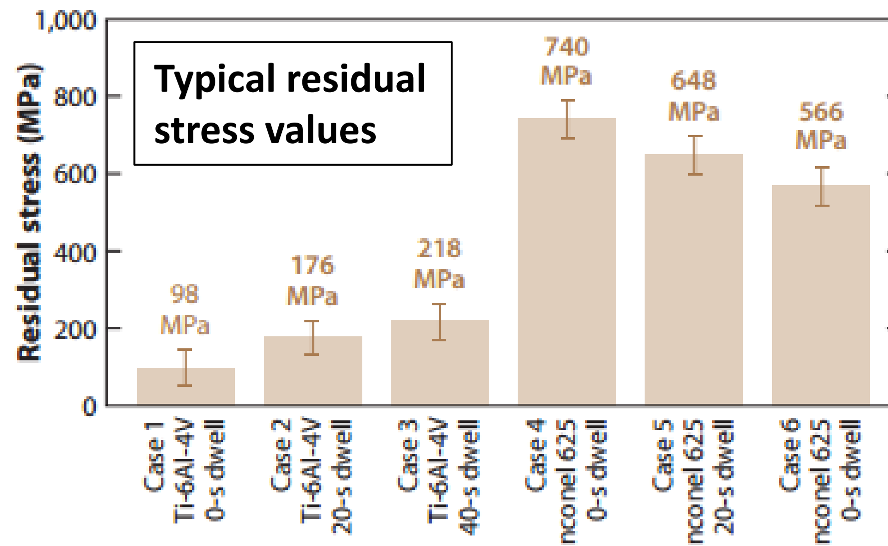
Note: A minimum of energy is required for fully dense material; however this can be incompatible with certain microstructures or phases!

Microstructure of AM metals

Macro-level microstructural features: Residual Stress

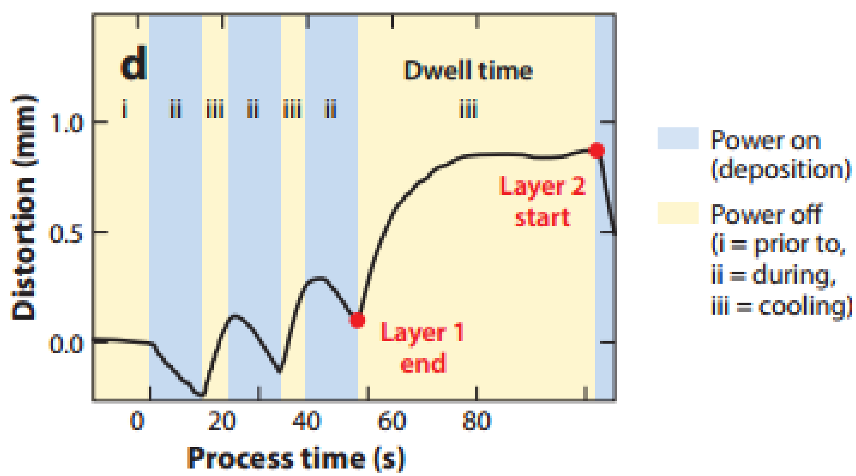


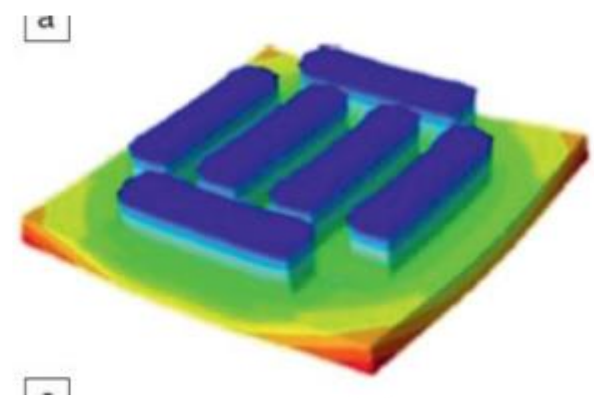
Origin of stress



Typical residual stress values

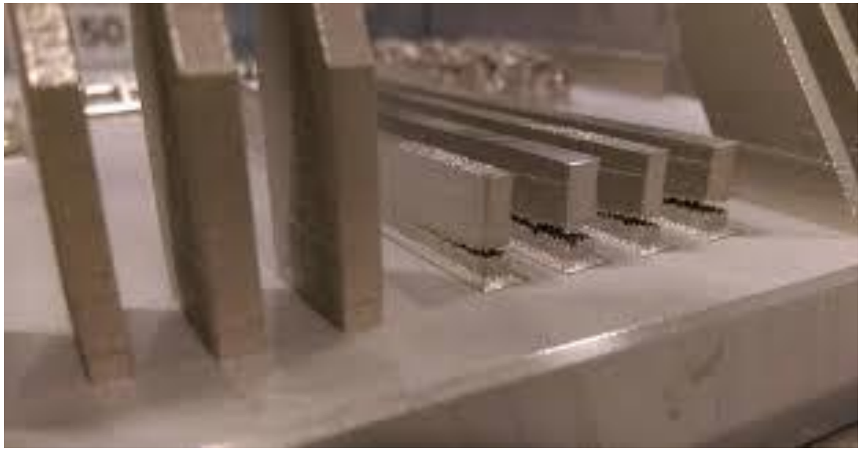
Stress-induced distortion

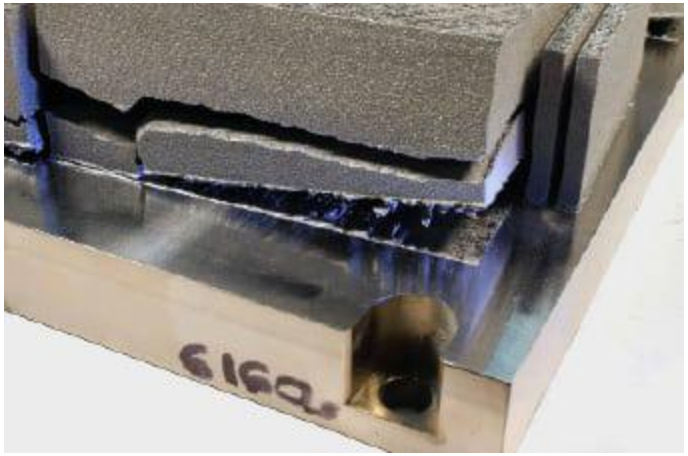




Microstructure of AM metals

Macro-level microstructural features: Residual Stress

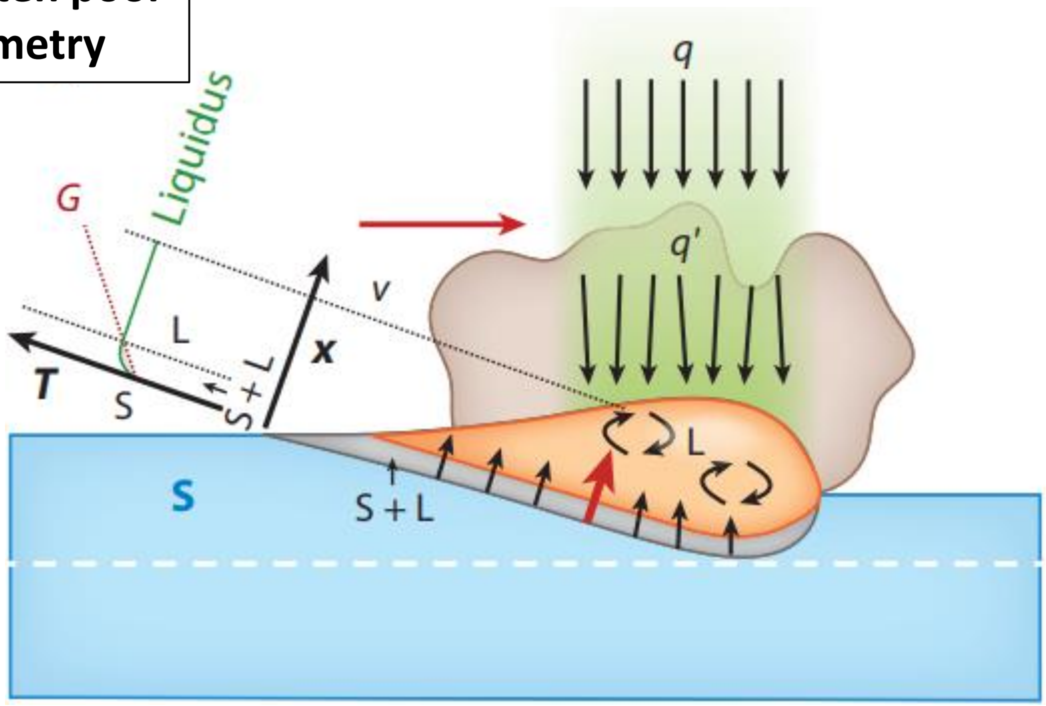


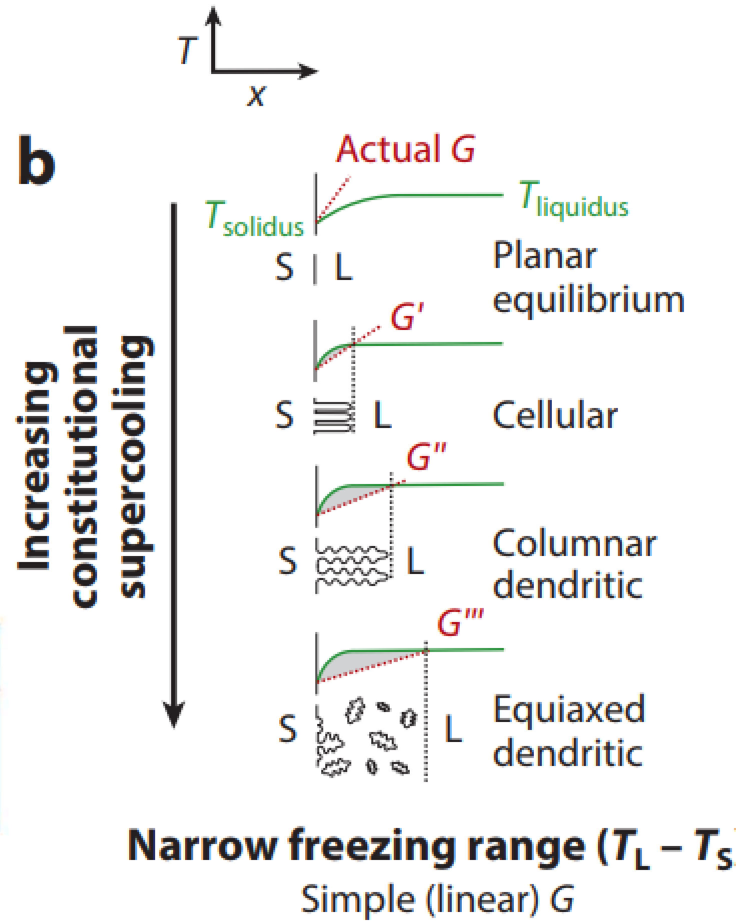


Microstructure of AM metals

Macro-level microstructural features: <u>Texture</u>

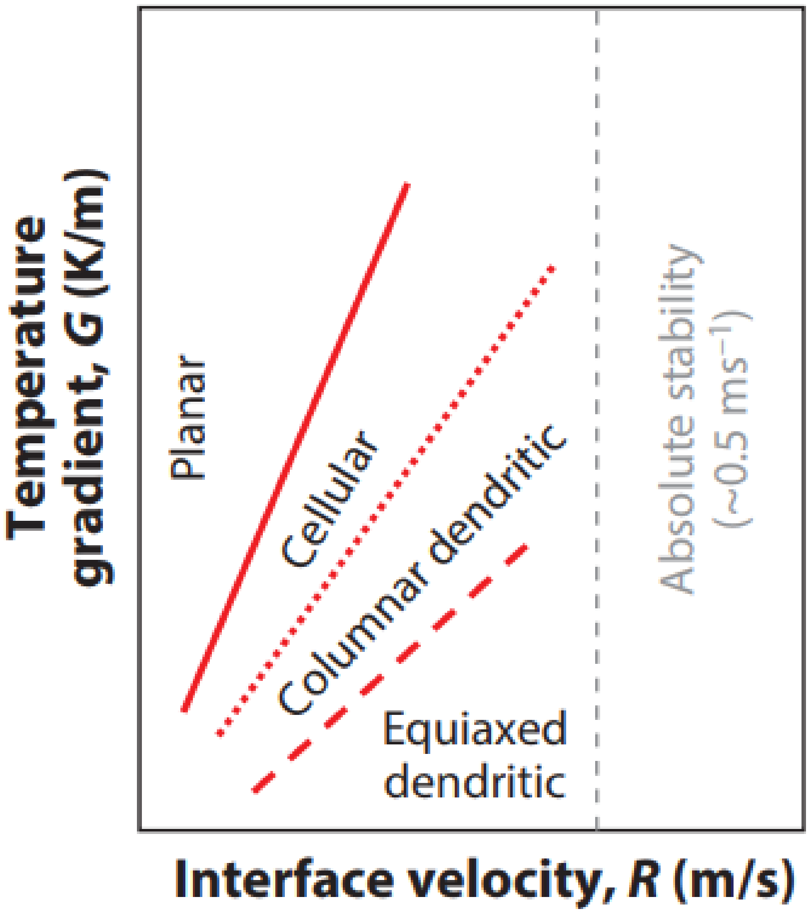
Molten pool geometry

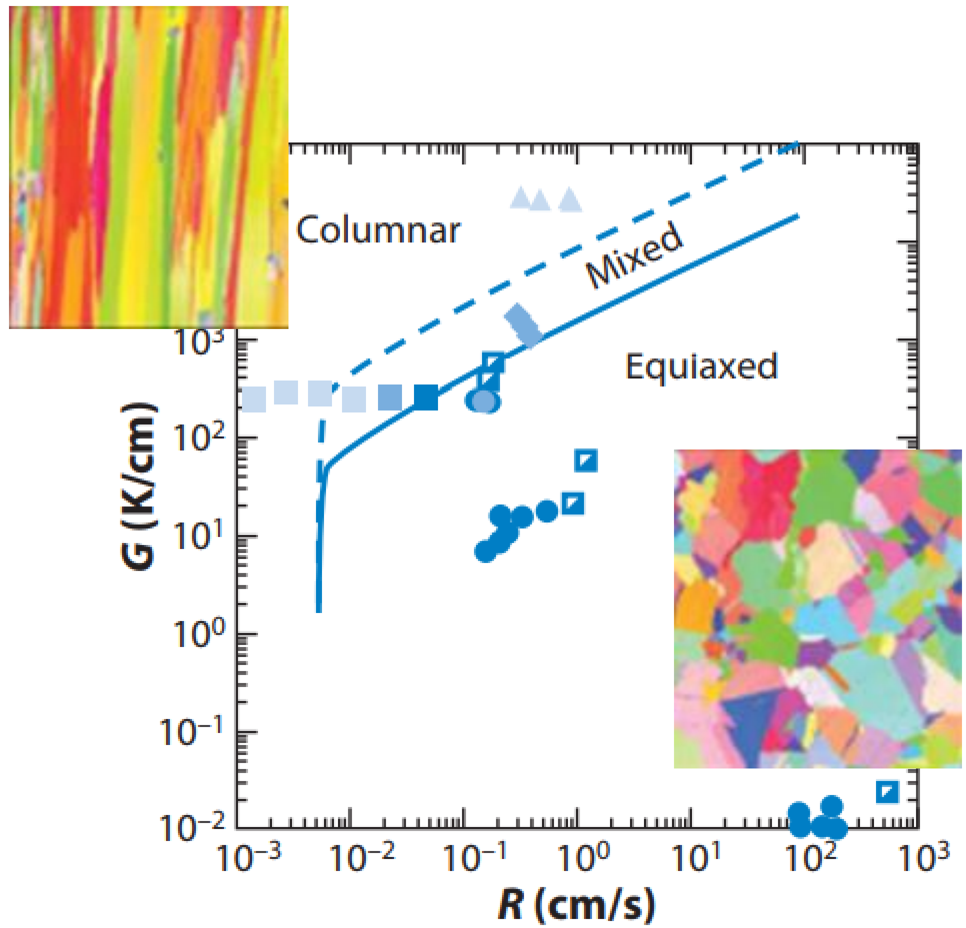




Microstructure of AM metals

Macro-level microstructural features: <u>Texture</u>

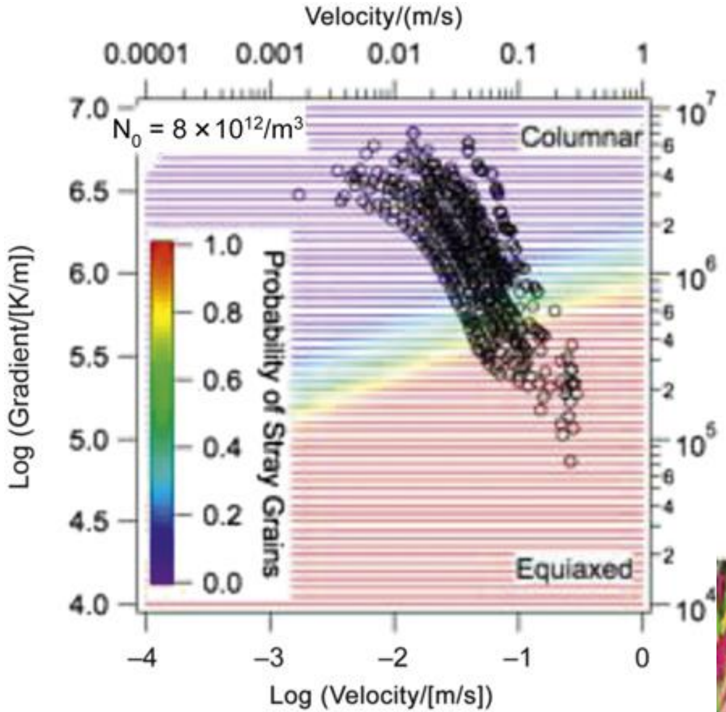




Microstructure of AM metals

- learning control: predicting texture by modelling -

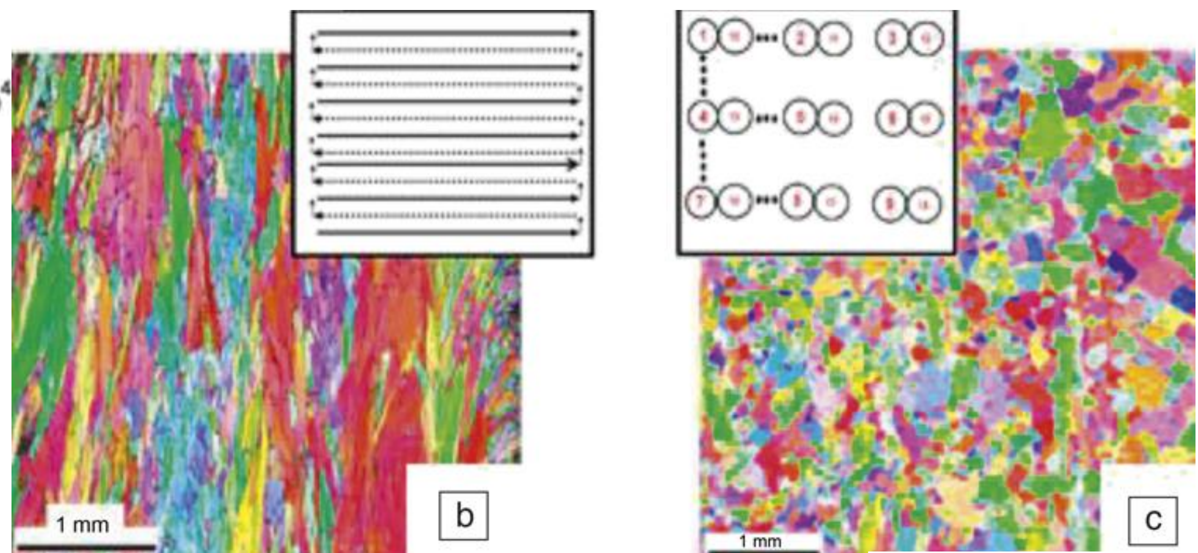
Macro-level microstructural features: <u>Texture</u>



R.R.Dehoff et al., Mater. Sci. Technol. 31, 931 (2015)

<u>Modeling-driven process design</u> (no trial-and-error):

Temperature gradient and **liquid interface velocity** control the microstructure in a predictable way



Ni superalloy by EBM

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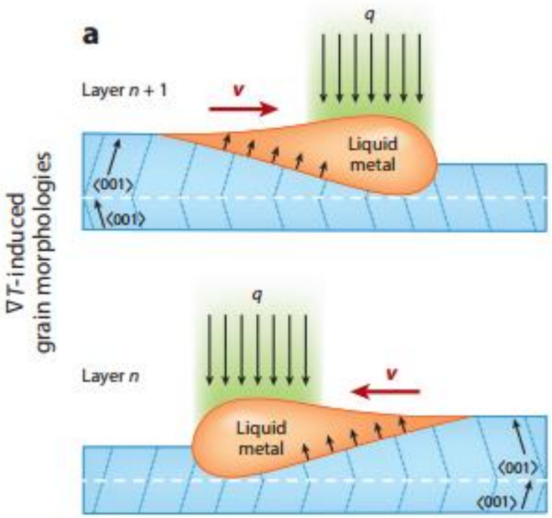
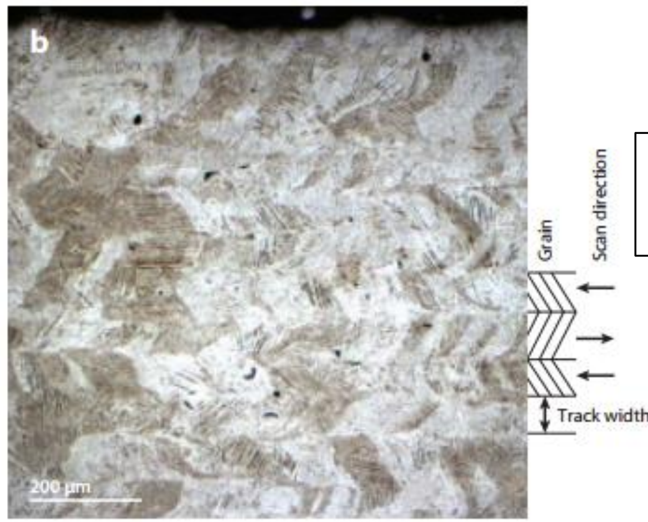
Microstructure of AM metals

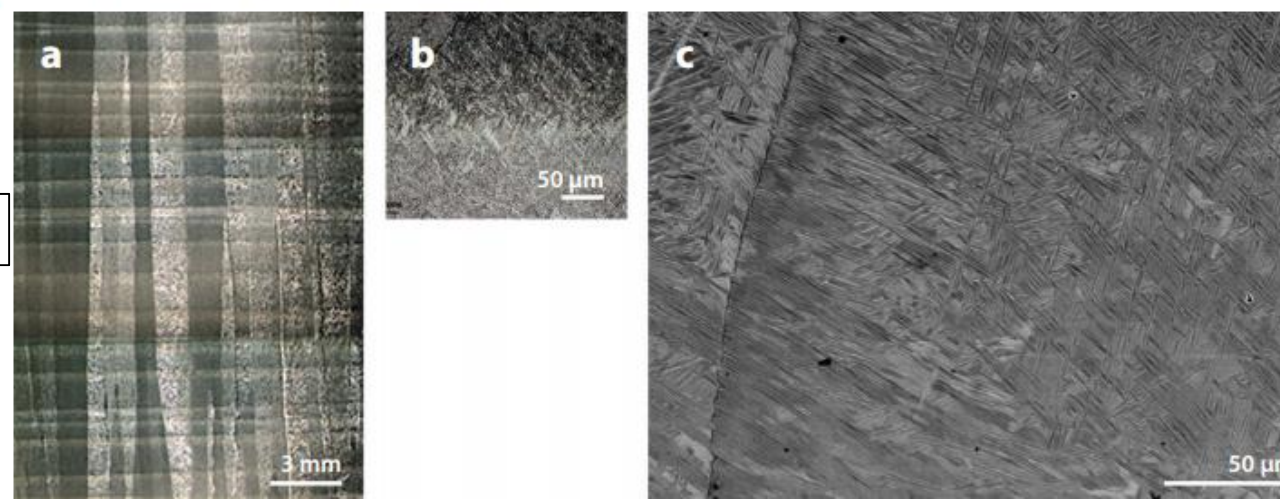
Micro-level microstructural features: <u>Grain size and morphology</u>





Zig-zag pattern and grain morphology

Grain size and shape



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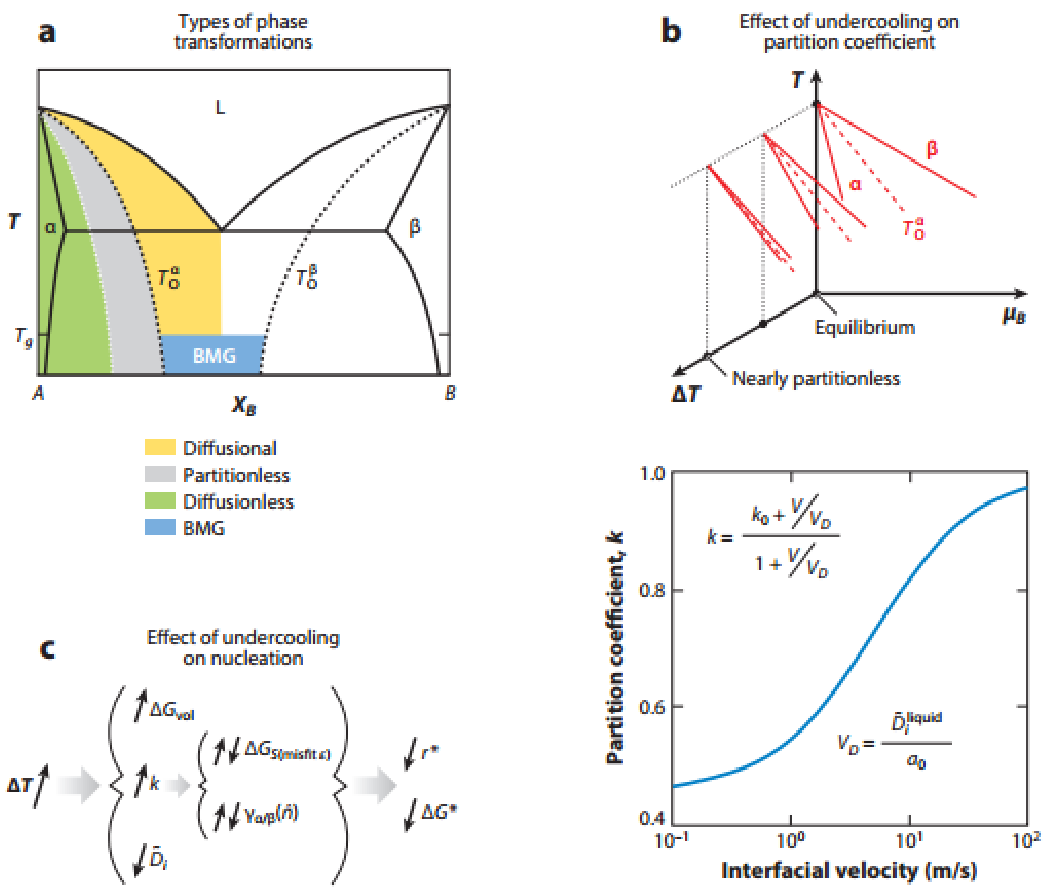
Microstructure of AM metals

Micro-level microstructural features: Phases



- Metastability is often promoted
- Subsequent heat cycles may promote spatially varying microstructures
- Far-from-equilibrium process often promotes highly refined precipitates
- Phase stability can be engineered via composition

Microstructure of AM metals

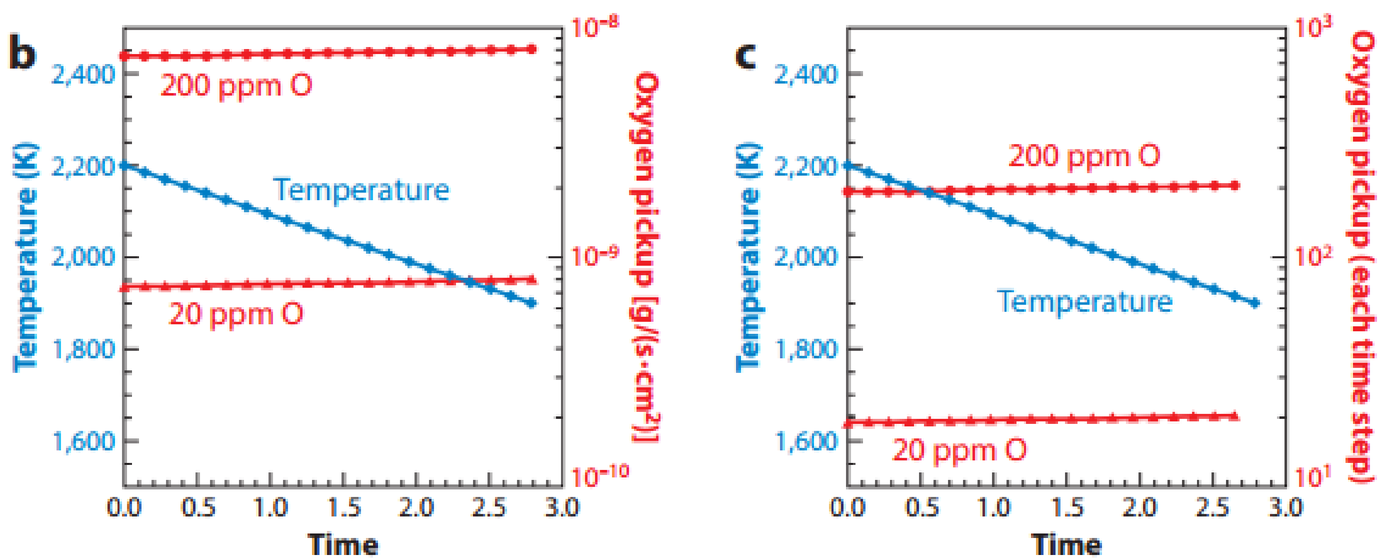
Process-induced effects on composition: Bulk Compositional Variations

Bulk compositional variations can arise from:

- Gettering
- Lossess due to differential vaporization of constituent elements (e.g. loss of Al in Ti6Al4V)

Compositional variations impact certification procedures of powders

Gettering and losses are predictable via Langmuir approach



Langmuir

$$m = \frac{wt_i}{A \cdot t} = \sqrt{\frac{M_i}{2\pi RT}} \cdot p_i$$

wt_i = weight of species i (g)
A = area of melt pool (mm²)
t = time (s)

From Rosenthal's approach

$$\frac{\partial T}{\partial t} = \frac{2\pi k v (T - T_0)^2}{H}$$

k = thermal conductivity
v = velocity
H = transferred energy

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P.C. Collins, D.A. Brice, P. Samimi, I. Ghamarian, and H.L. Fraser
Ann. Rev. Mater. Res Vol. 46, 2016, pp. 63–91

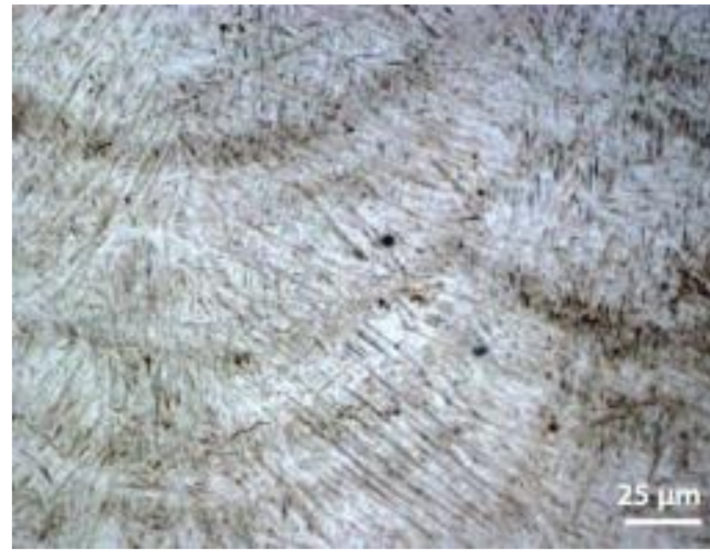
Microstructure of AM metals

Process-induced effects on composition: <u>Non-equilibrium Partitioning</u>

Nonequilibrium partitioning:

rapid solidification (nonequilibrium)
→high supersaturation
→ solute trapping
→ higher solid solubility and mechanical properties

- Trapping leads to banded structures
- Local compositional variations can be an opportunity if engineered.



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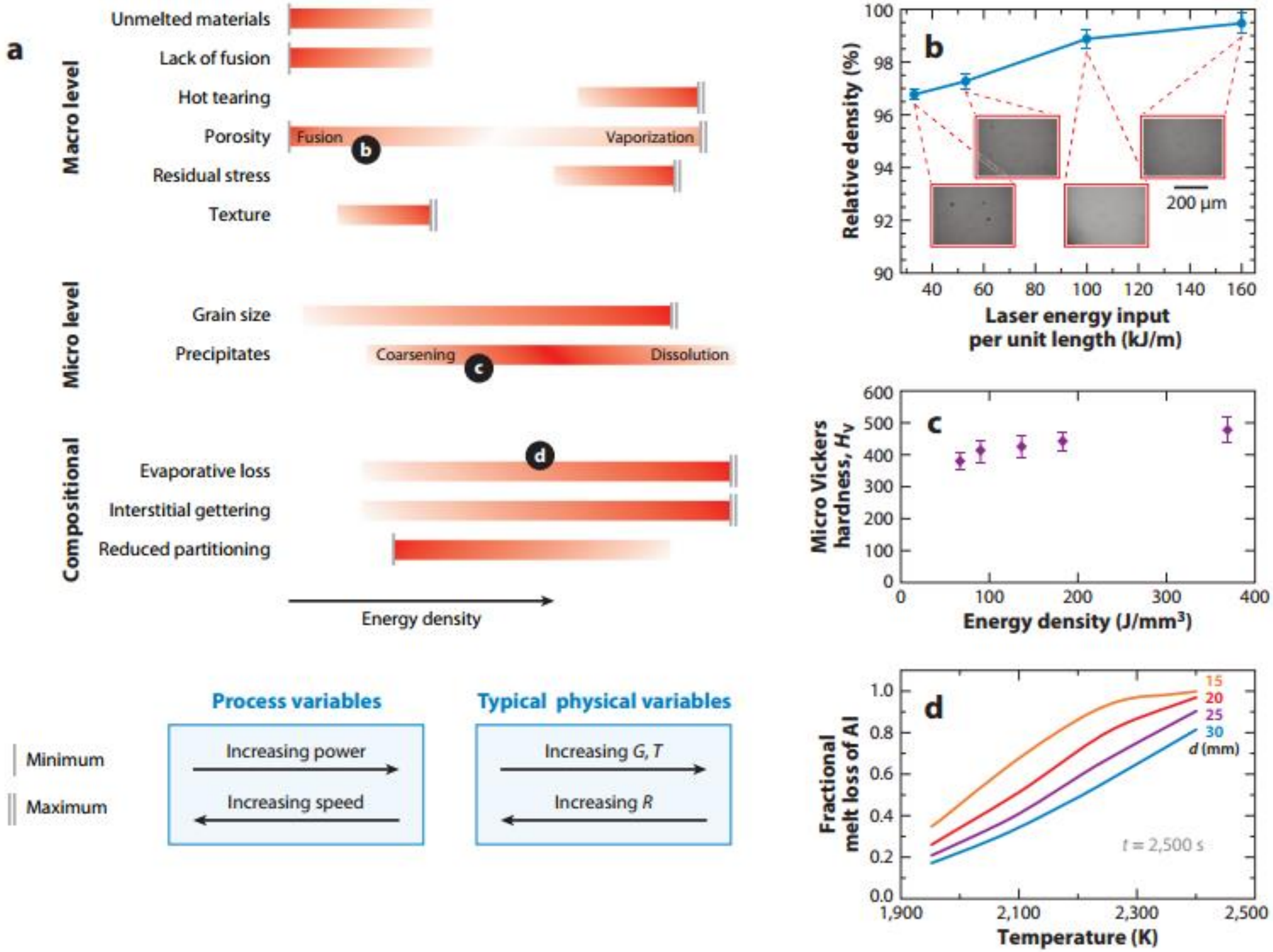
Microstructure of AM metals

Summary of control parameters



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Microstructure of AM metals

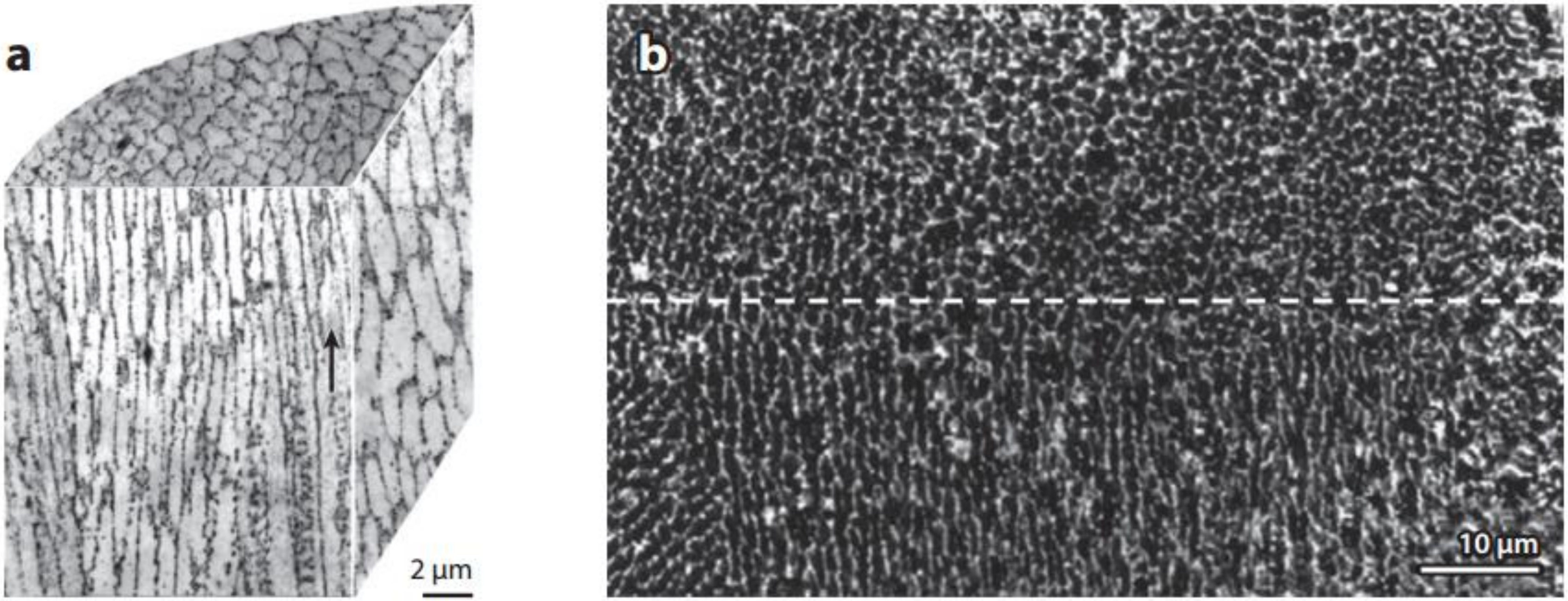
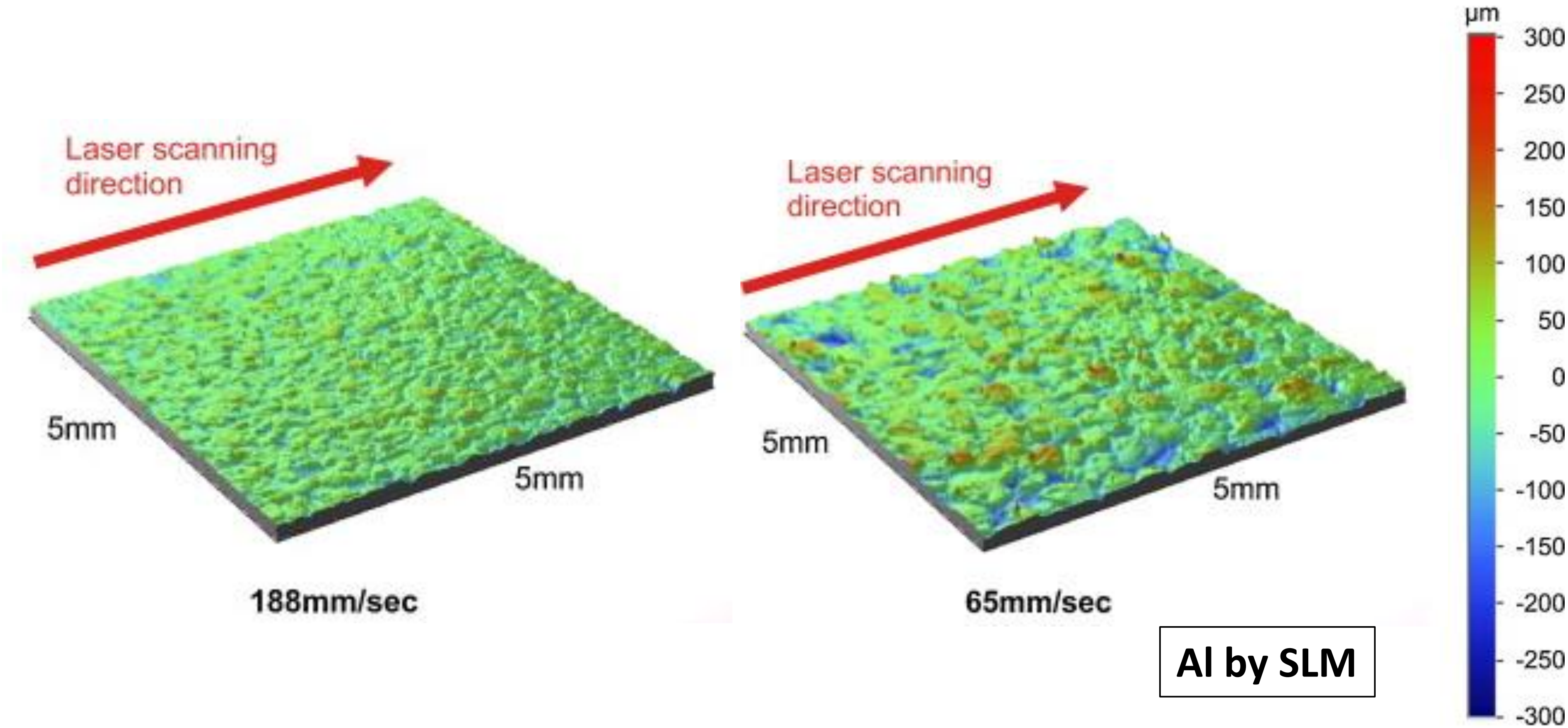


Figure 4

(*a*) A 3D composite image representing a typical section of a cylindrical specimen illustrating the columnar microstructures. The cylindrical specimen is made of pure Cu. The arrow pointing upward indicates the layer-building direction. Reproduced with permission from Reference 47. (*b*) Change in microstructure from columnar to equiaxed morphology in the LM-processed deposit made of Al-15Cu (wt%). The dashed white line represents the morphological transition zone. Reproduced with permission from Reference 52.

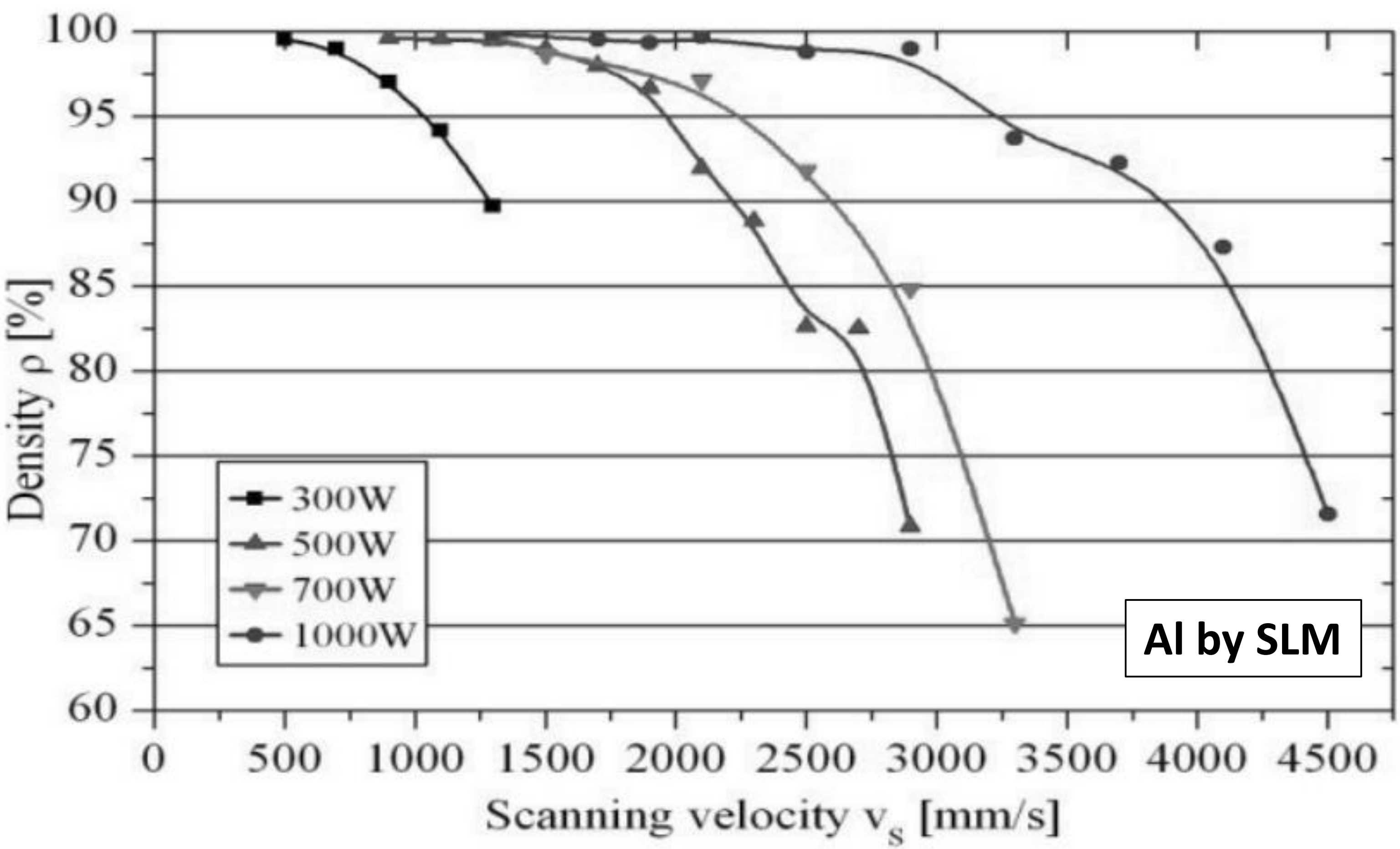
AM Process → Microstructure → Properties
- learning control: surface finish -



Al by SLM

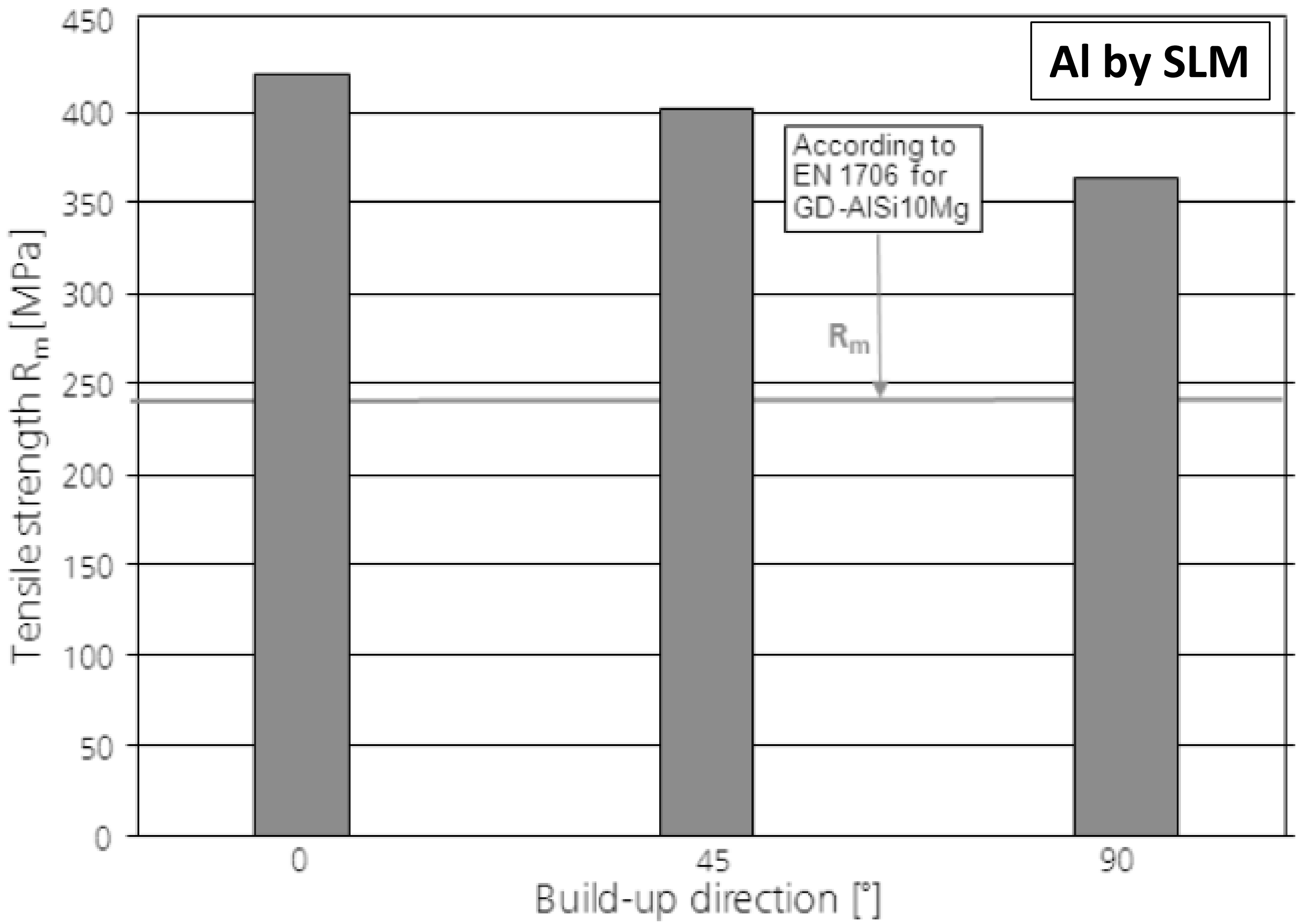
Louvis et al., J Materials Processing Tech. 211 (2011) p275

AM Process → Microstructure → Properties
- learning control: porosity -



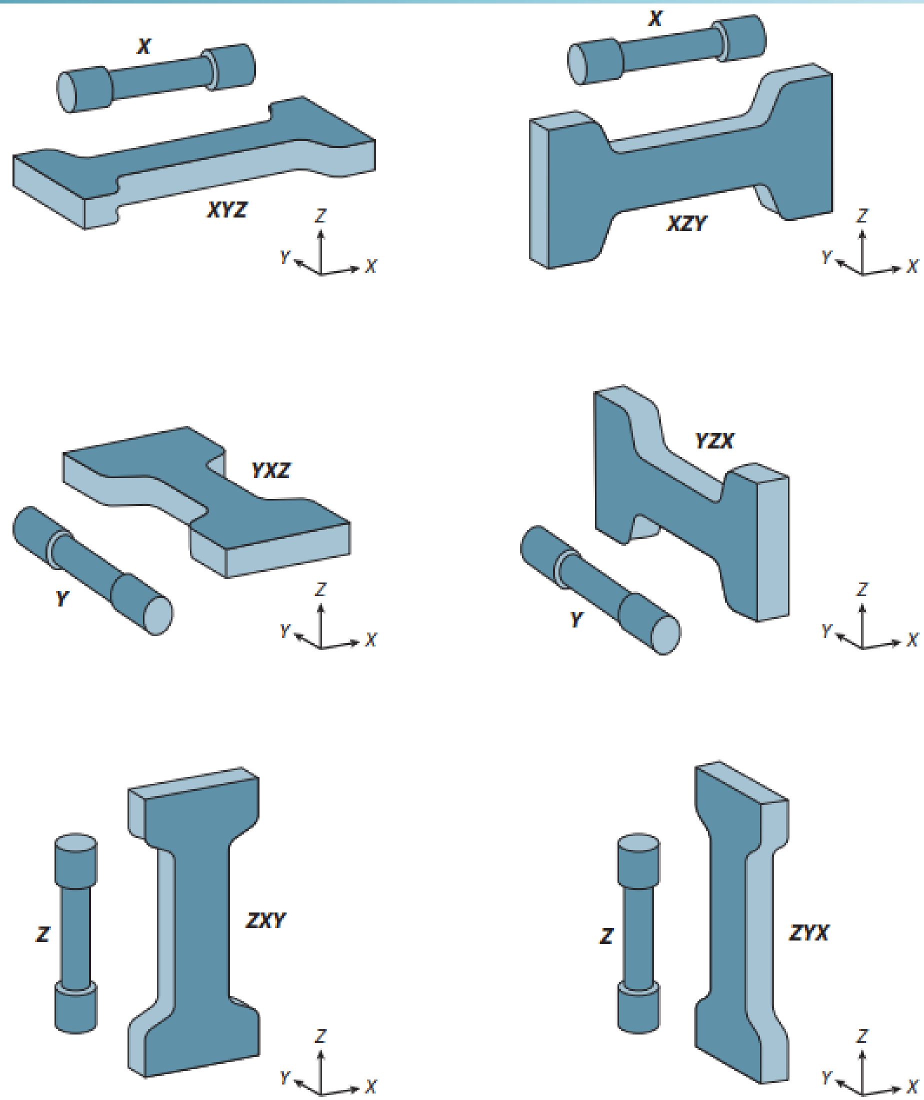
Buchbinder et al., Phys. Proc. 12 (2011) 271

AM Process → Microstructure → Properties
- learning control: strength -



Buchbinder et al., Phys. Proc. 12 (2011) 271

Mechanical properties of AM components



John J. Lewandowski and Mohsen Seifi
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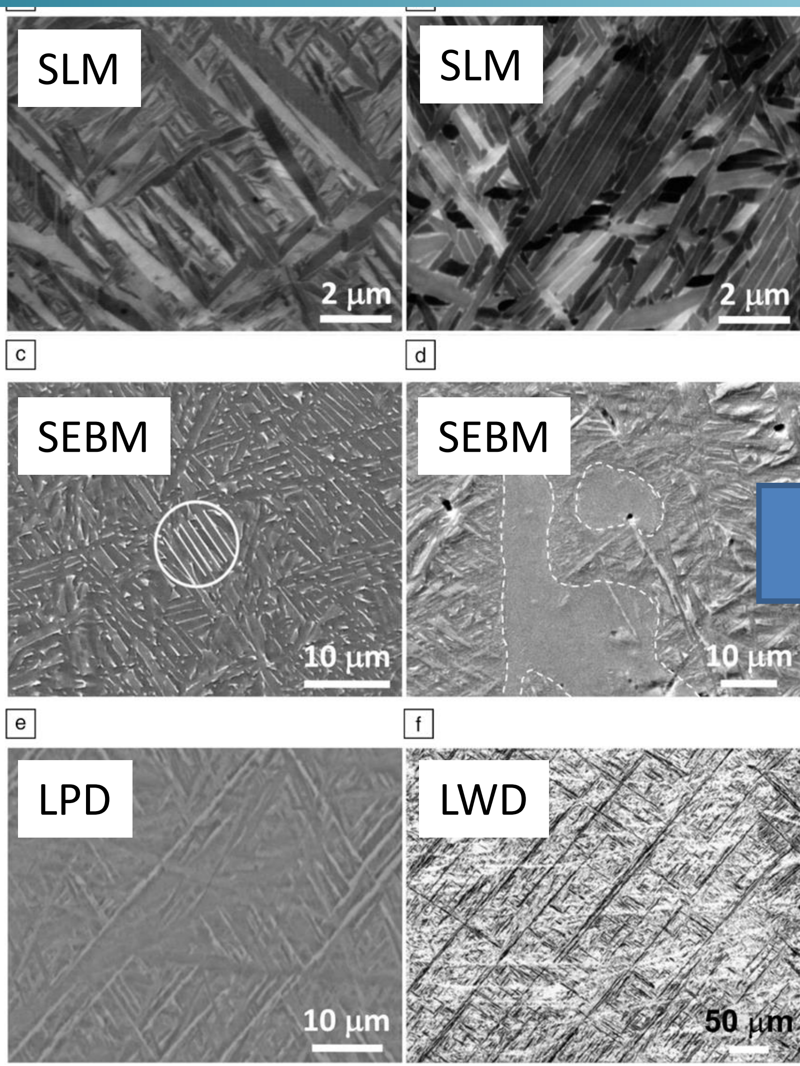
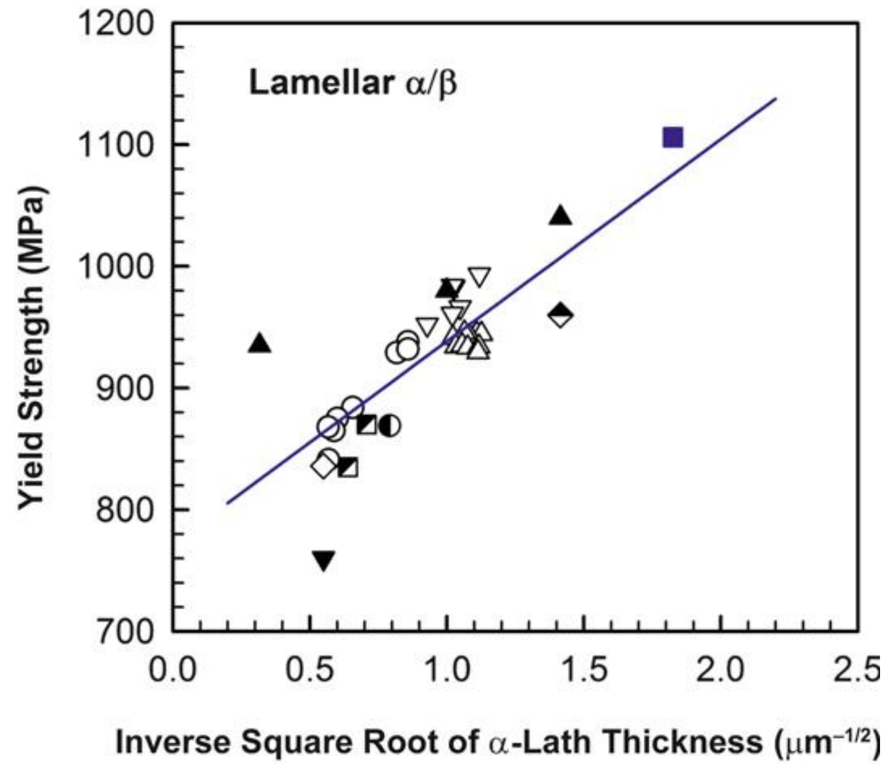
AM Process → Microstructure → Properties





C.Qiu et al., J. Alloys Compd. 629, 351 (2015)
E.Brandl et al., Mater. Des. 32, 4665 (2011)
W.Xu, Acta Mater. 85, 74 (2015)
S.L.Lu, Acta Mater. 104, 303 (2016)

Mechanical properties of AM components

	PBF		DED				
	EBM (powder)	Laser (powder)	EBM (wire; Sciaky)	EBM (powder)	Laser (wire)	Laser (powder; LENS)	WAAM (wire)
Titanium alloys	12–48	49–71			72–79	80–83	74
TiAl (intermetallics)	199, 203–222	171, 172, 223, 224					
Steel alloys		84–93	94		95		96
Nickel alloys	97–102	103–110			111, 112		
Aluminum alloys		113–124	125				126, 127
High-entropy alloys	128	129					

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AM of Al Alloys

Motivations for AM of Al alloys

- Exploit ultralightweight desing (hollow, shell structures, lattice configurations: AM enables wall thickness previously unattainable by casting)
- Functionality (especially in thermal applications)
- Reduced buy-to-usage ratio is very beneficial for pricy Al alloys

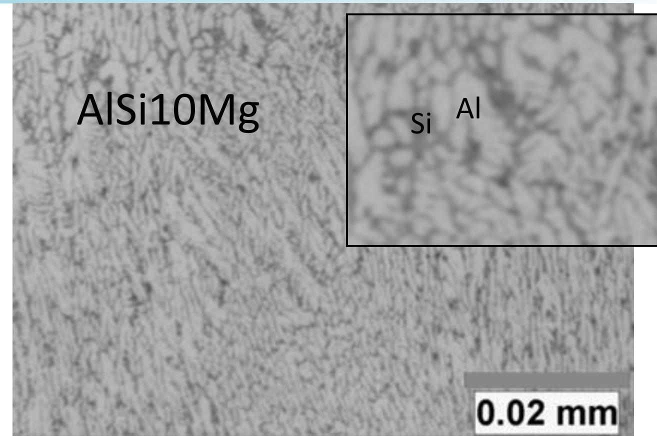
Challenges for AM of Al alloys

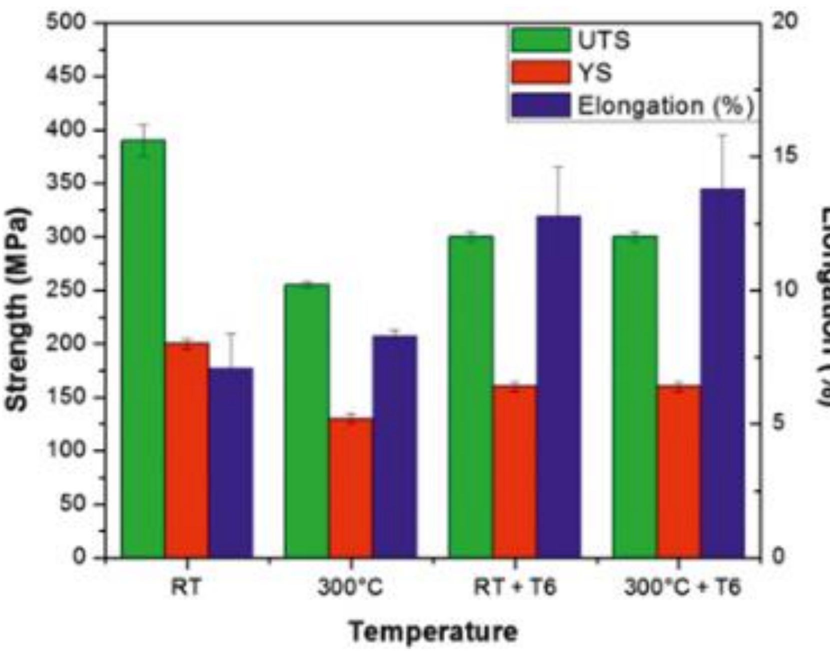
- Same that limit Al weldabilty (surface oxide scale, high thermal conductivity, high thermal expansion coefficient, high solidification shrinkage, high H solubility…)
- Amplified in powder bed techniques, specifically:
  - Powder flowability: Al powders are light and this reduces flowability, which affects final porosity
  - High thermal conductivity: this requires higher power, which in turn might lead to problems (balling, loss of alloying elements…)
  - Surface oxide film: leads to defects
- Same countermeasures as for enhancing weldability of traditional materials may apply

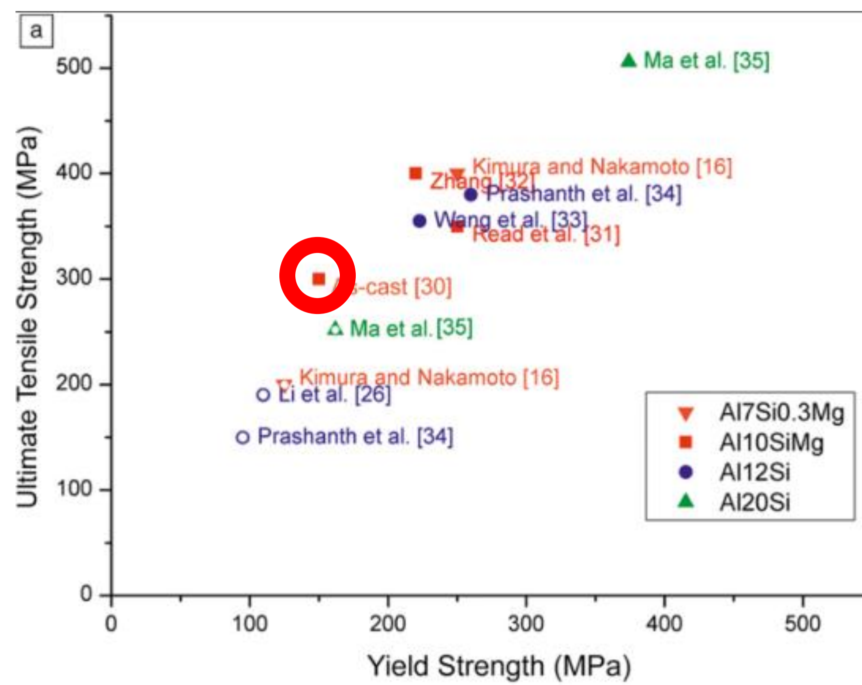
AM of Al Alloys

Pure Al – not many data available

Foundry alloys (Al-Si)
Many AM processes are viable
SLM can be optimized to provide extremely fine microstructure and excellent mechanical properties
Typically anisotropic







AM of Al Alloys

Nonheat-treatable alloys: 3XXX and 5XXX (Mn, Mg)

- Example: AlMgScZr

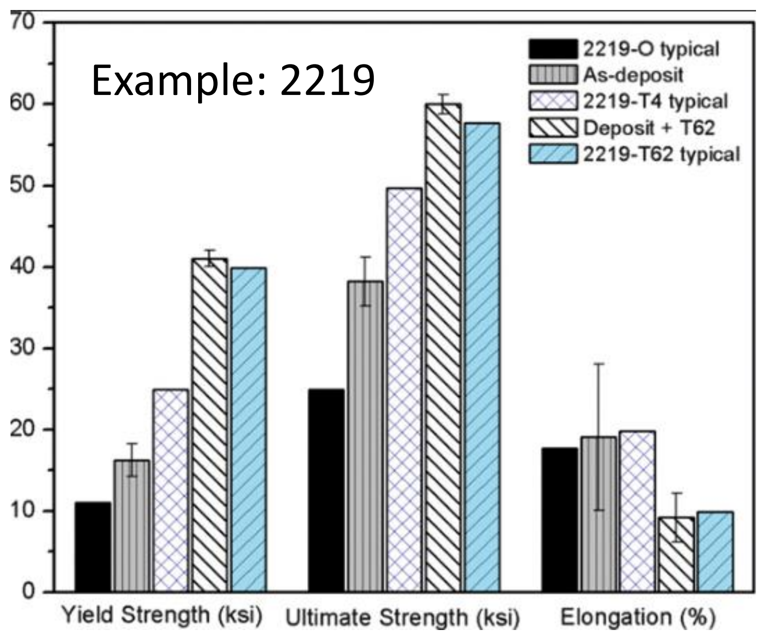
Print Direction	Heat Treatment	YS (MPa)	UTS (MPa)	Elongation (%)
Horizontal	Annealed	370 ± 38	415 ± 30	20 ± 2.3
	Annealed + HIP	476 ± 2	500 ± 3	12 ± 2.0
Vertical	Annealed	450 ± 16	480 ± 11	13 ± 1.6
	Annealed + HIP	490 ± 2	522 ± 4	14 ± 0.7

Heat-treatable wrought alloys

Al-Cu-Mg (2XXX)

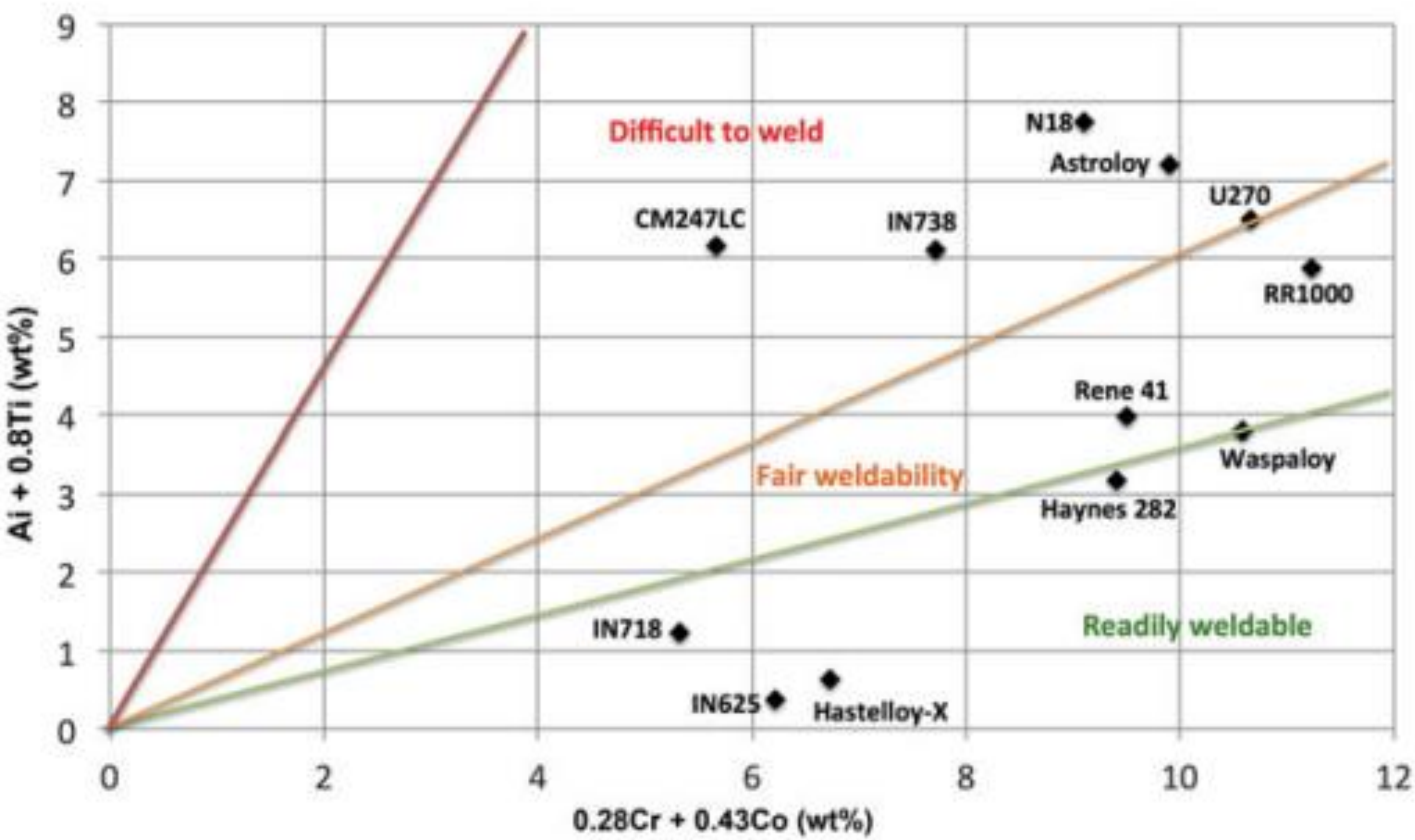
Al-Si-Mg (6XXX)

Al-Zn-Mg-Cu (7XXX)



AM of Inconel

Ni-based superalloy manufactured by AM suffer from similar limitations as for weldability



γ'-forming elements

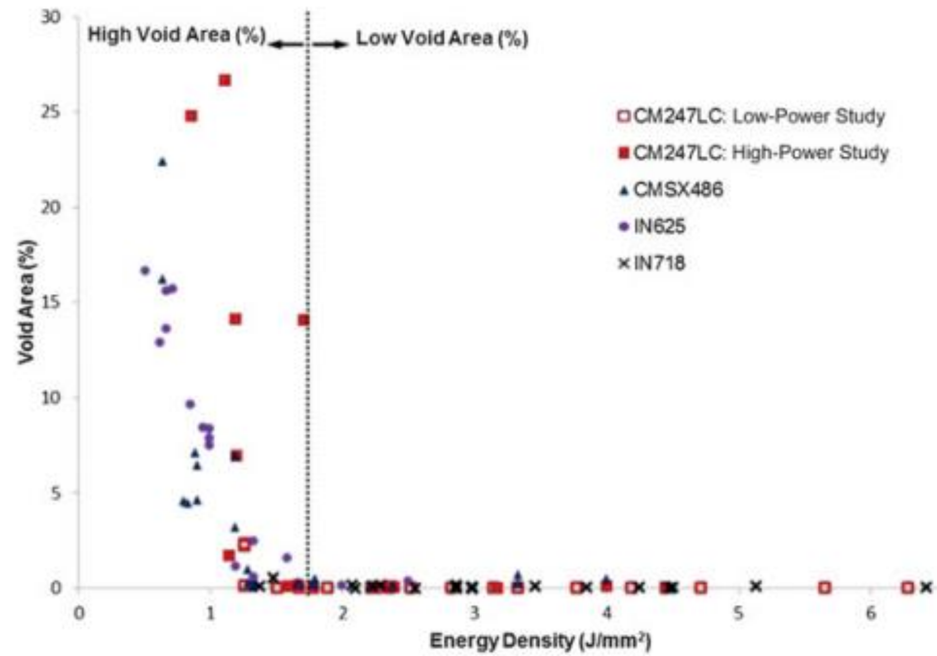
Carbide-forming elements

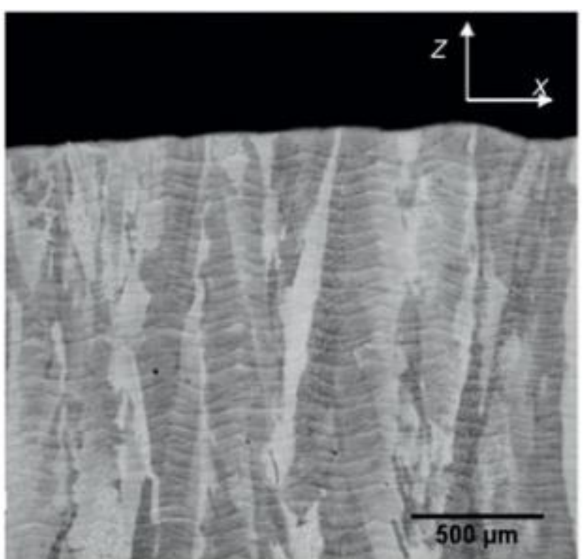
Attallah, M., Jennings, R., Wang, X., & Carter, L. (2016). *MRS Bulletin, 41*(10), 758-764

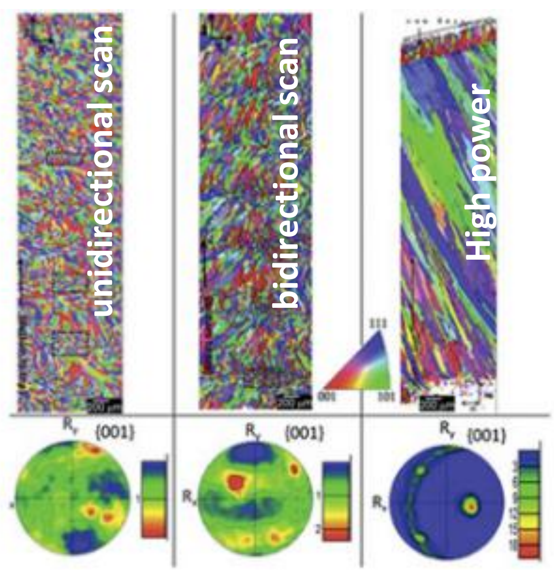
AM of Inconel

Challenges

- Residual stress
- Porosity
- Undesired, solidification-induced phases → thermal treatment (HIP) often required
- Large anisotropy (an opportunity?)





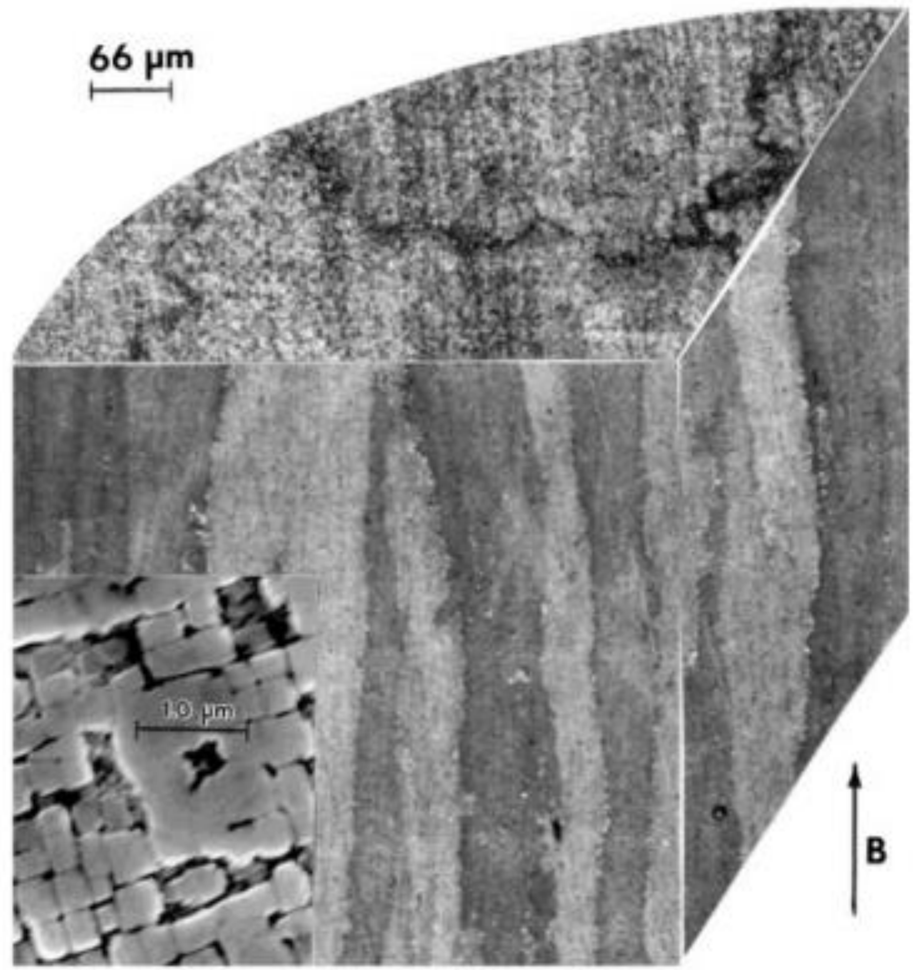


Attallah, M., Jennings, R., Wang, X., & Carter, L. (2016).*MRS Bulletin, 41*(10), 758-764.

LAMA

AM of Ni-based superalloys

- Ni-based superalloy components can be manufactured by AM and obtaining the **same microstructure that is obtained by conventional fabrication** (cuboidal γ' wtih optimal spacing)
- Conventional **heat treatments can be skipped** beause of the heat cycles intrinsic of the process



J.M. Oblak , B.H. Kear , in Electron Microscopy and Structure of Materials, G. Thomas , R.M. Fulrath , R.M. Fisher , Eds. (University of California Press , Berkeley , 1972), p. 566

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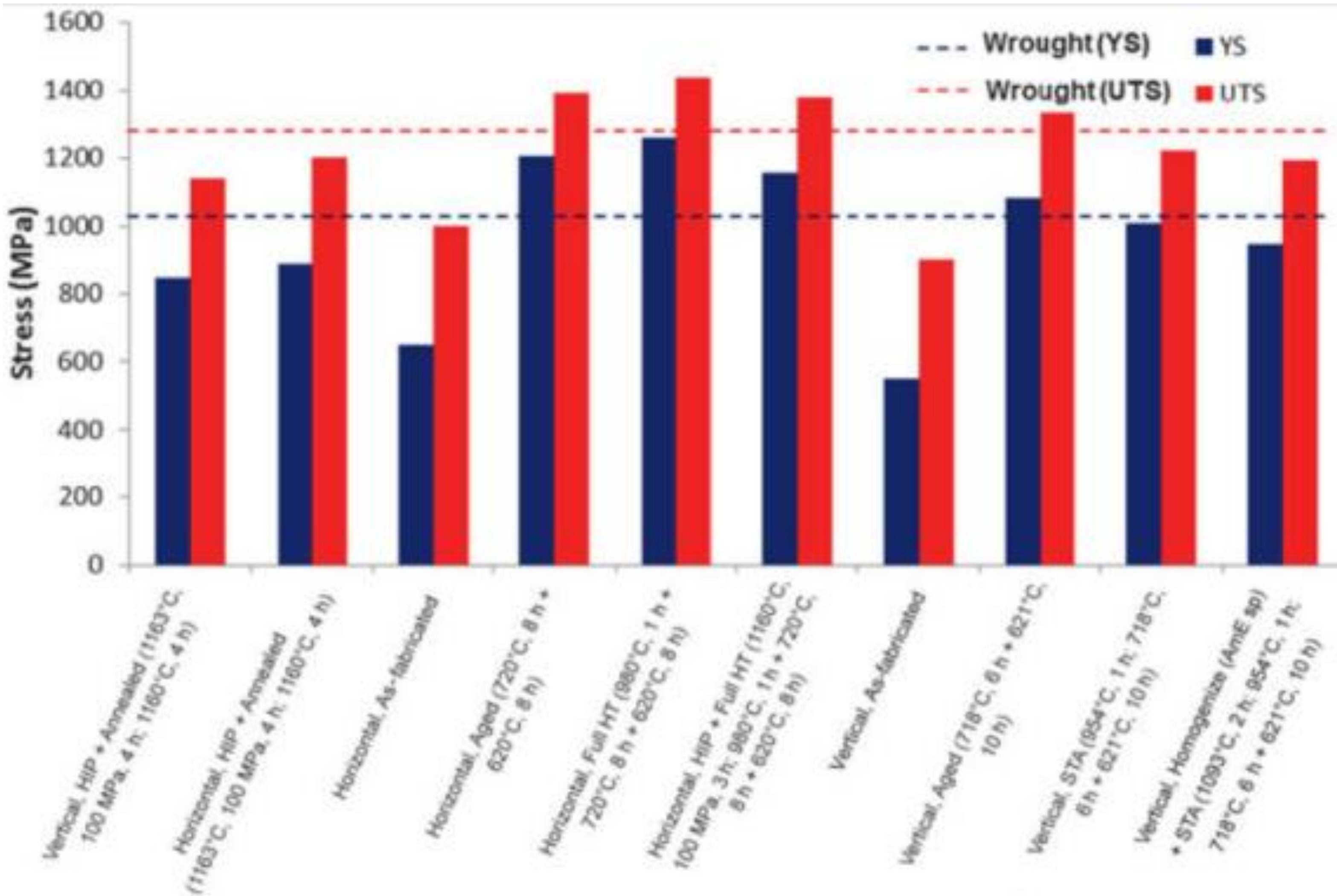
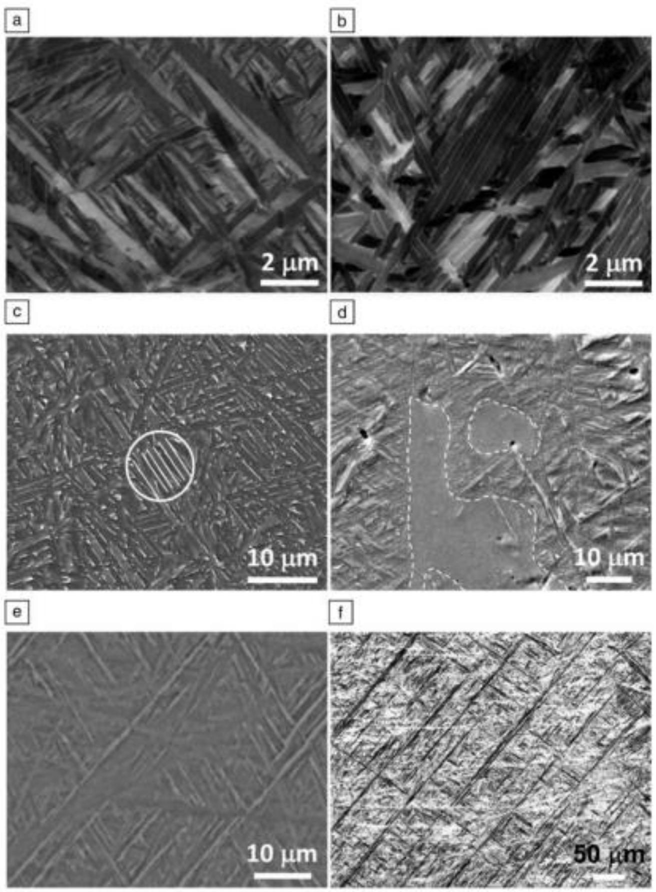
AM of Ni-based superalloys



AM of Ti6Al4V

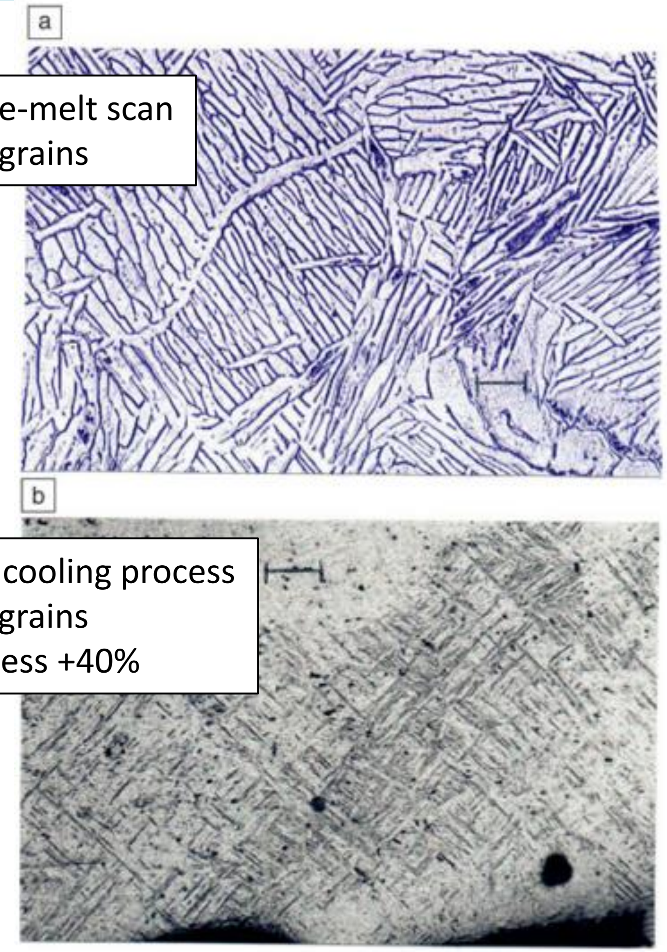
- Typical microstructure of conventional Ti6Al4V is conserved in AM parts

- Microstructure can be tailored



Double-melt scan
Large grains

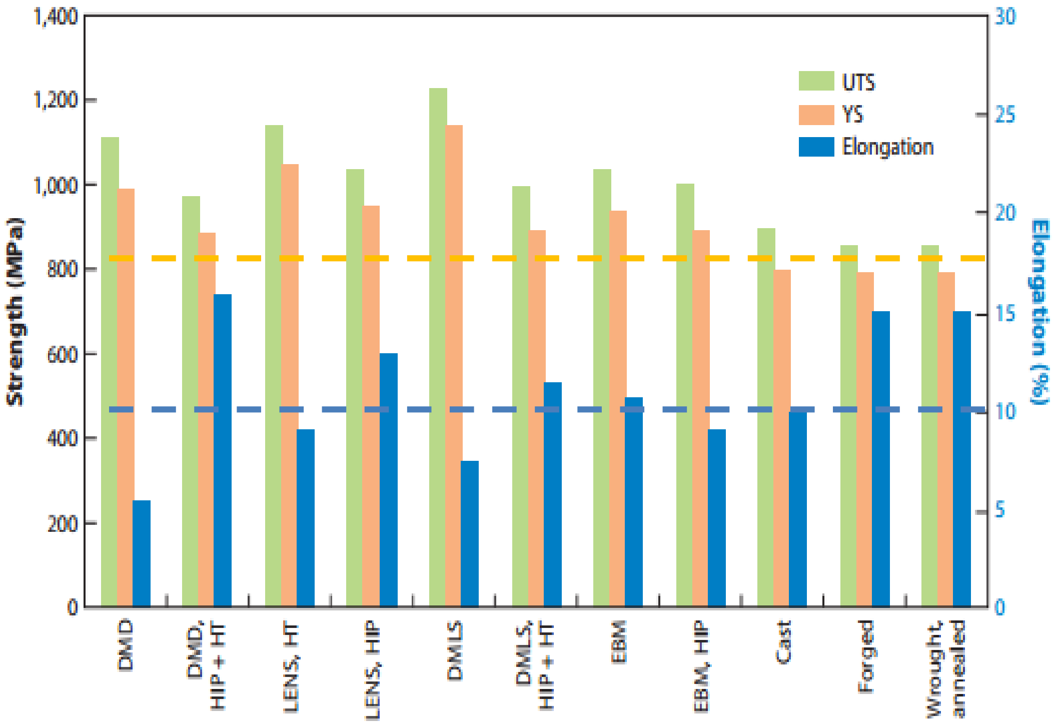
Rapid cooling process
Small grains
Hardness +40%



Murr, L., & Li, S. (2016). Electron-beam additive manufacturing of high-temperature metals. *MRS Bulletin, 41*(10), 752-757. doi:10.1557/mrs.2016.210

AM of Ti6Al4V

Mechanical properties and heat treatments



- **AM parts in as-built condition do not meet 10% elongation requirement**
- **Heat treatments improve ductility**
- Elongation of 10% or more is always obtained with high temperature heat treatments (>940°C)
- **Tensile strenght always matches conventional processes**
- Anisotropy is always present; High temperature (about 1000°C) treatments can mitigate it but are often coupled with grain growth
- HIP treatments at 920°C for 2 hrs under 100MPa in argon reduce defects (resolution 5um)
- Lathe thickness grows under HIP. Exceeding 8µm leads to an excessive drop of tensile strength

John J. Lewandowski and Mohsen Seifi, Ann. Rev. Mater. Res. Vol. 46, 2016, pp. 151–186

Qian, M., Xu, W., Brandt, M., & Tang, H. (2016). Additive manufacturing and postprocessing of Ti-6Al-4V for superior mechanical properties. *MRS Bulletin, 41*(10), 775-784. doi:10.1557/mrs.2016.215

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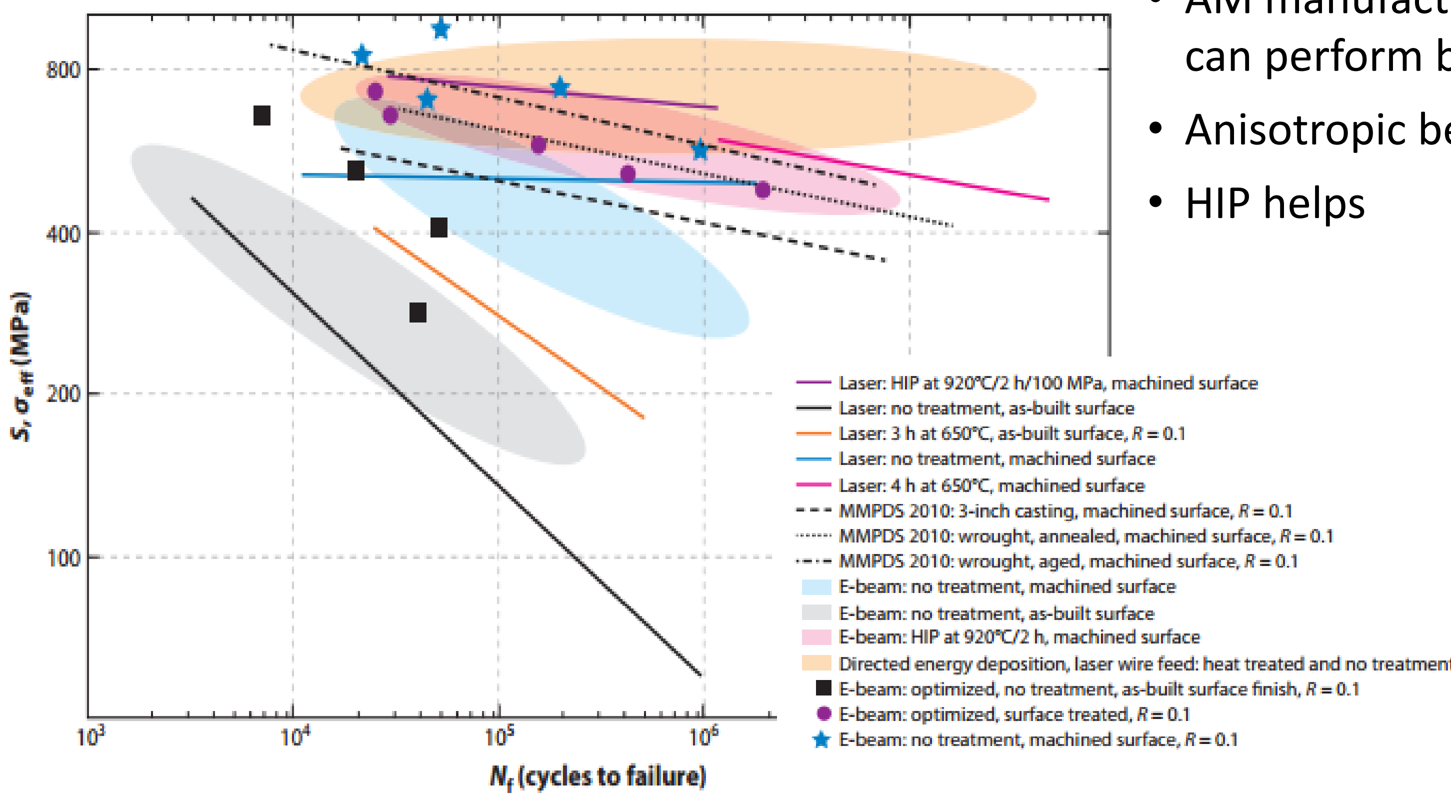
AM of Ti6Al4V

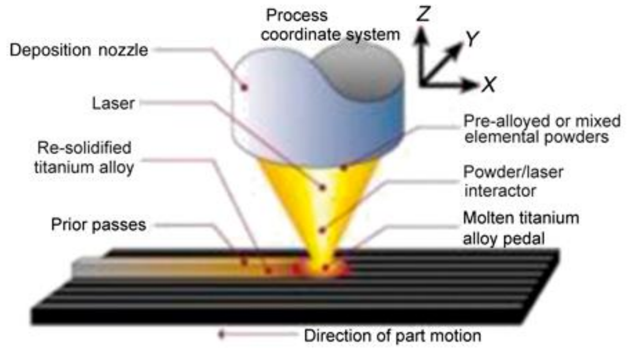
Fatigue behavior

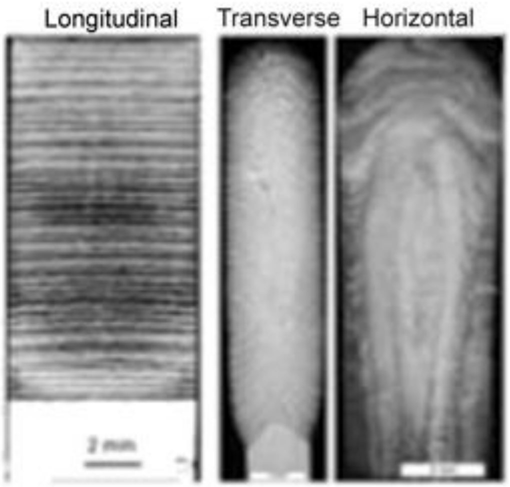


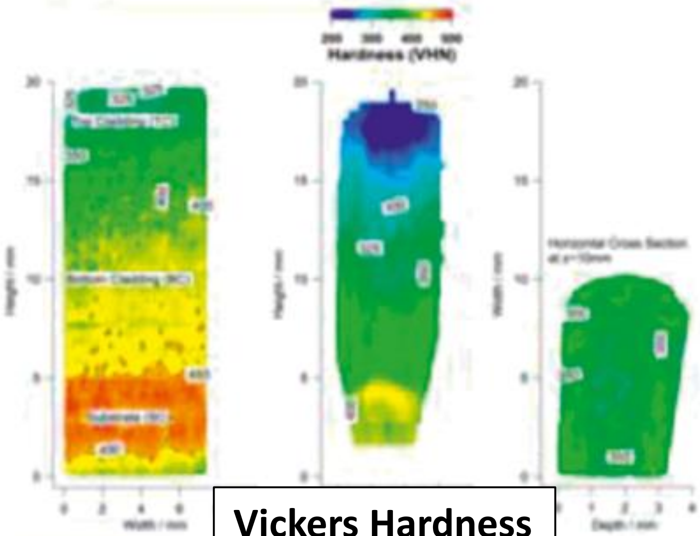
- Post-AM surface treatments are essential (polishing, shot peening)
- AM manufactured components can perform better than standard
- Anisotropic behavior
- HIP helps

John J. Lewandowski and Mohsen Seifi, Ann. Rev. Mater. Res. Vol. 46, 2016, pp. 151–186

Cu cladding on IN718

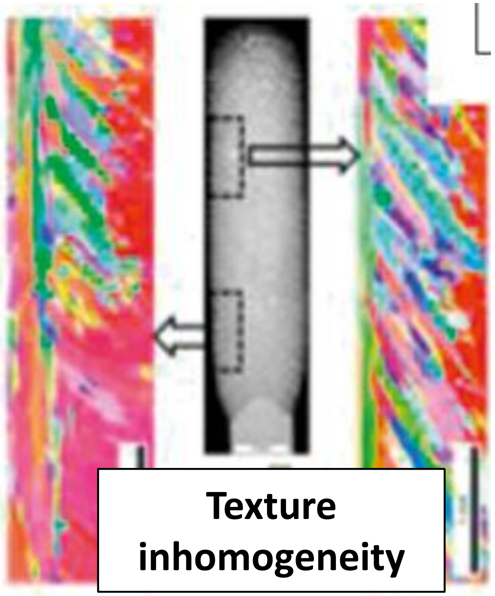






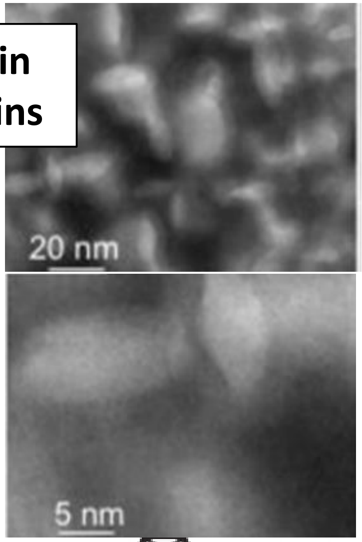
Vickers Hardness

Microscale inhomogeneities (dendrites)



Texture inhomogeneity

γ'' within the grains



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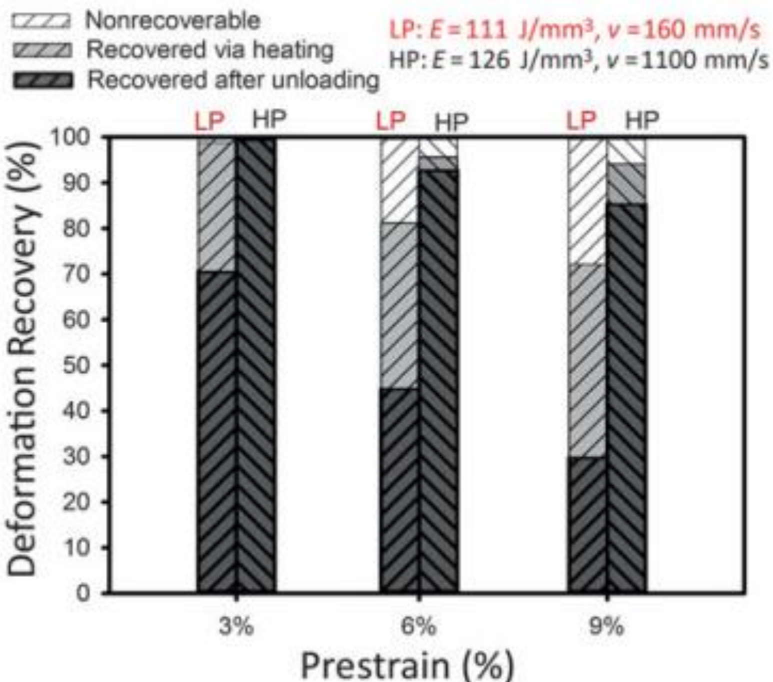
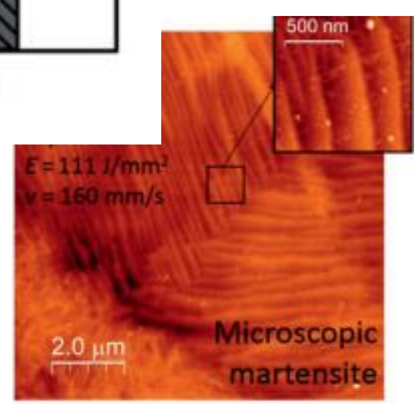
LAMA FVG

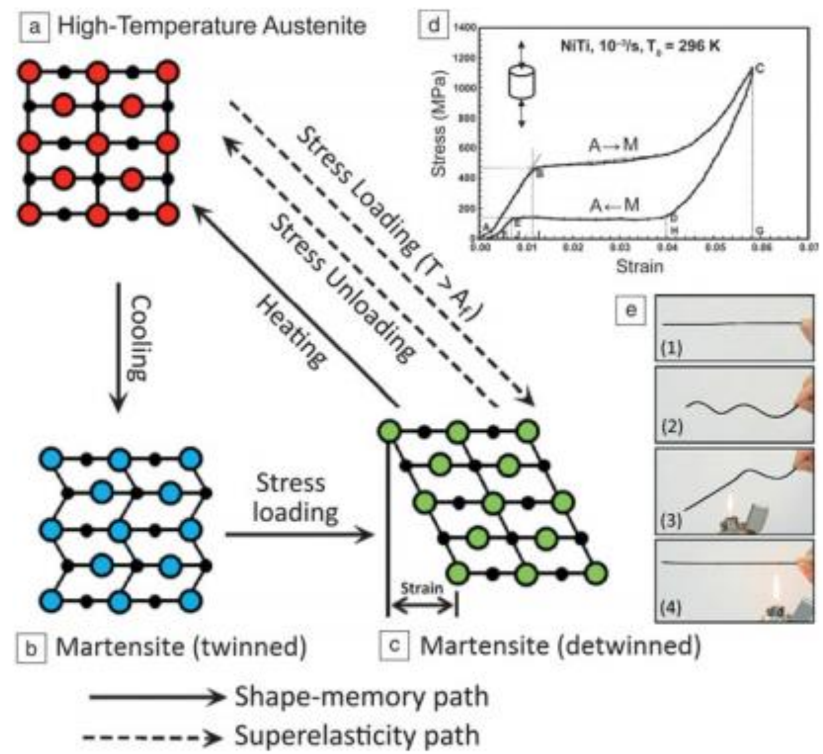
AM of NiTi Shape-Memory Alloys

Shape-memory and superelastic characteristics can be tailored through appropriate AM-controlled microstructures



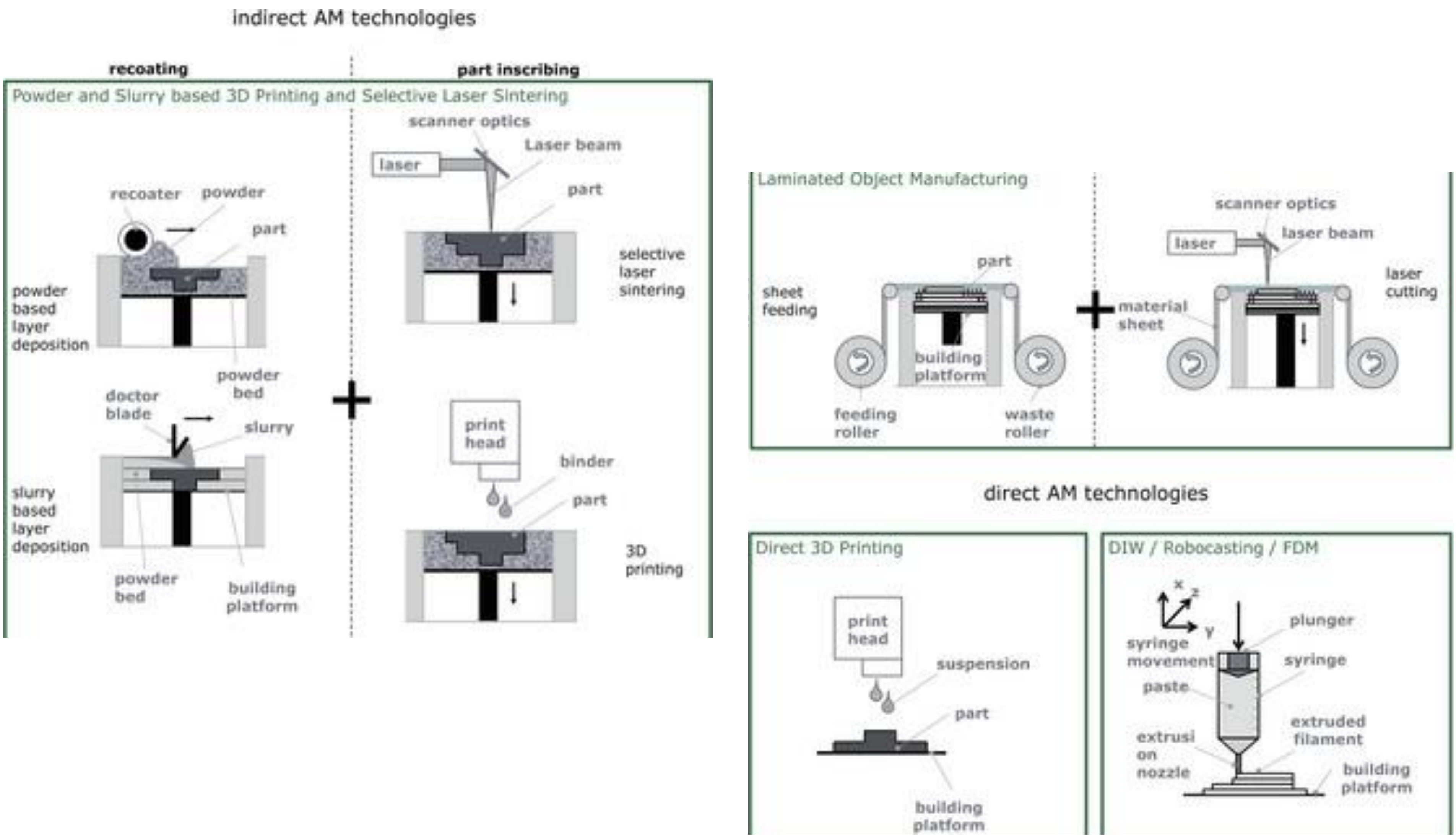


Shape-memory effect



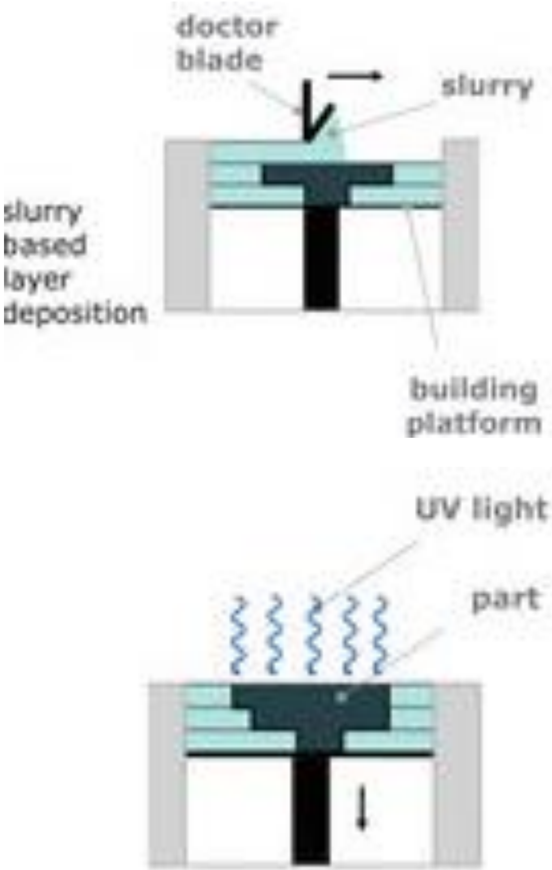
Dadbakhsh, S., Speirs, M., Van Humbeeck, J., & Kruth, J. (2016). Laser additive manufacturing of bulk and porous shape-memory NiTi alloys: From processes to potential biomedical applications. *MRS Bulletin, 41*(10), 765-774. doi:10.1557/mrs.2016.20

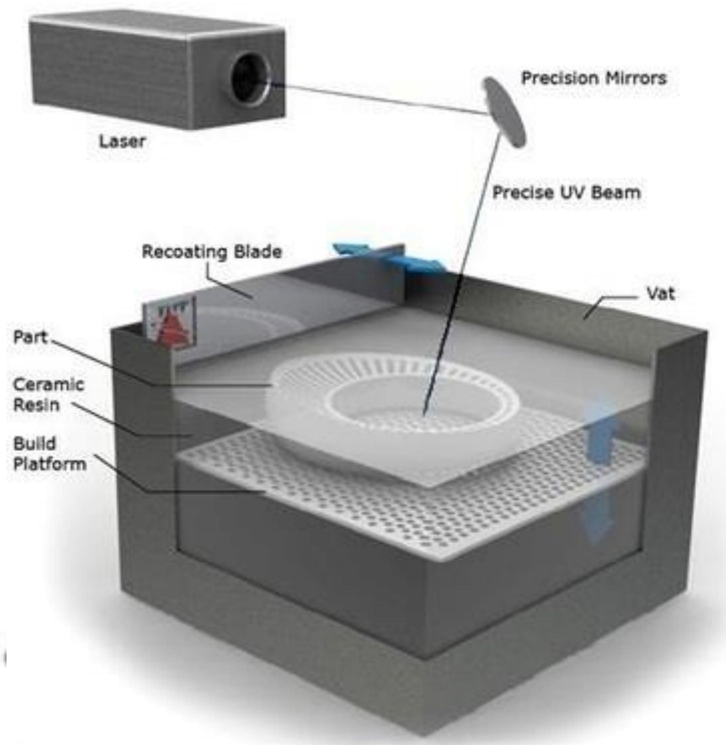
AM of Ceramic Materials

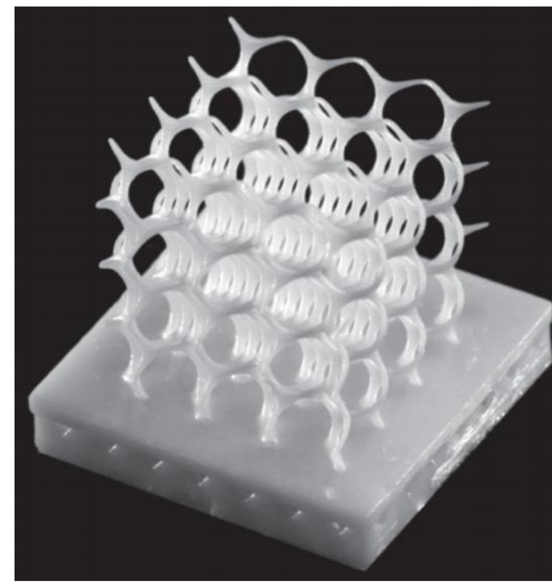


AM of Ceramic Materials

Ceramic stereolithography (Photopolymerization)



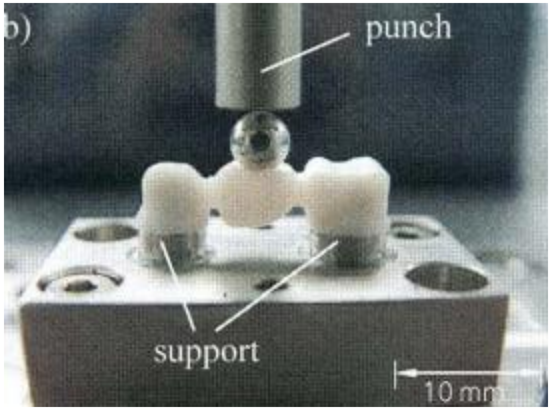


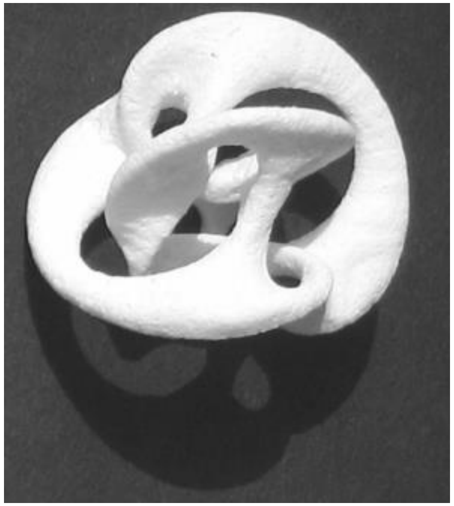


Jan Wilkes, Yves-Christian Hagedorn, Wilhelm Meiners, Konrad Wissenbach, (2013) "Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting", Rapid Prototyping Journal, Vol. 19 Issue: 1, pp.51-57, doi: 10.1108/13552541311292736

J. Ceram. Sci. Tech., 05 [04] 245-260 (2014)

AM of Ceramic Materials





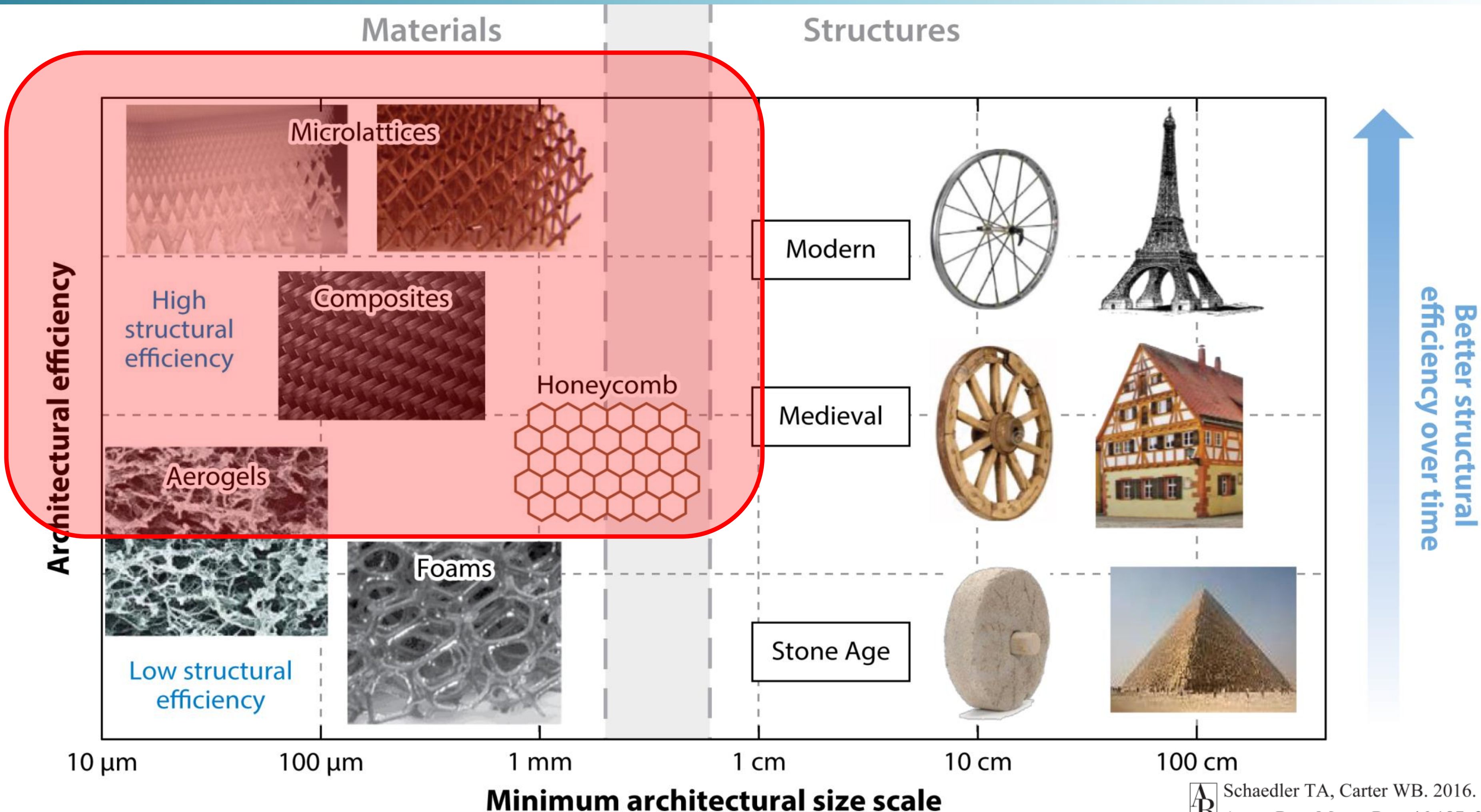
- Single-step AM (e.g. SLM, EBM, …): rapid manufacturing
- Double step AM (use of binders): more versatile
- Ceramic AM parts that do not present macro cracks or pores have properties that closely approach those of conventional ceramics
- Some processes require an extra densification step
- Fully dense, Al2O3-ZrO2 ceramic composites have been produced succesfully, with excellent mechanical performances (tensile strength > 500 MPa)

Jan Wilkes, Yves-Christian Hagedorn, Wilhelm Meiners, Konrad Wissenbach, (2013) "Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting", Rapid Prototyping Journal, Vol. 19 Issue: 1, pp.51-57, doi: 10.1108/13552541311292736

J. Ceram. Sci. Tech., 05 [04] 245-260 (2014)

Better desing with Architected materials

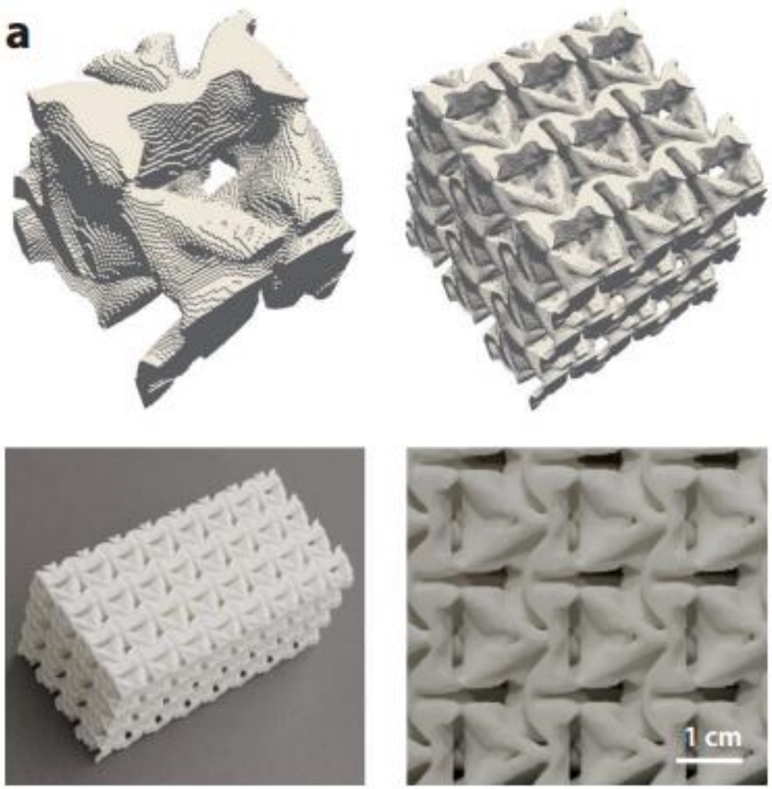
- AM as an opportunity for high architectural efficiency and function integration -

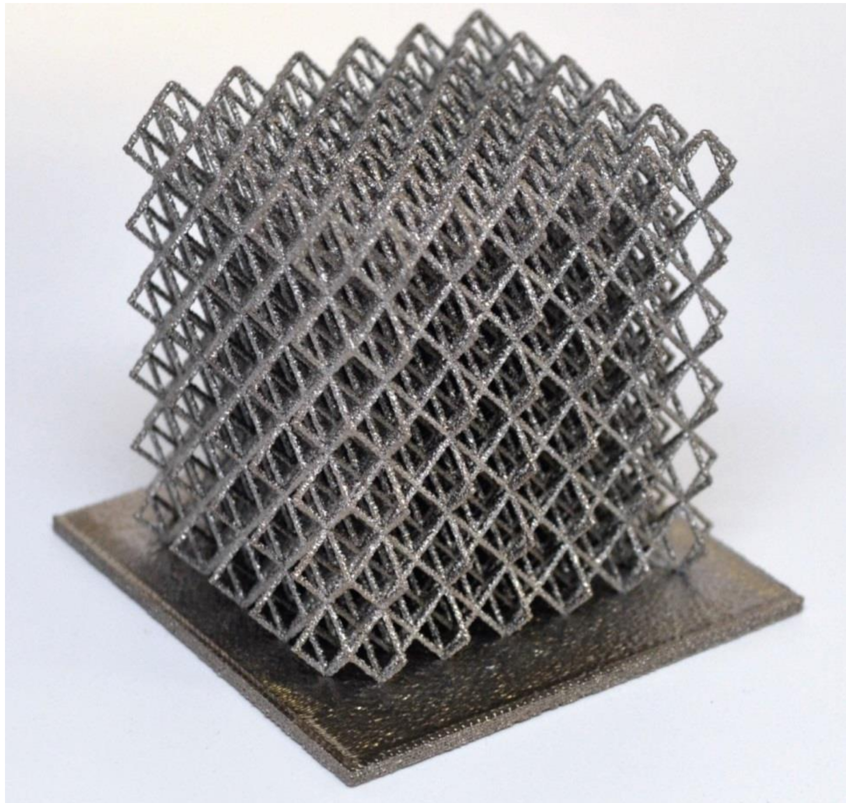


Schaedler TA, Carter WB. 2016. Annu. Rev. Mater. Res. 46:187–210

Additive Manufacturing for Architected Materials

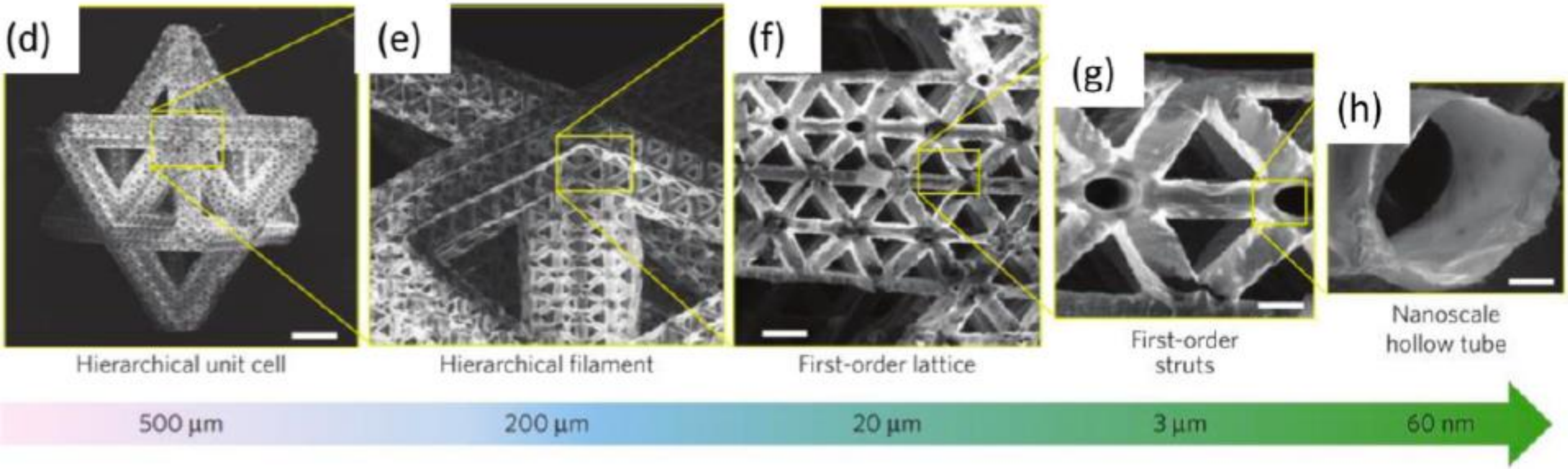
A convenient way to fabricate components with complex structural topologies





Mikhail Osanov and James K. Guest
Ann. Rev. Mater. Res. Vol. 46, 2016, pp. 211-233

Additive Manufacturing and Hierarchical Structures



Mikhail Osanov and James K. Guest
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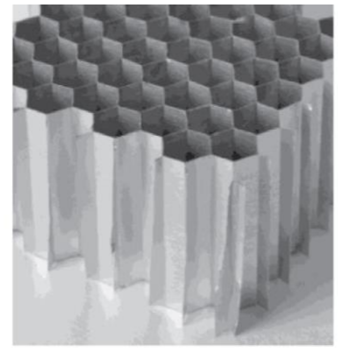
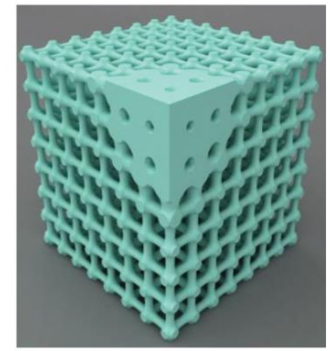
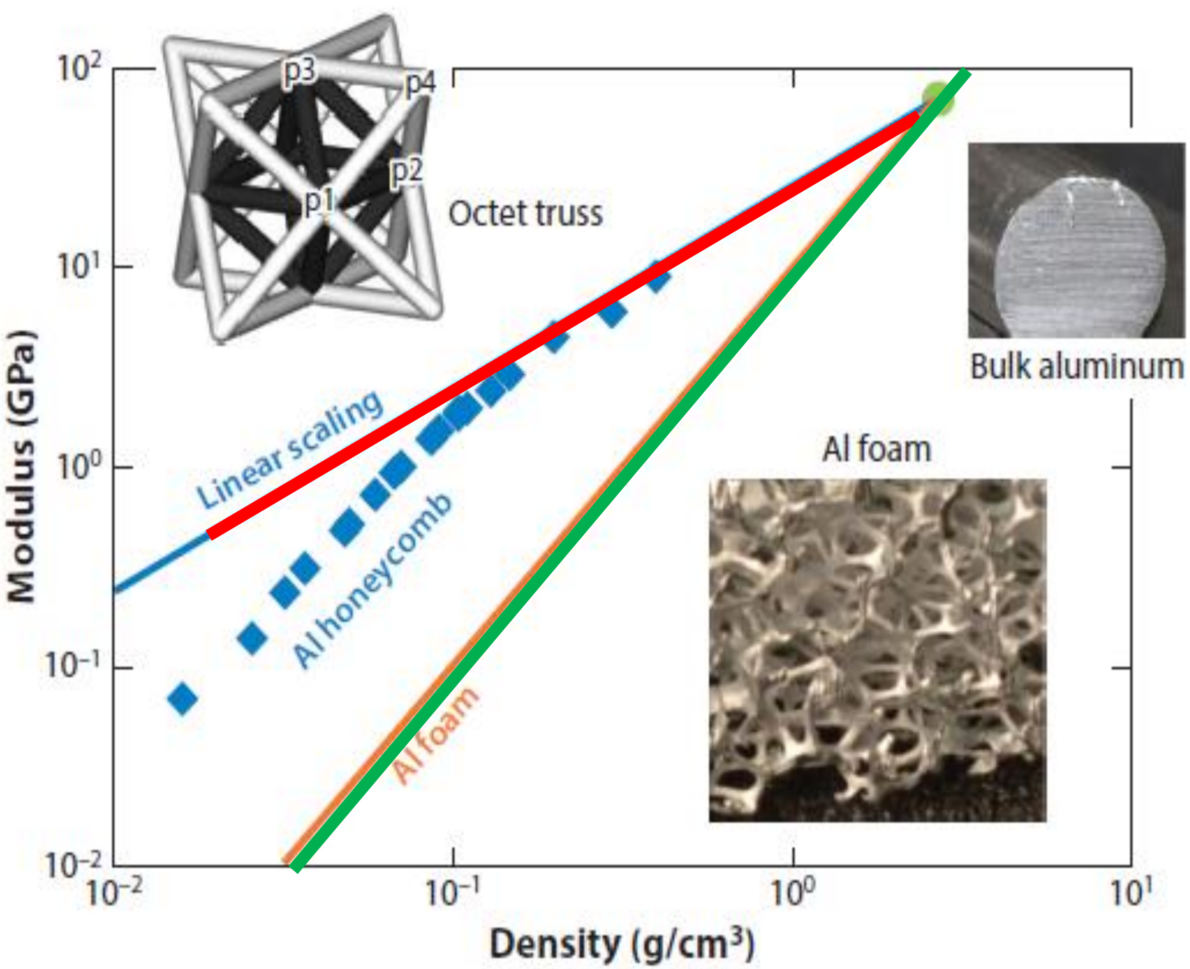
Architected Cellular Materials

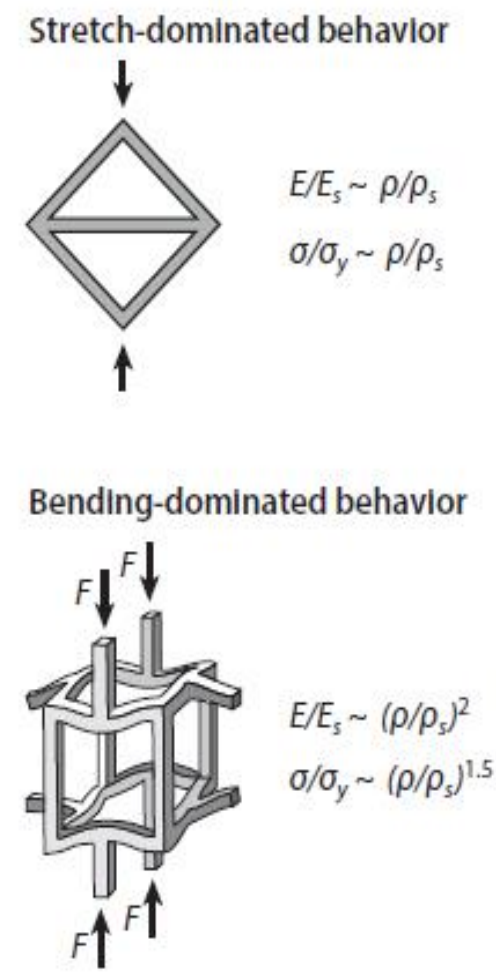
				
Cellular architecture	None	Random	Ordered	Ordered and location specific
Properties	Continuous and homogeneous	Homogeneous at scales > cell	Homogeneous and highly anisotropic	Inhomogeneous and highly anisotropic
Design degrees of freedom	Solid constituent	Solid constituent, cell size	Solid constituent, cell size, and orientation	Cell size/shape, node topology, ligament shape, material...

Tobias A. Schaedler and William B. Carter
Ann. Rev. Mater. Res. Vol. 46, 2016, pp. 187–210

Architected Cellular Materials for Enhancing E/ρ

Foams vs Trusses → Bending-dominated vs Stretch-dominated structures





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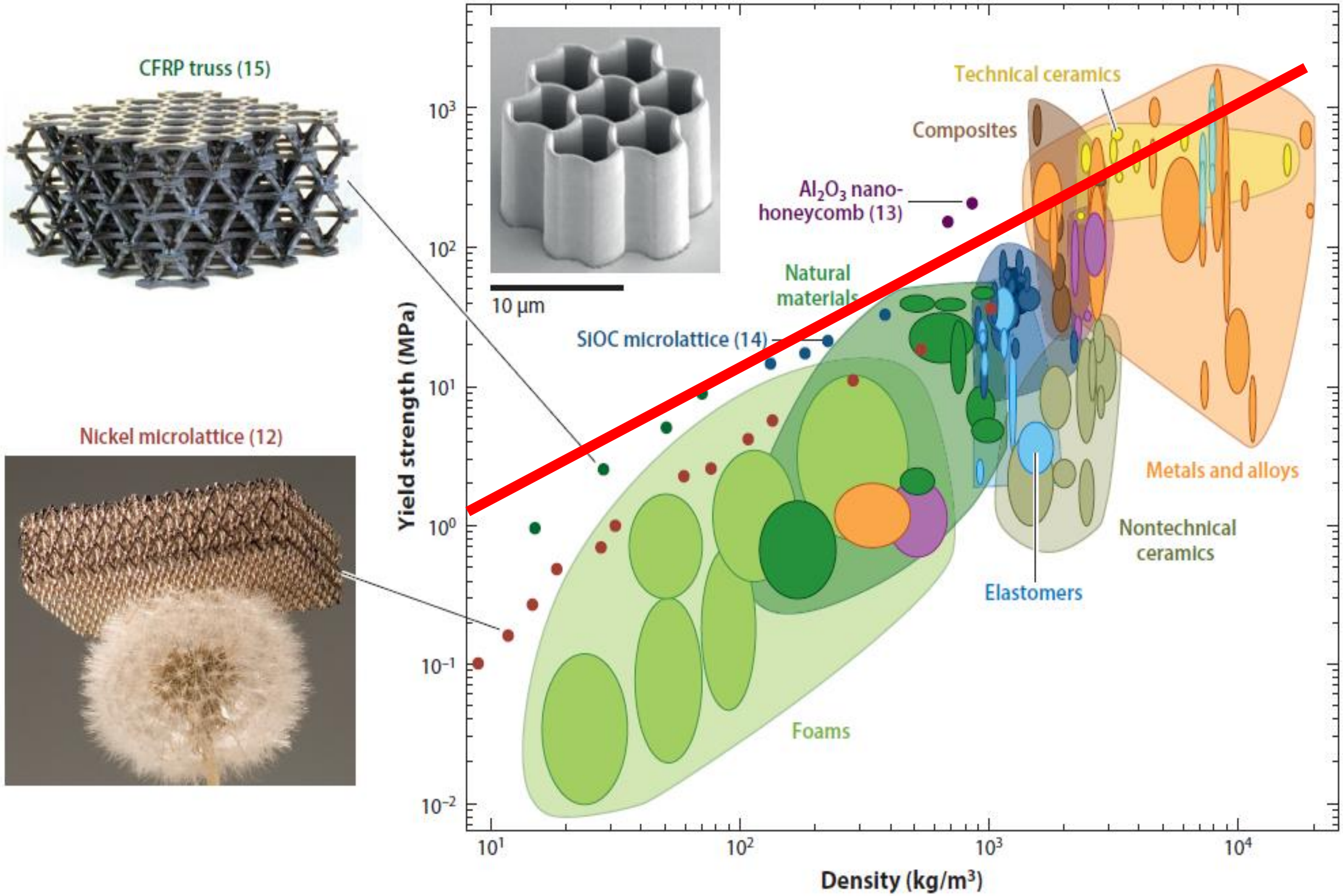
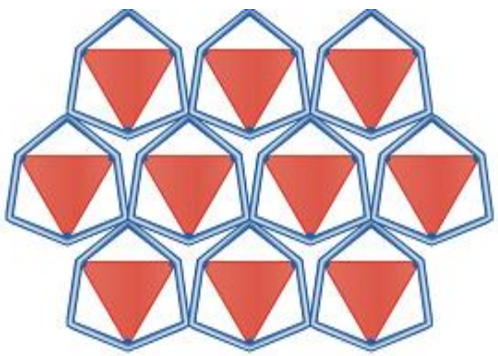
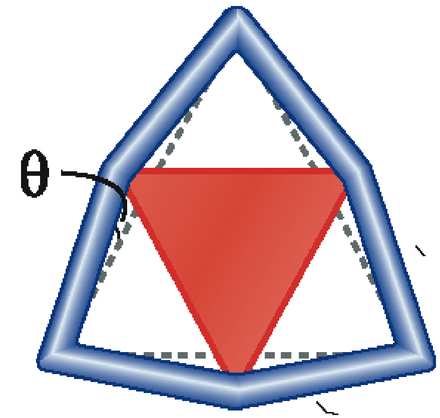
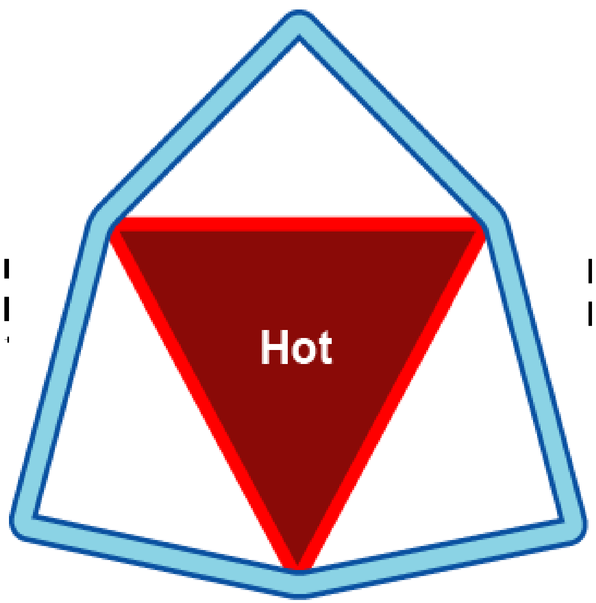
Advanced Cellular Design

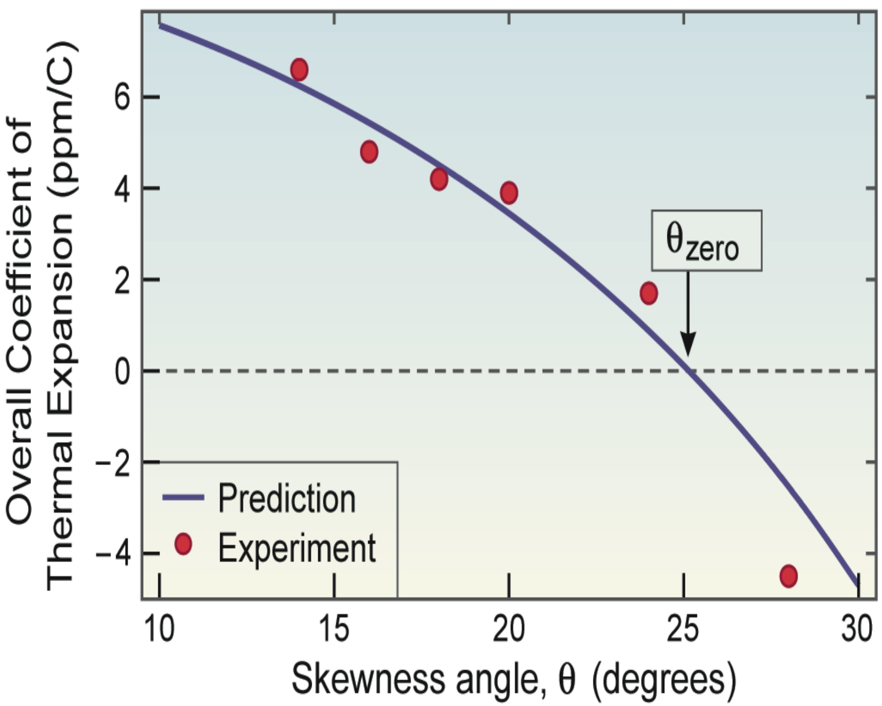


Configuration: controlling thermal expansion

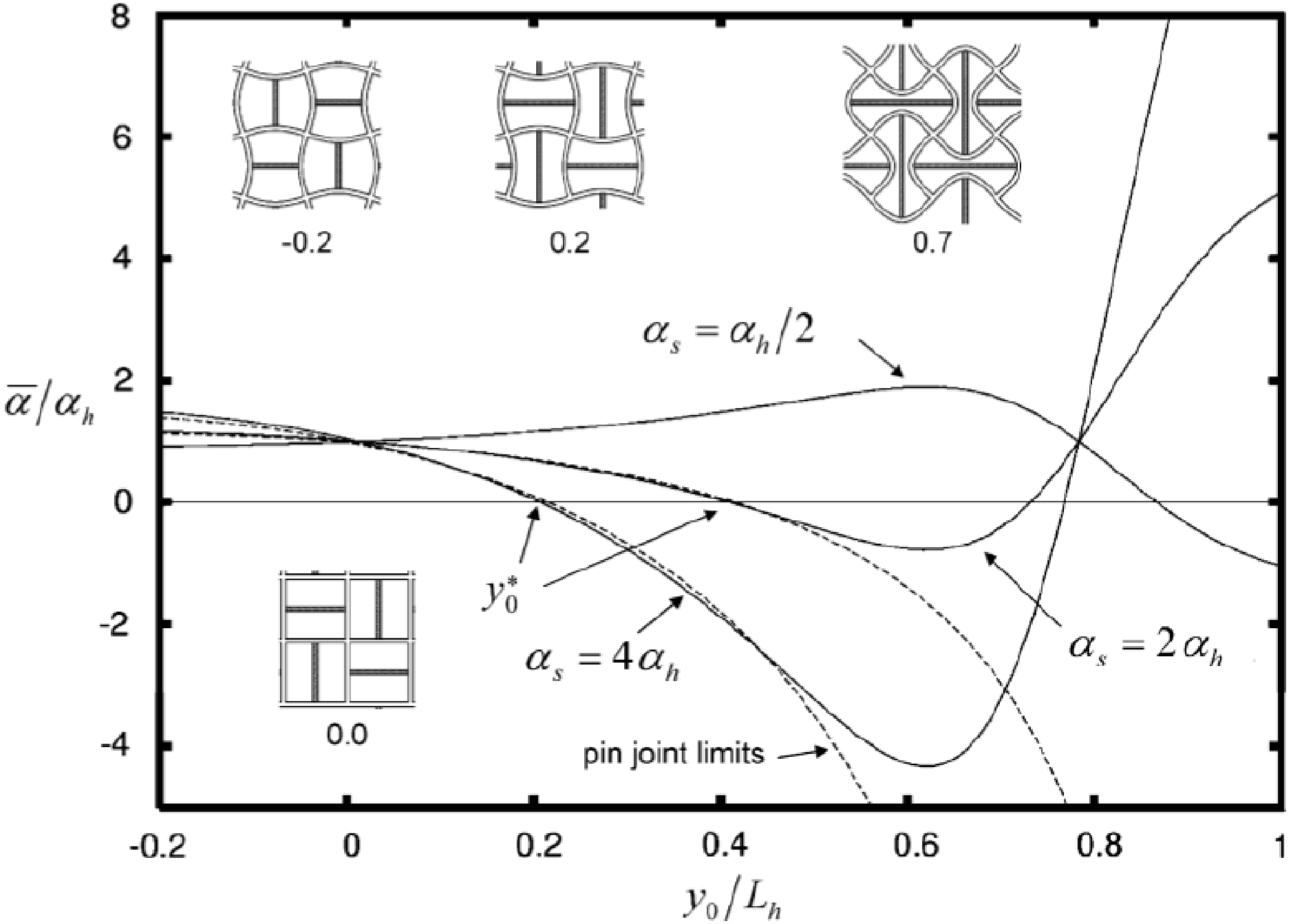


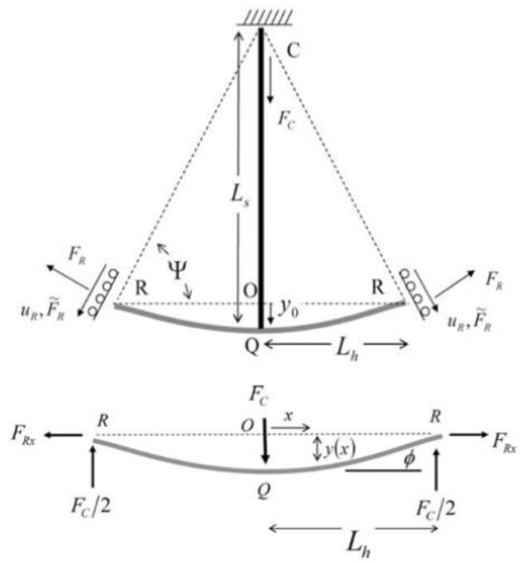




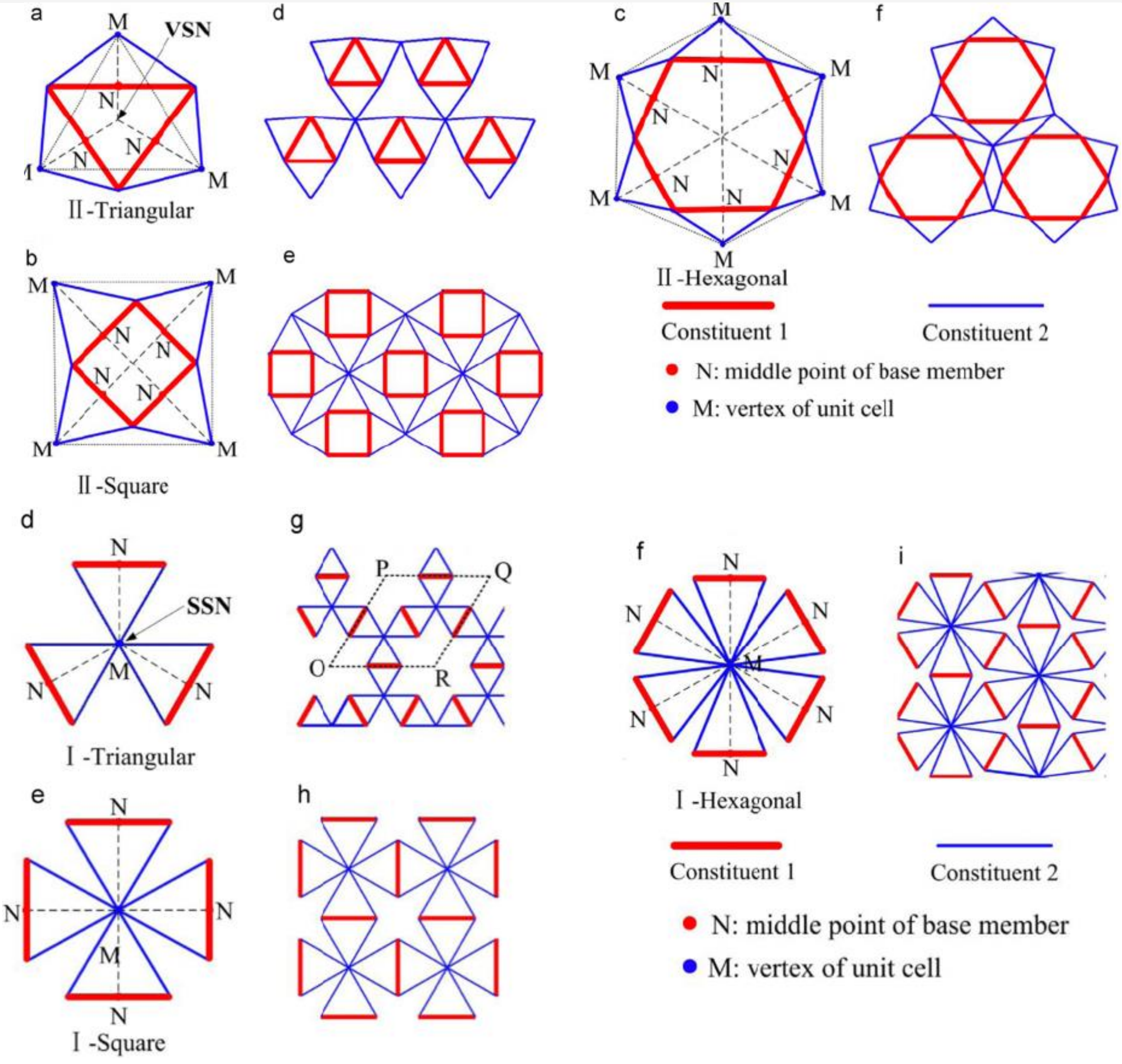


Configuration: controlling thermal expansion

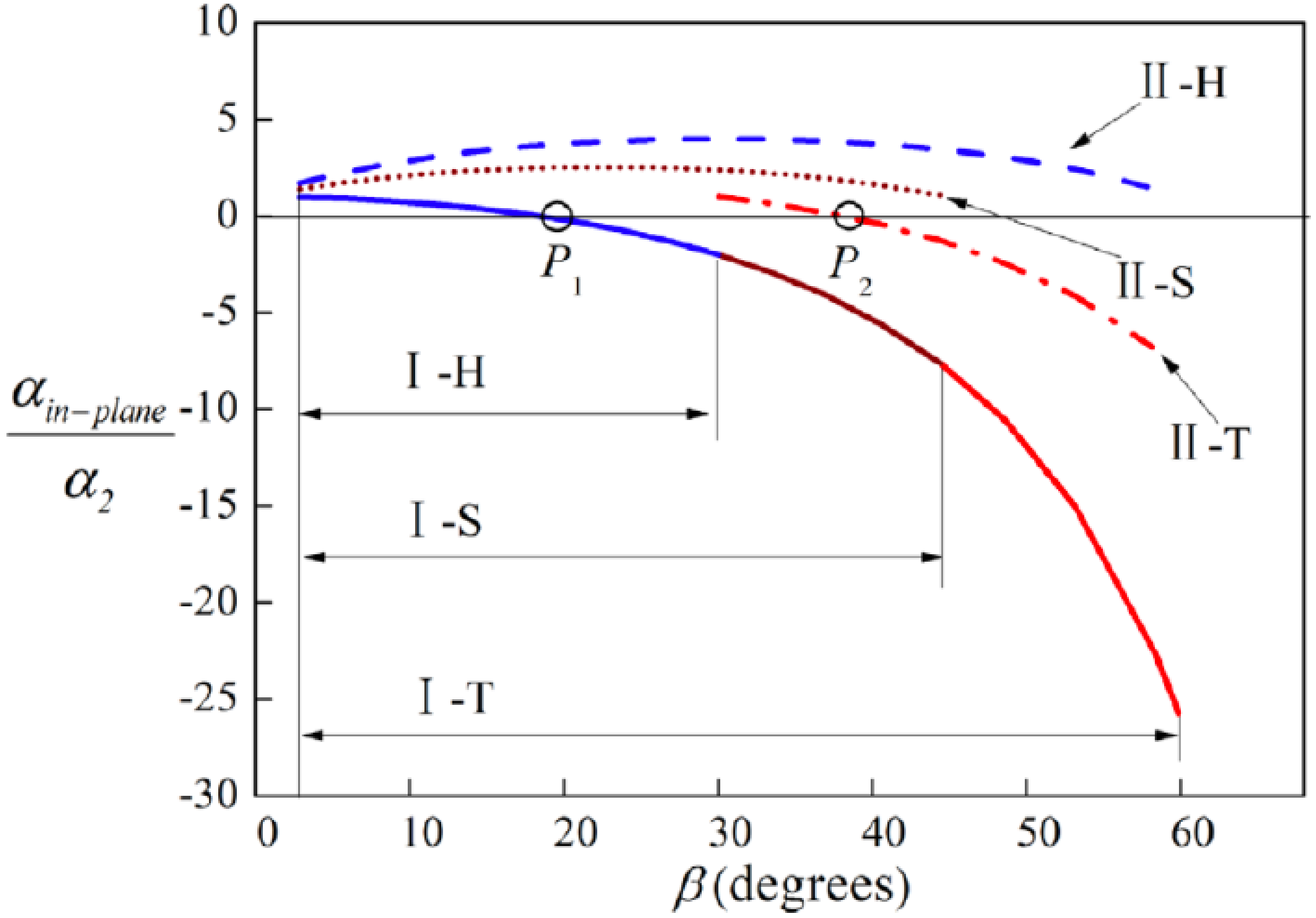




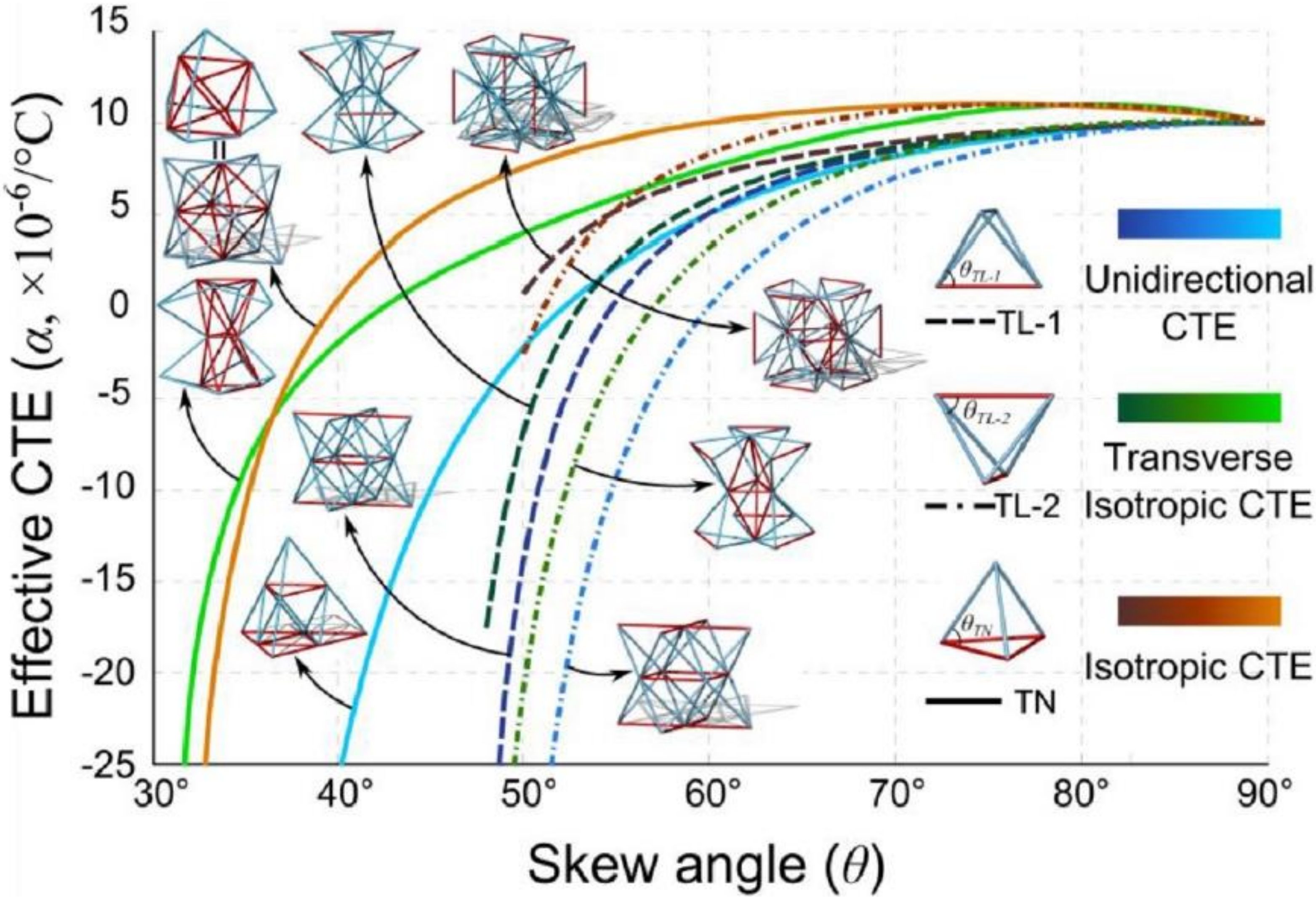
Configuration: controlling thermal expansion



Configuration: controlling thermal expansion



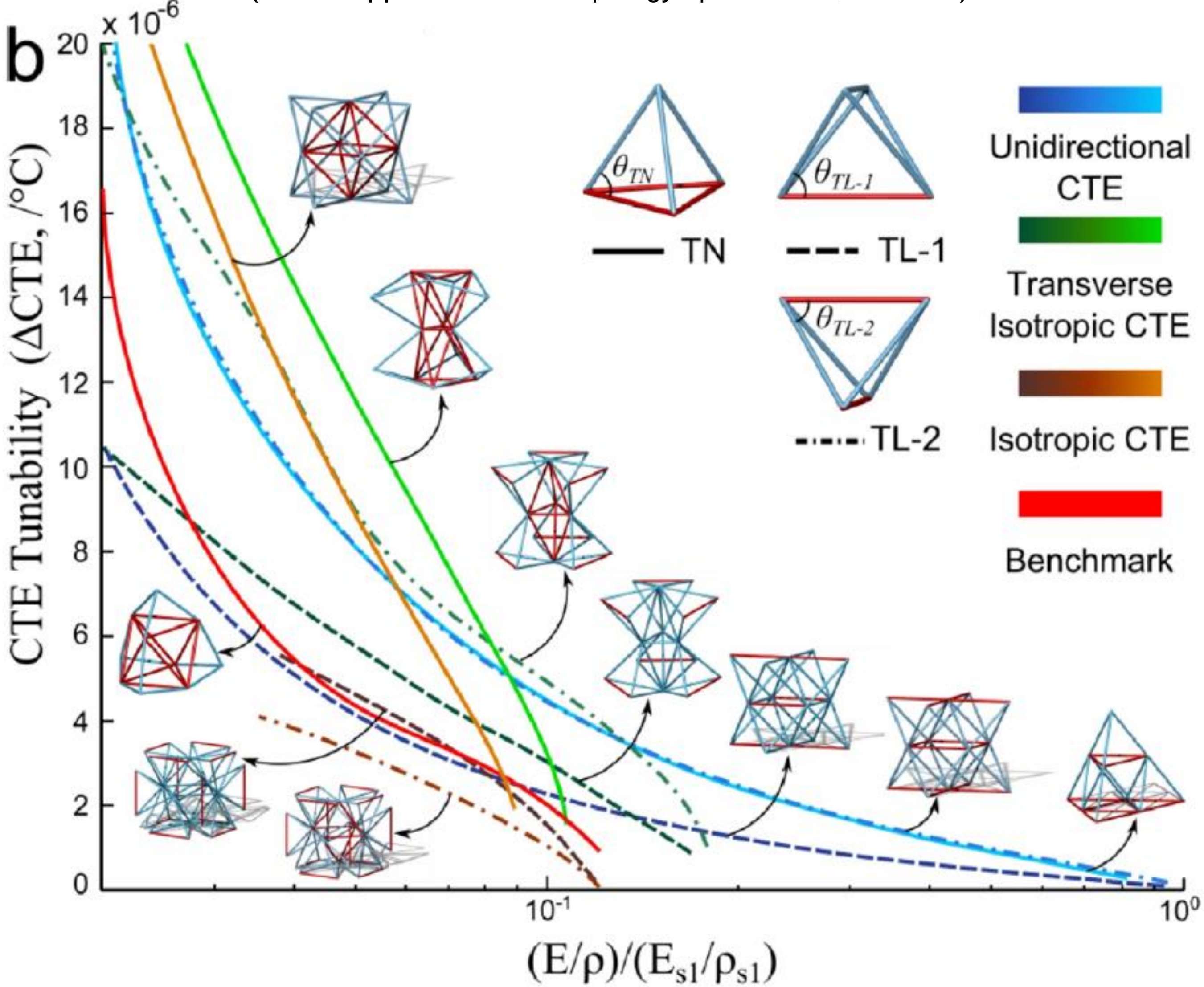
Configuration: controlling thermal expansion



Configuration: controlling thermal expansion

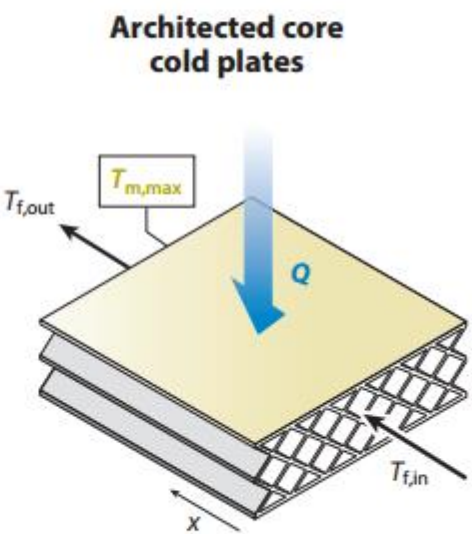
Trade-off between CTE tunability and rigidity

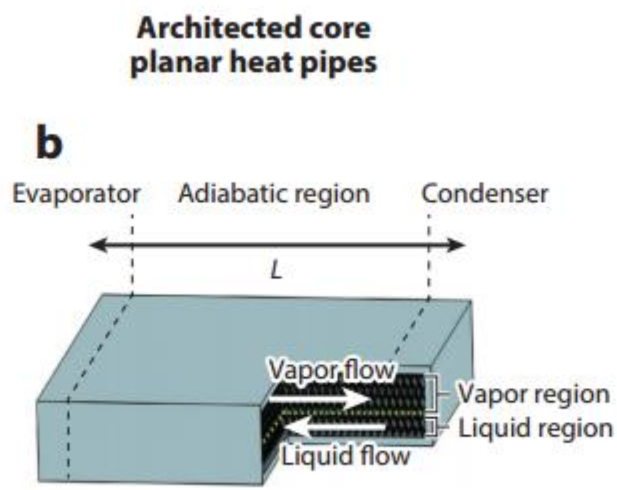
(can be approached with topology optimization, see later)

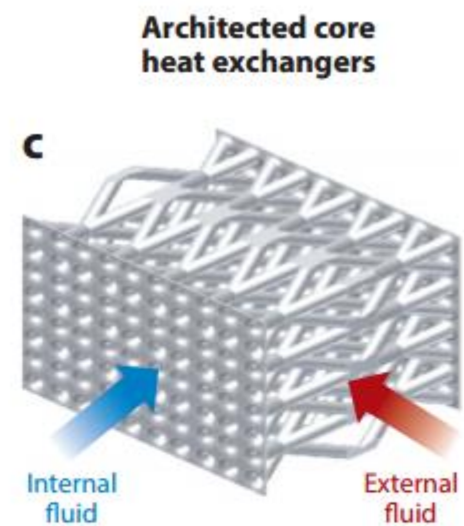


Architected Materials

Integrating functionality







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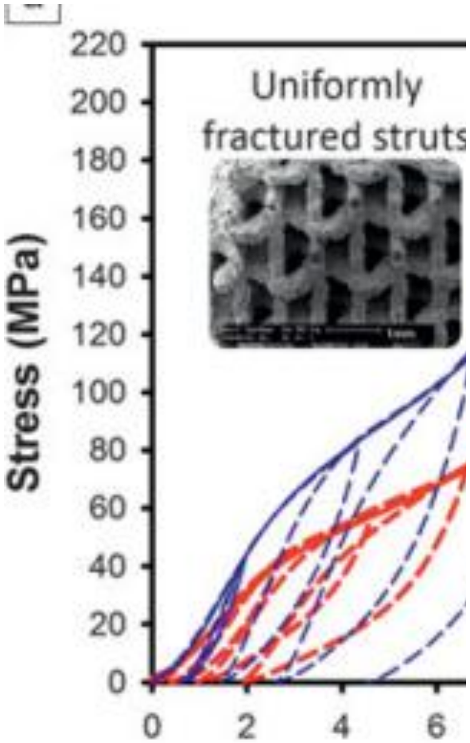
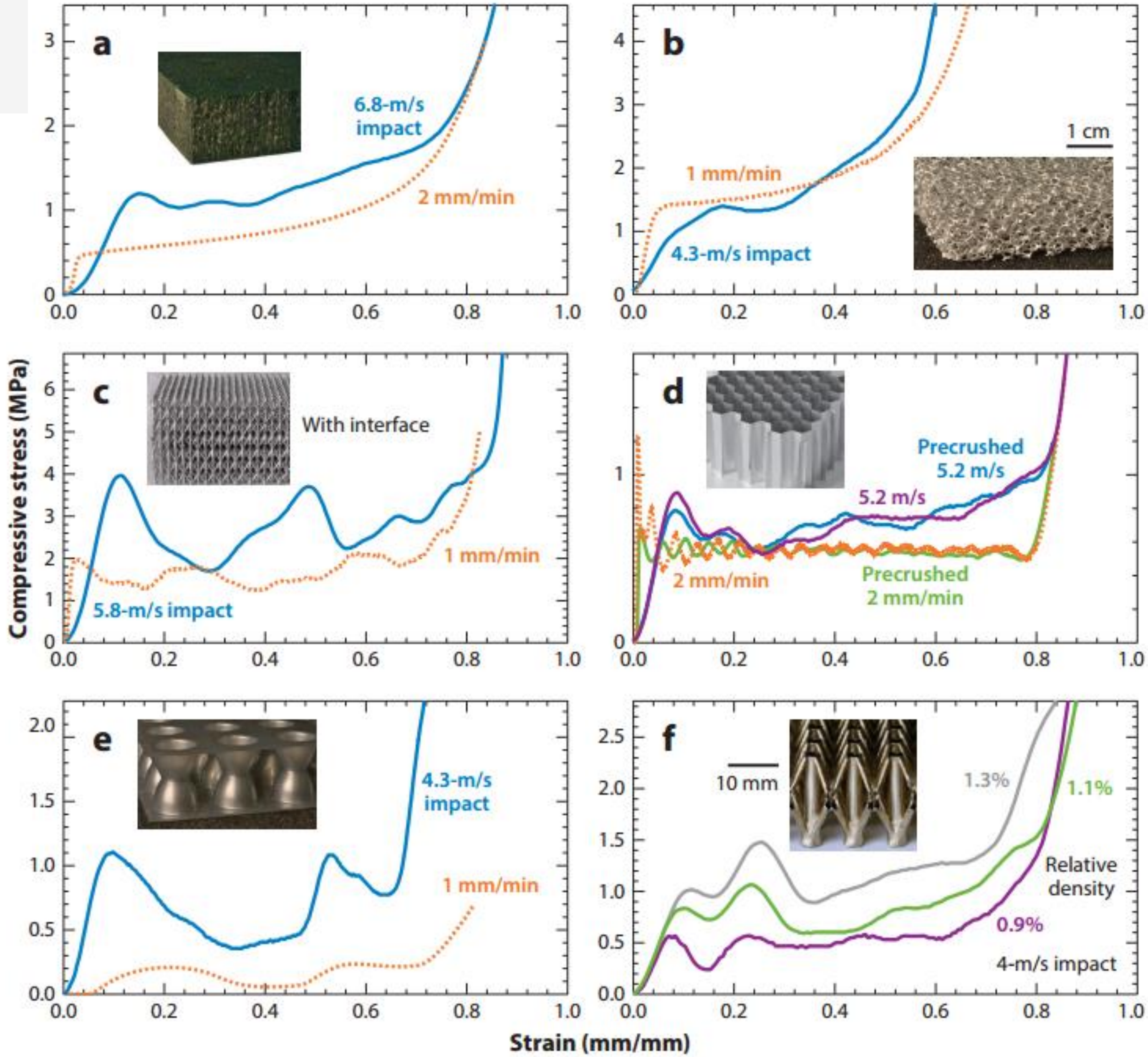
Architected Materials

Engineerir
Mechanical Pro





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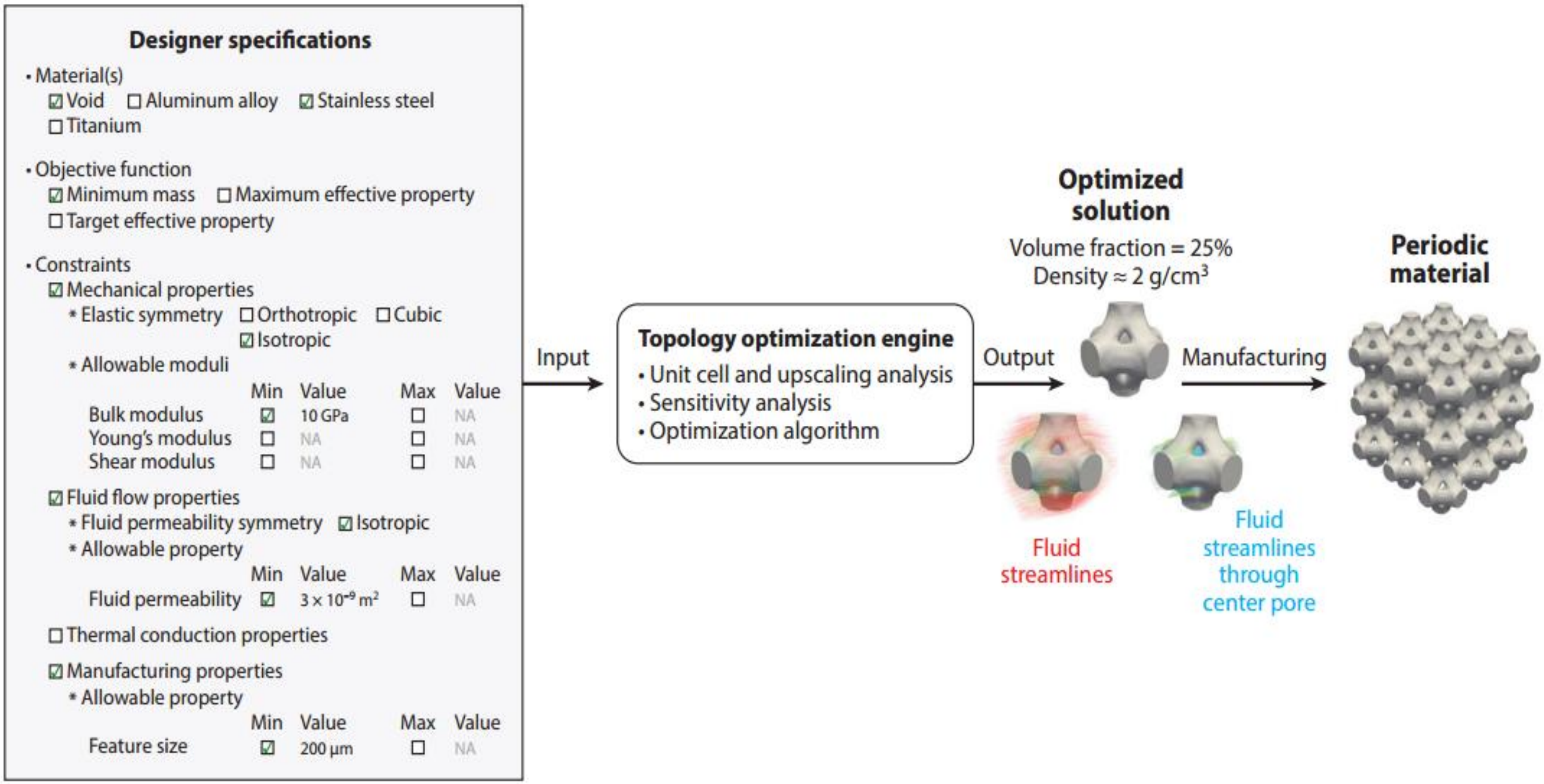
Optimizing Structural Topology



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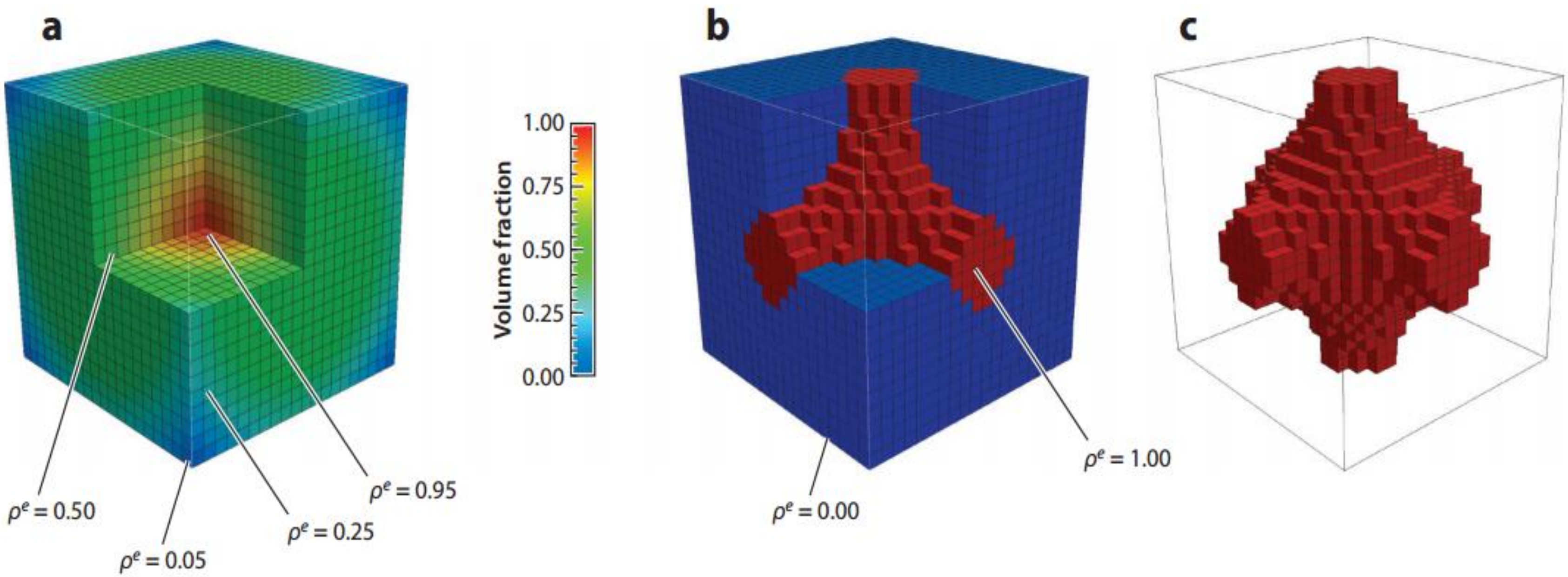
Finite Element Modeling for Topology Optimization



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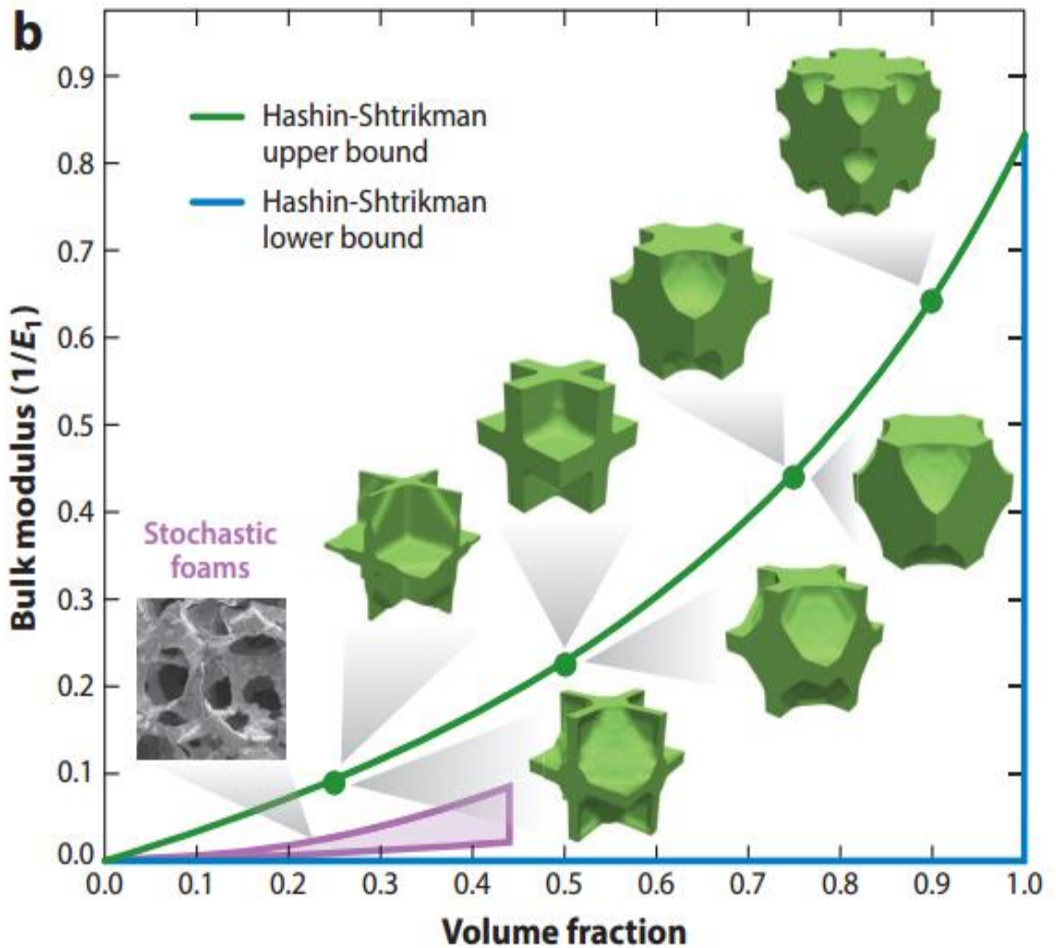
Example of Topology Optimization

Maximum Stiffness vs Minimum Density



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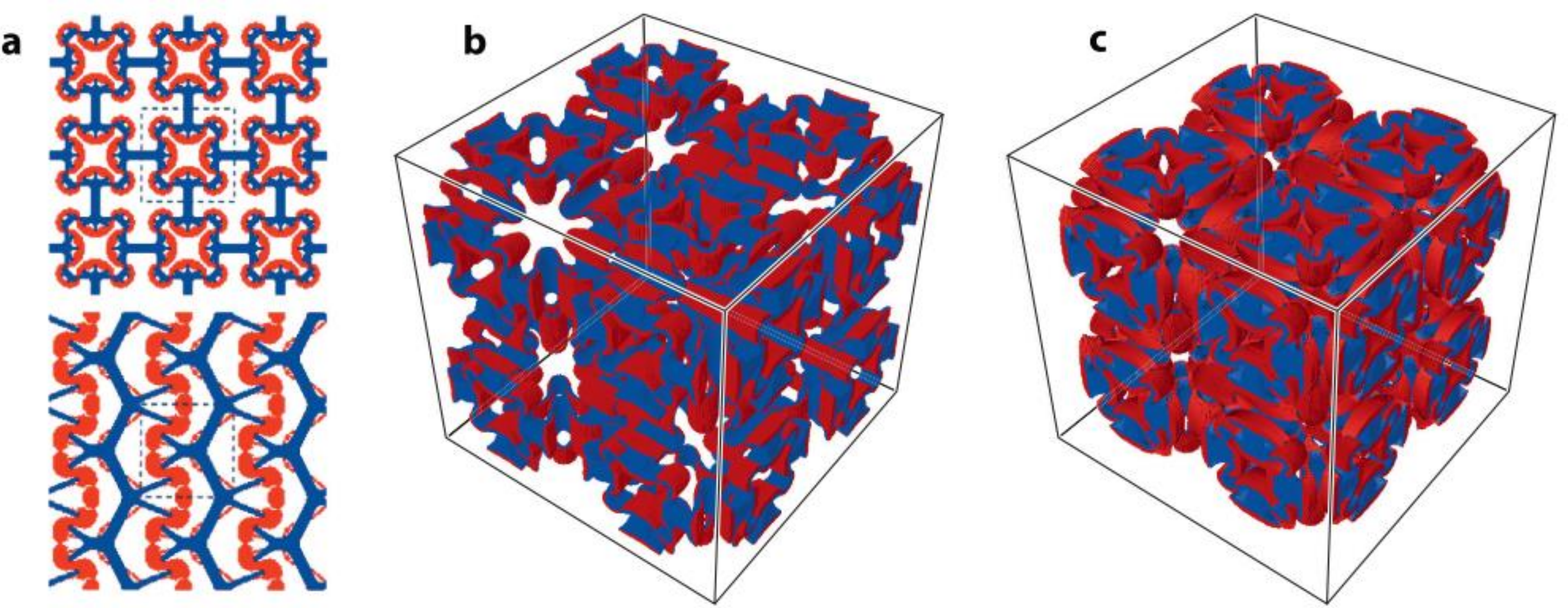
Example of Topology Optimization

Optimal CTE (Negative, 3D, trade-off with stiffness)



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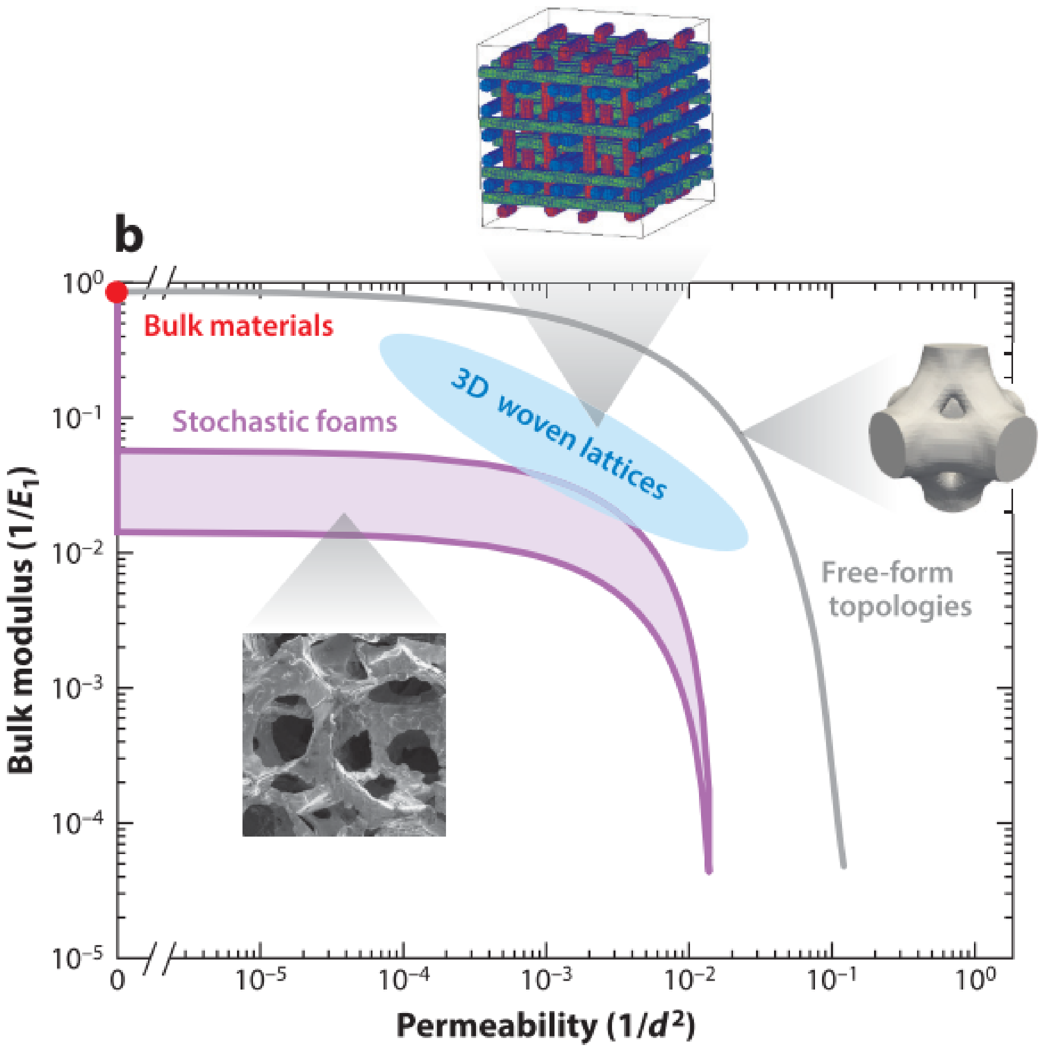
Example of Topology Optimization

Optimal trade-off between rigidity and permeability

(useful for scaffolds, fluidic actuators, thermal transport…)



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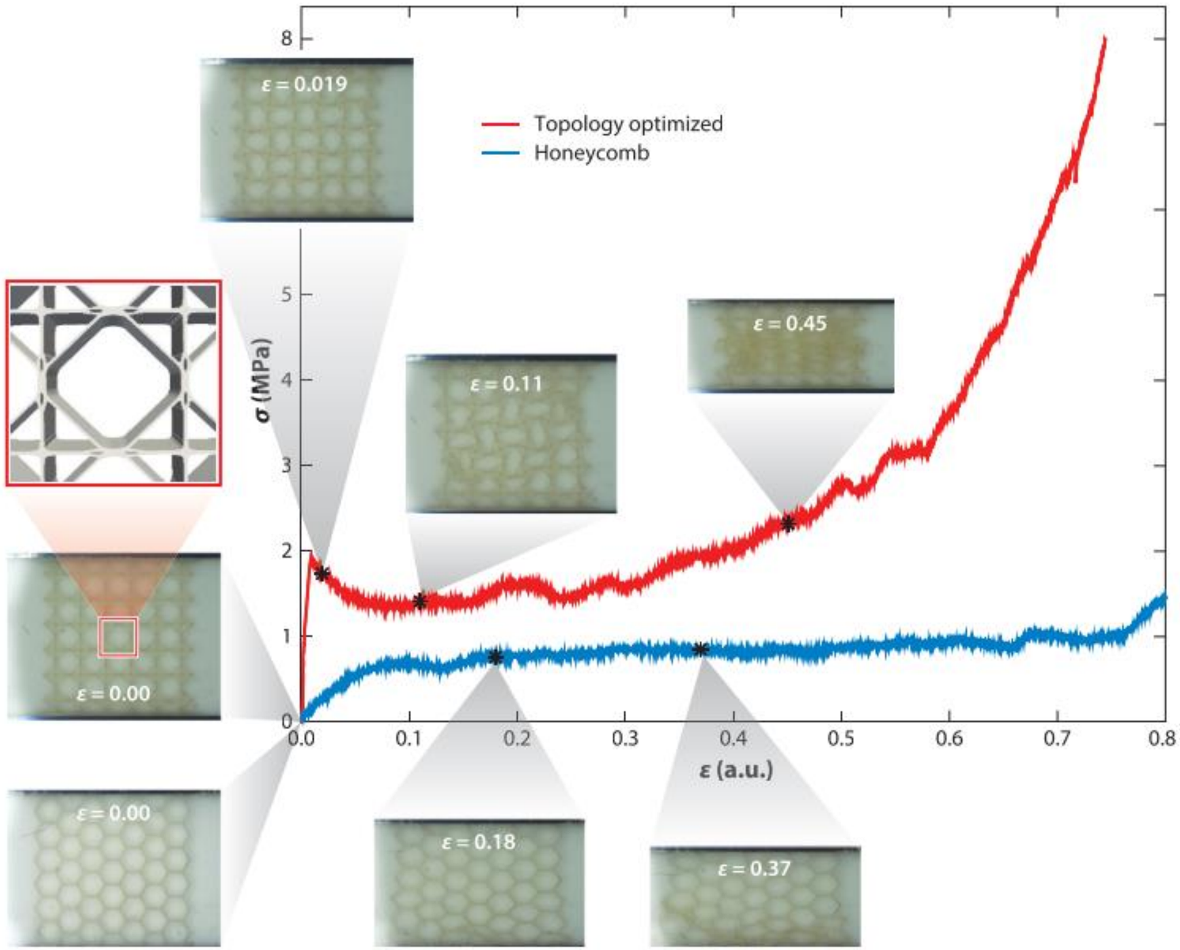
Example of Topology Optimization

Optimal energy absorption

(e.g. for blast-resistant materials)



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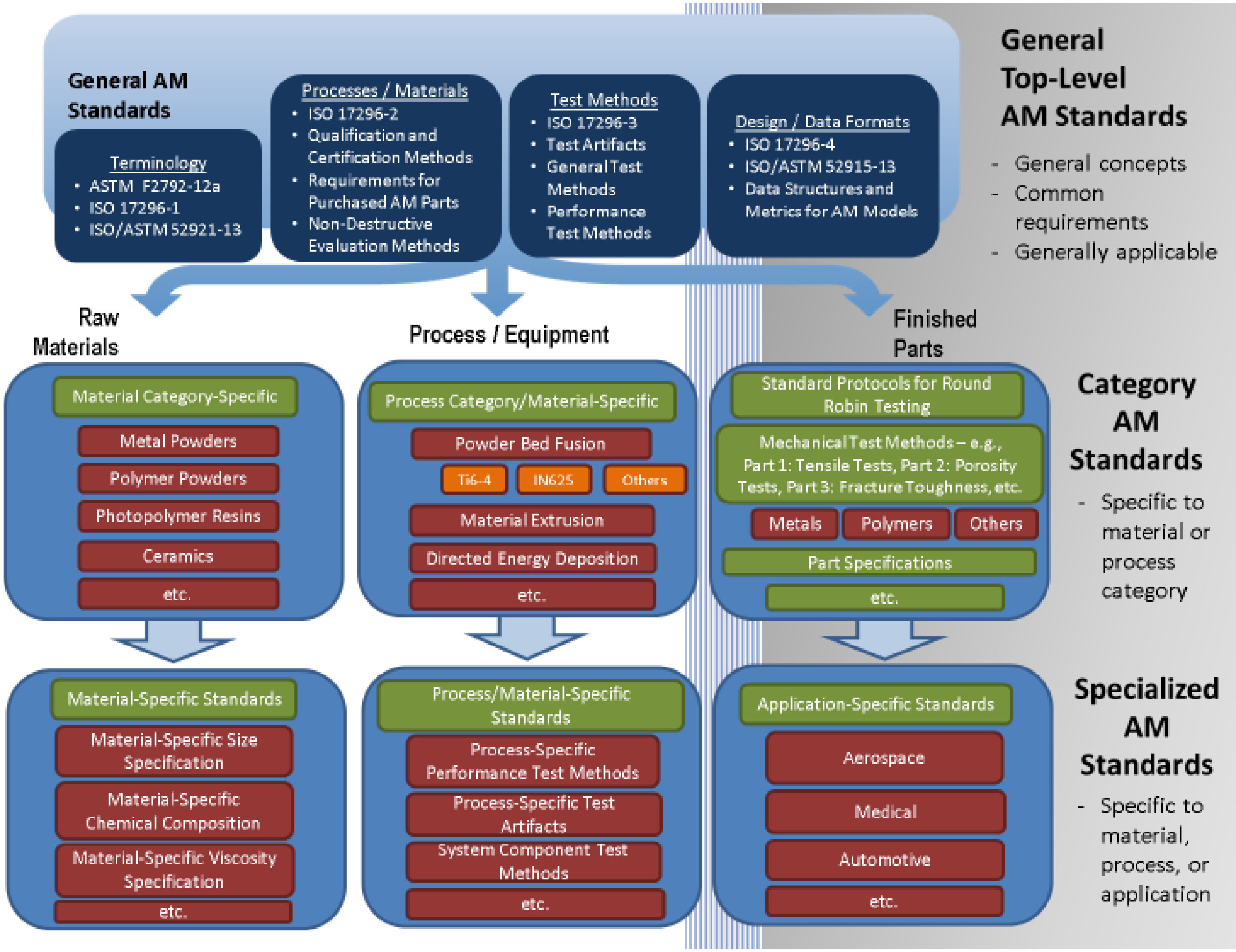
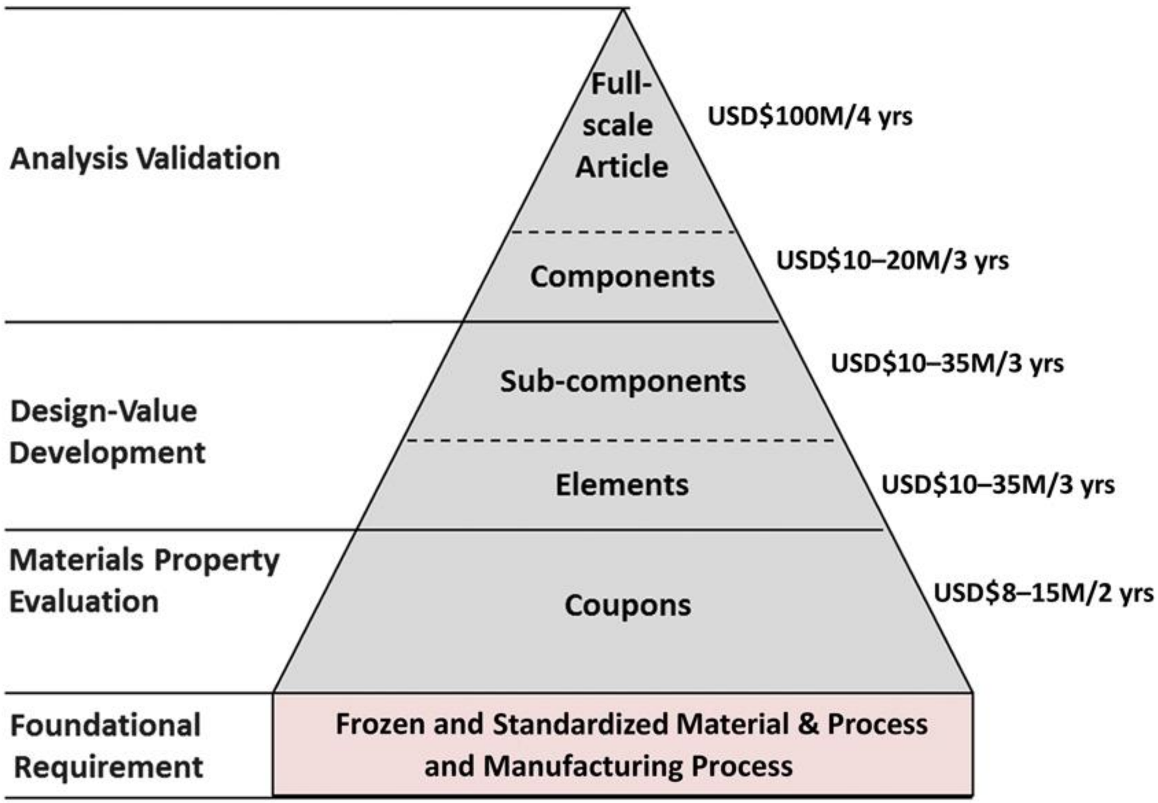
Qualification Issues

Process qualification – development of standards



Process qualification



Linear approach to qualification is unfit forAM

Need a paradigm shift towards **Integrated Computational Materials Engineering**

Process qualification

- **Detailed logging and analysis** of parameters during manufacturing
- **In-situ monitoring** of layers (optical and thermal imaging)
- **Modelling of process and material:** identify the tendency to defect formation or microstructural heterogeneity
- **Sacrificial samples** for testing (US, X-ray or neutron CAT, residual stress distribution, …)

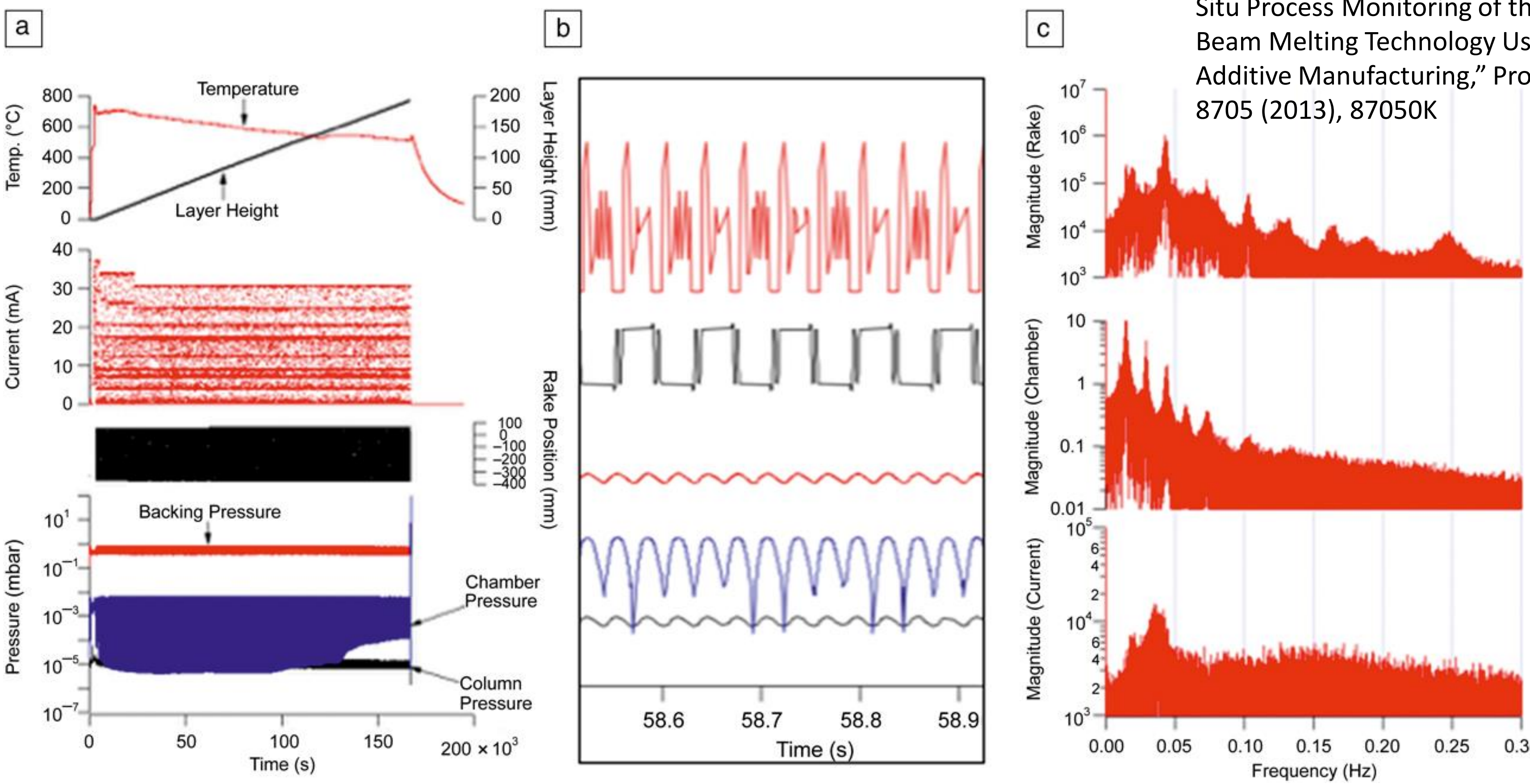
Table 2 - Excerpt from ISO 17296-3:2014

		Suggested ISO standard for Metal Testing	
Surface Requirements	Appearance	16348	
	Surface Texture	1302 /4288	
	Colour	11664-i	[i = 1 - 5]
Geometric Requirements	Size,length and angle dimensions, dimensional tolerances	129-1, 286-1, 14405-1, 1938-1c, 2786-1	
	Geometrical tolerancing (deviations in shape and position)	1101, 2786-2	
Mechanical Requirements	Hardness	6507	
	Tensile strength	6892-1[a]	
	Impact Strength	148-j	j = 1,2(charpy)[a]
	Compressive Strength	4506	
	Flexural Strength	3327	
	Fatigue Strength	1099,1143	
	Creep	204	
	Ageing	Not relevant	
	Frictional coefficient	No ISO specified	
	Shear Resistance	148-1	
	Crack Extension	2889	
Build Material Requirements	Density	3369	
	Physical and physico-chemical properties	5579	
		3452-k	k = [1,2]
		61675	nb. IEC not ISO
Additional	Microstructure (DT)	9934-1	

Process qualification

- **Detailed logging and analysis** of parameters during manufacturing

R.B.Dinwiddie et al., “Thermographic In Situ Process Monitoring of the Electron-Beam Melting Technology Used in Additive Manufacturing,” Proc. SPIE 8705 (2013), 87050K



Process qualification

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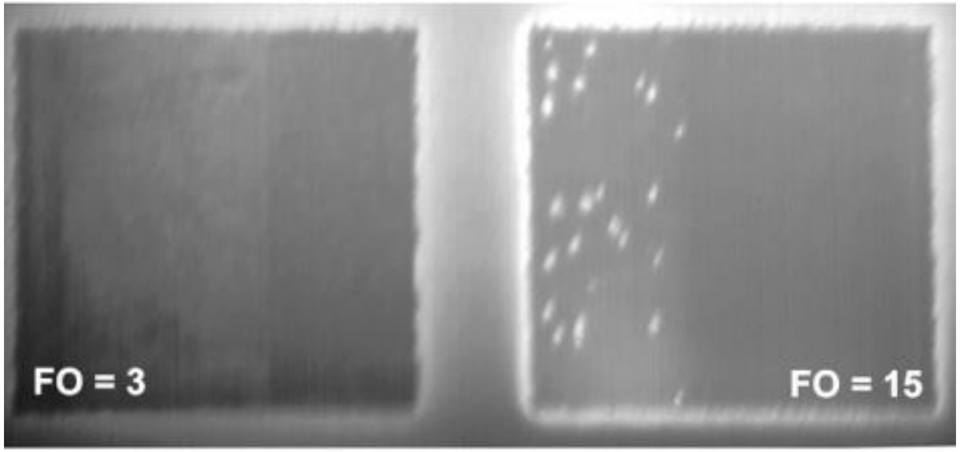
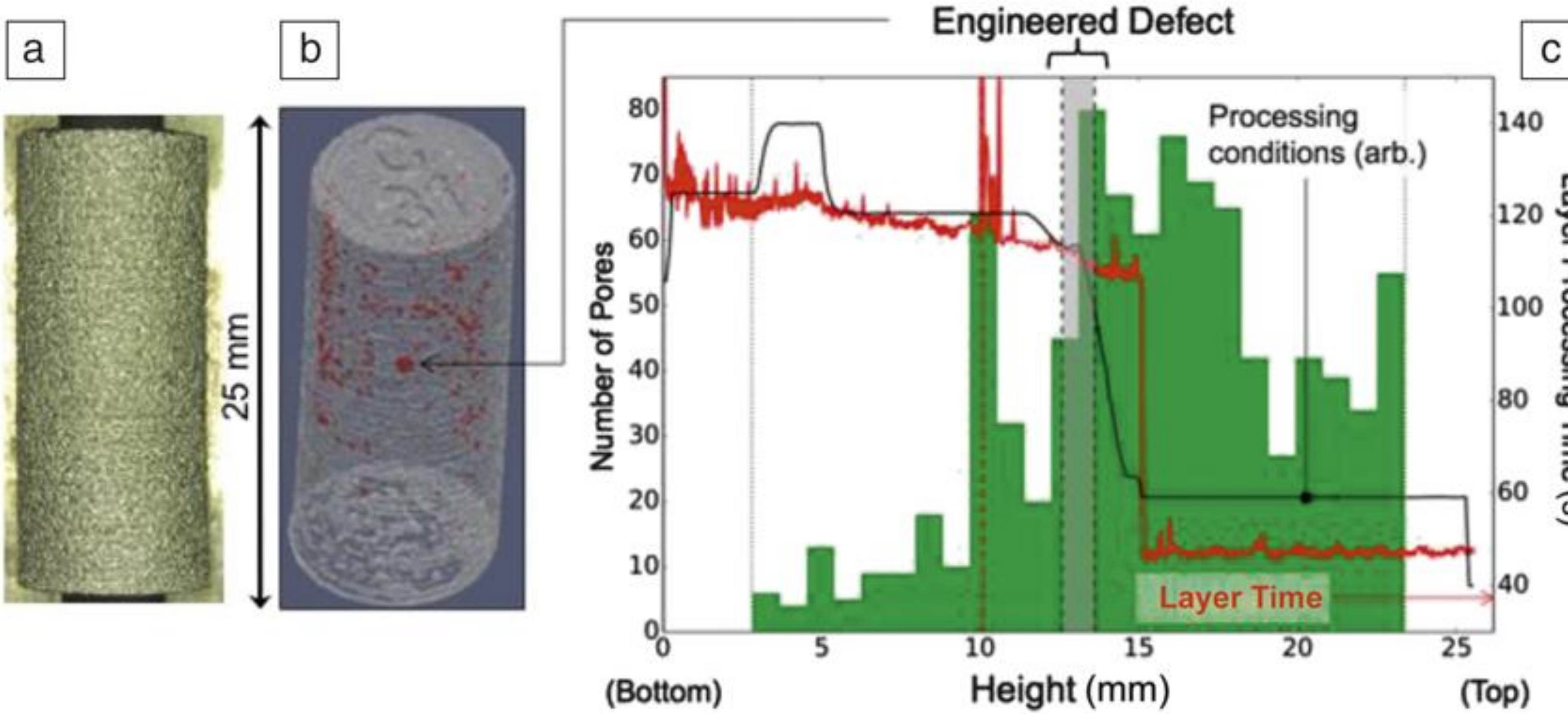
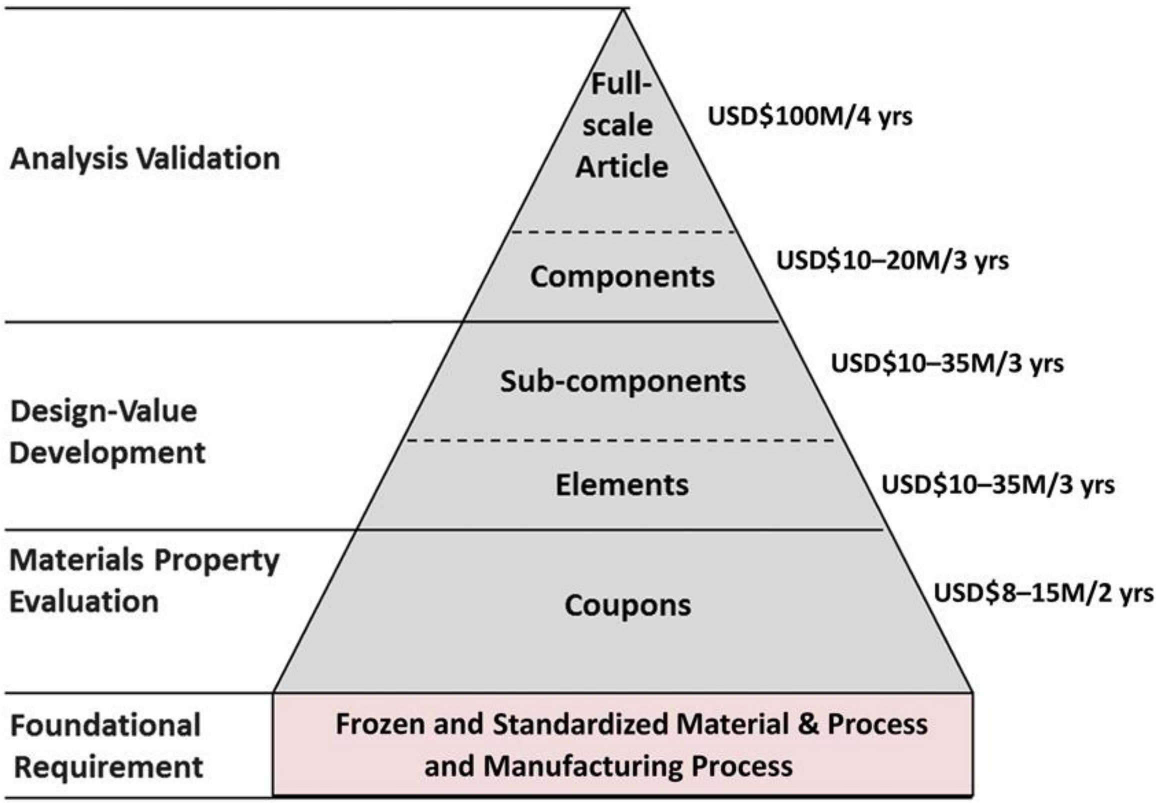


Process qualification



E.Schwalbach , M.Groeber , "Multi-Model Data Collection and Integration for Metallic Additive Manufacturing," AAAS Annual Meeting: Symposium on Integrated Computational Materials Engineering Principles for Additive Manufacturing, San Jose, CA (2015)

Process qualification

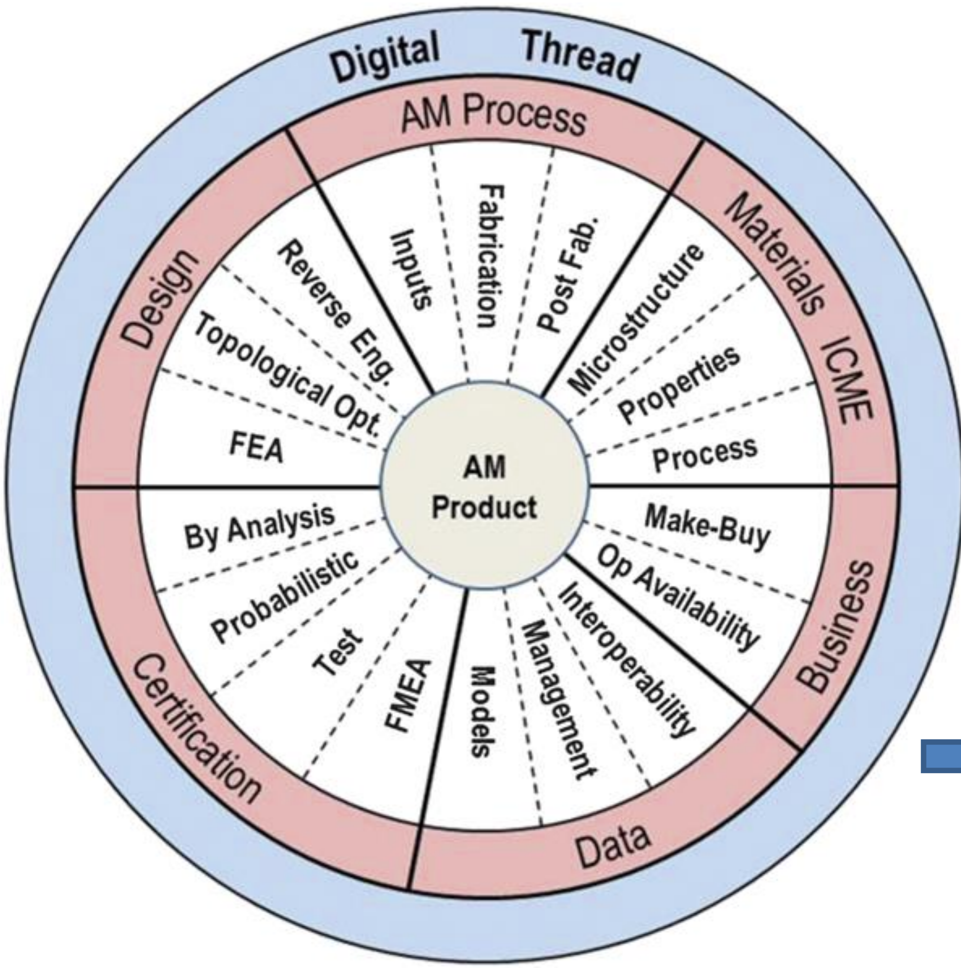


Linear approach to qualification is unfit forAM

Need a paradigm shift towards **Integrated Computational Materials Engineering**

ICME

Integrated Computational Materials Engineering



ICME-informed qualification leverages an **integrated system** of:

- Design tools
- Data management and analysis
- Materials (multiscale modeling)
- Business modeling
- Manufacturing process

A process **“quality envelope”** is defined

Sensors and controls are needed to maintain the process within the quality envelope

Concluding remarks

- Comparison of AM with traditional manufacturing requires an **integral, lifetime analysis**

- **Traditional manufacturing is cheaper** in most cases
- **Other benefits** should be factored in (e.g. faster production)
- Capital cost can hardly be recovered; using AM providers might be a better business case

- Once a satisfactory technological level is reached (predictability and qualification):
  - AM allows for **faster production**
  - AM requires less tooling, **less investments, less working capital**
  - AM allows for **optimization of design: synergic effects**

- **Standardization, classification, quality control, validation of design and product**, are needed at both the technological and regulatory level

- Need more focus on the **materials aspects**:
  - Develop a larger portfolio
  - More work about the relationship material-process-microstructure-properties