GDR Groupement de recherche
ARCHI-META
Architectured Metamaterials

Matériaux architecturés métalliques obtenus par Fabrication Additive (FA) : état de l'art et perspectives

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GIS HEAD

Journée de lancement
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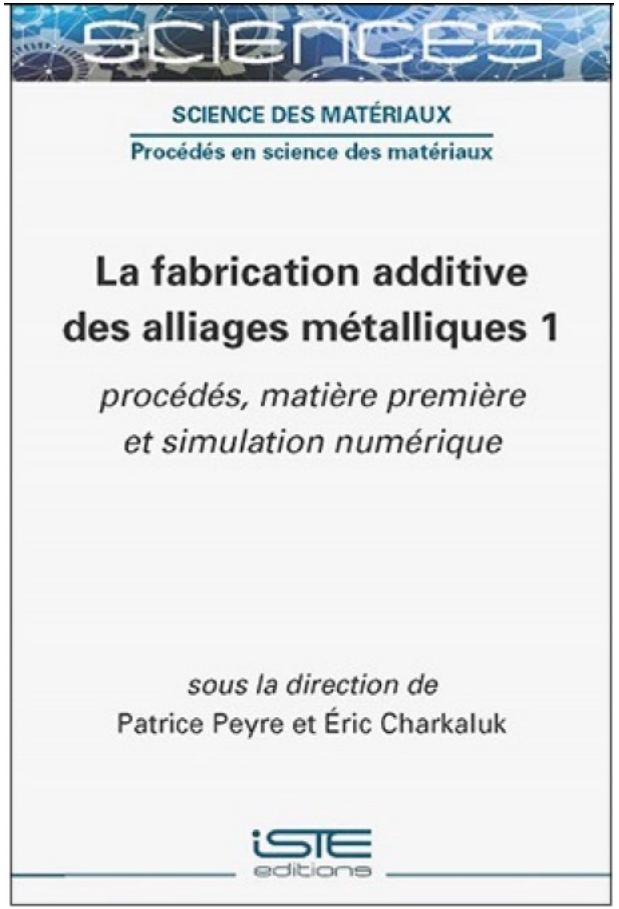
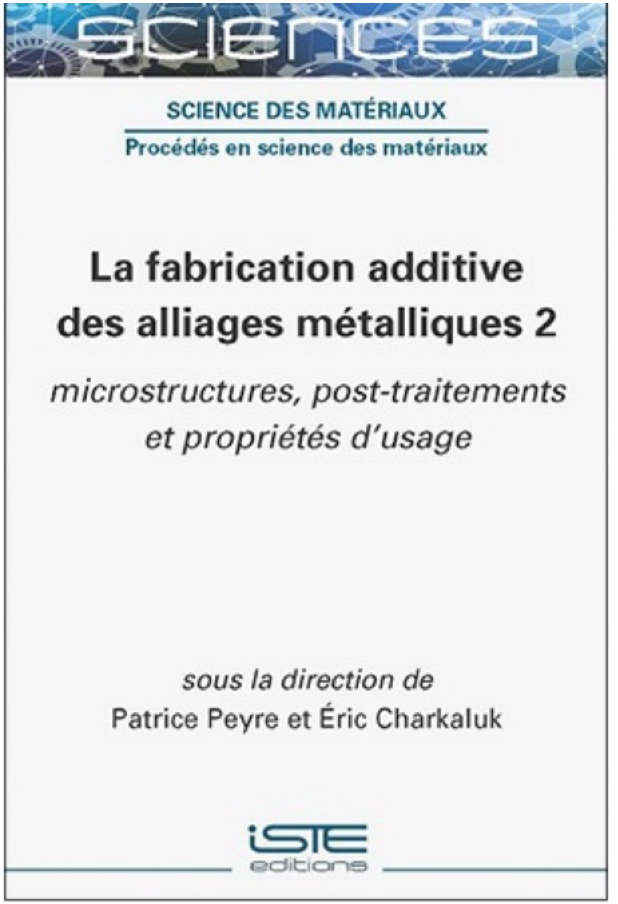
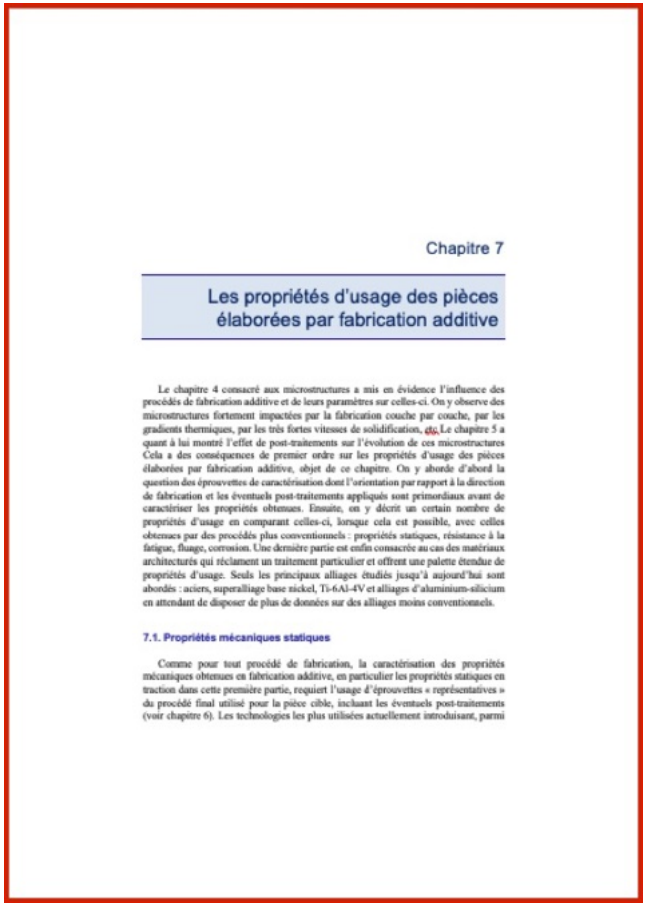
- Some generalities on metallic Additive Manufacturing (AM)
- Materials, microstructures, defects : some variabilities
- Mechanical characterization
- Numerical simulations
- Conclusions and open questions

Recent books





Recent books



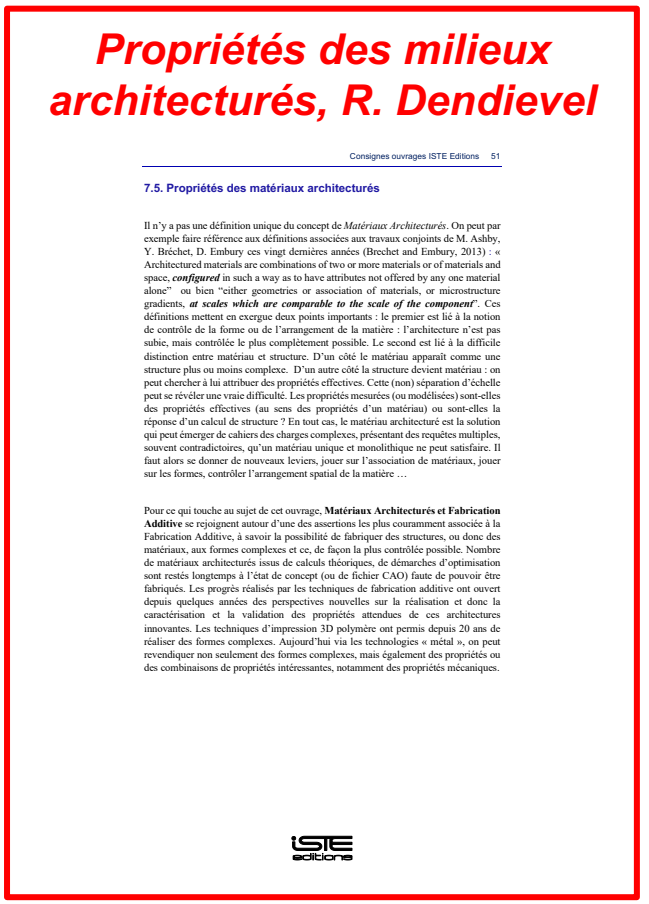
Chapitre 7

Les propriétés d'usage des pièces élaborées par fabrication additive

Le chapitre 4 consacré aux microstructures a mis en évidence l'influence des procédés de fabrication additive et de leurs paramètres sur celles-ci. On y observe des microstructures fortement impactées par la fabrication couche par couche, par les gradients thermiques, par les très fortes vitesses de solidification, etc. Le chapitre 5 a quant à lui montré l'effet de post-traitements sur l'évolution de ces microstructures. Cela a des conséquences de premier ordre sur les propriétés d'usage des pièces élaborées par fabrication additive, objet de ce chapitre. On y aborde d'abord la question des éprouvettes de caractérisation dont l'orientation par rapport à la direction de fabrication et les éventuels post-traitements appliqués sont primordiaux avant de caractériser les propriétés obtenues. Ensuite, on y décrit un certain nombre de propriétés d'usage en comparant celles-ci, lorsque cela est possible, avec celles obtenues par des procédés plus conventionnels : propriétés statiques, résistance à la fatigue, fluage, corrosion. Une dernière partie est enfin consacrée au cas des matériaux architecturés qui réclament un traitement particulier et offrent une palette étendue de propriétés d'usage. Seuls les principaux alliages étudiés jusqu'à aujourd'hui sont abordés : aciers, superalliage base nickel, Ti-6Al-4V et alliages d'aluminium-silicium en attendant de disposer de plus de données sur des alliages moins conventionnels.

7.1. Propriétés mécaniques statiques

Comme pour tout procédé de fabrication, la caractérisation des propriétés mécaniques obtenues en fabrication additive, en particulier les propriétés statiques en traction dans cette première partie, requiert l'usage d'"éprouvettes « représentatives » du procédé final utilisé pour la pièce cible, incluant les éventuels post-traitements (voir chapitre 6). Les technologies les plus utilisées actuellement introduisant, parmi



Propriétés des milieux architecturés, R. Dendievel

7.5. Propriétés des matériaux architecturés

Il n'y a pas une définition unique du concept de *Matériaux Architecturés*. On peut par exemple faire référence aux définitions associées aux travaux conjoints de M. Ashby, Y. Bréchet, D. Embury ces vingt dernières années (Brechet and Embury, 2013) : « Architectured materials are combinations of two or more materials or of materials and space, ***configured*** in such a way as to have attributes not offered by any one material alone" ou bien "either geometries or association of materials, or microstructure gradients, ***at scales which are comparable to the scale of the component***". Ces définitions mettent en exergue deux points importants : le premier est lié à la notion de contrôle de la forme ou de l'arrangement de la matière : l'architecture n'est pas subie, mais contrôlée le plus complètement possible. Le second est lié à la difficile distinction entre matériau et structure. D'un côté le matériau apparaît comme une structure plus ou moins complexe. D'un autre côté la structure devient matériau : on peut chercher à lui attribuer des propriétés effectives. Cette (non) séparation d'échelle peut se révéler une vraie difficulté. Les propriétés mesurées (ou modélisées) sont-elles des propriétés effectives (au sens des propriétés d'un matériau) ou sont-elles la réponse d'un calcul de structure ? En tout cas, le matériau architecturé est la solution qui peut émerger de cahiers des charges complexes, présentant des requêtes multiples, souvent contradictoires, qu'un matériau unique et monolithique ne peut satisfaire. Il faut alors se donner de nouveaux leviers, jouer sur l'association de matériaux, jouer sur les formes, contrôler l'arrangement spatial de la matière …

Pour ce qui touche au sujet de cet ouvrage, **Matériaux Architecturés et Fabrication Additive** se rejoignent autour d'une des assertions les plus couramment associée à la Fabrication Additive, à savoir la possibilité de fabriquer des structures, ou donc des matériaux, aux formes complexes et ce, de façon la plus contrôlée possible. Nombre de matériaux architecturés issus de calculs théoriques, de démarches d'optimisation sont restés longtemps à l'état de concept (ou de fichier CAO) faute de pouvoir être fabriqués. Les progrès réalisés par les techniques de fabrication additive ont ouvert depuis quelques années des perspectives nouvelles sur la réalisation et donc la caractérisation et la validation des propriétés attendues de ces architectures innovantes. Les techniques d'impression 3D polymère ont permis depuis 20 ans de réaliser des formes complexes. Aujourd'hui via les technologies « métal », on peut revendiquer non seulement des formes complexes, mais également des propriétés ou des combinaisons de propriétés intéressantes, notamment des propriétés mécaniques.

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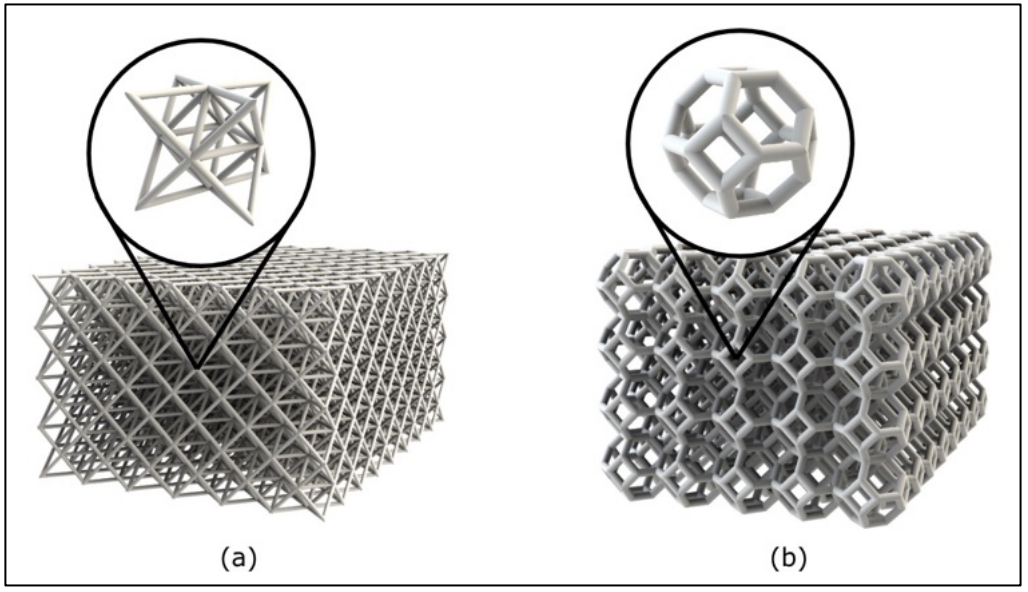
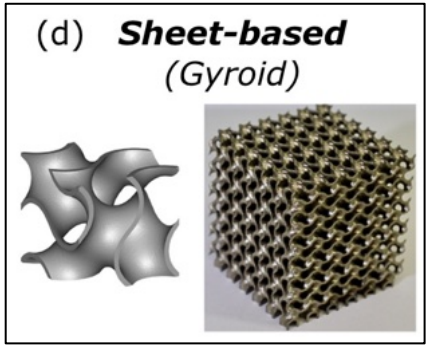
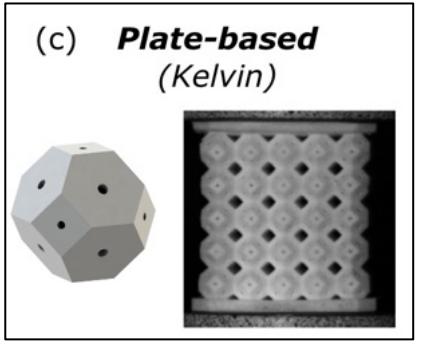
Generalities on metallic AM

- In this talk:
  - Metallic powders: a few tens of micrometers
  - Direct processes: high energies (laser, electron beam), local melting and solidification



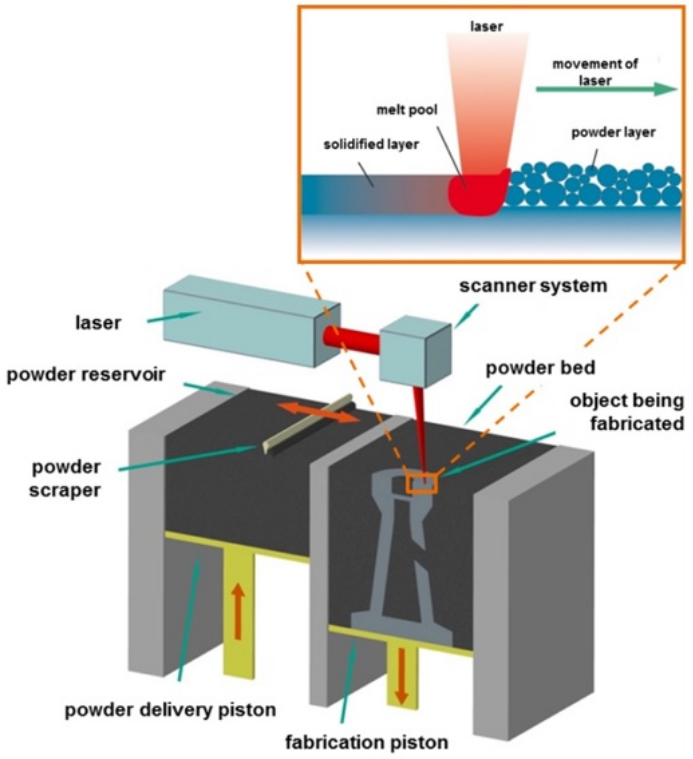




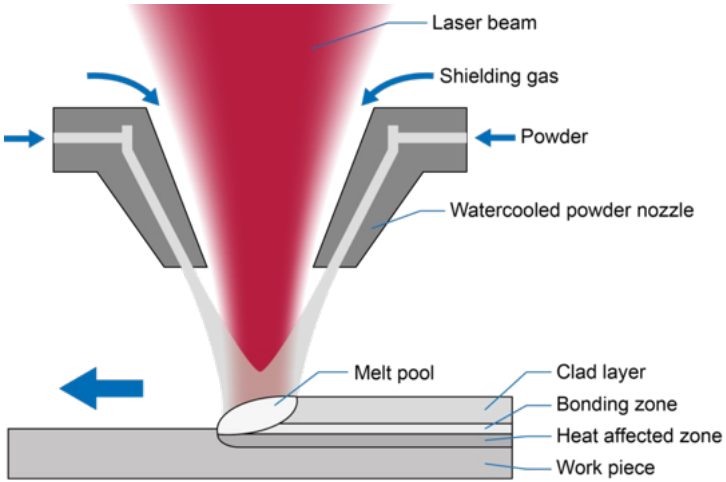
[J. Weeks, PhD, CalTech, 2022]

AM processes

Laser- or Electron- Powder Bed Fusion (L-PBF or E-PBF)



Directed Energy Deposition (DED)



AM processes

Laser- or Electron- Powder Bed Fusion
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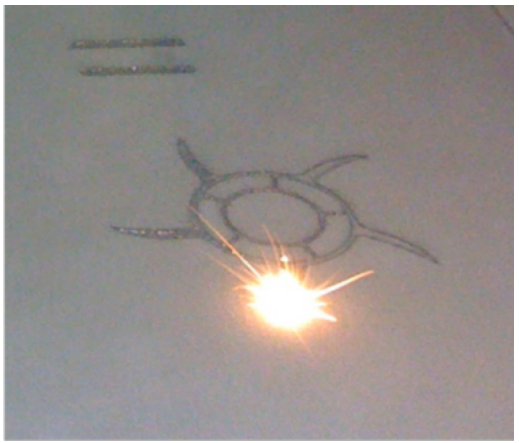
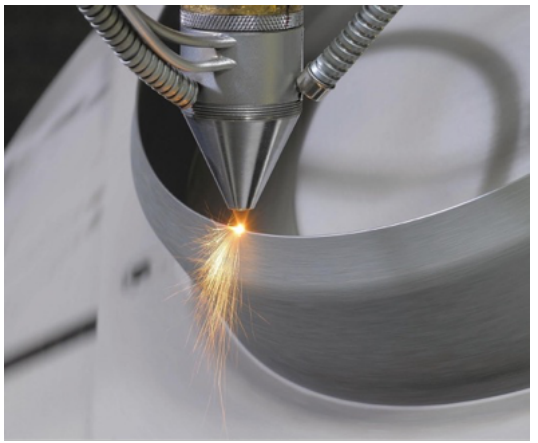


http://www.unm.fr/

E-PBF @ SIMaP

Directed Energy Deposition
(DED)



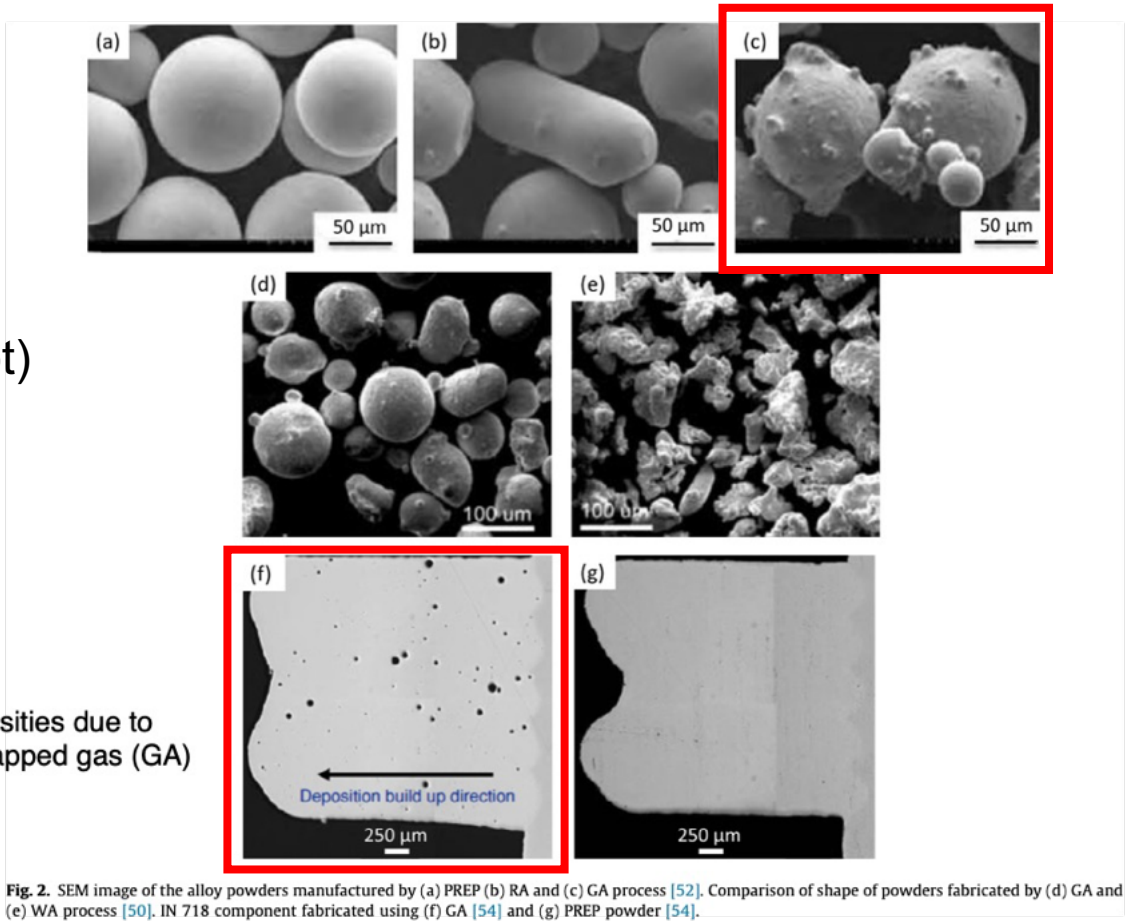
https://industrie.airliquide.fr

Powders

- Different processes for powders
  - Water / Gas atomization
  - Shapes (spheres or not)
  - Diameters (large distribution or not)
  - Defects (internal porosities or not, satellites)

- First order impact on manufacturing quality (pososities)

Porosities



Porosities due to entrapped gas (GA)

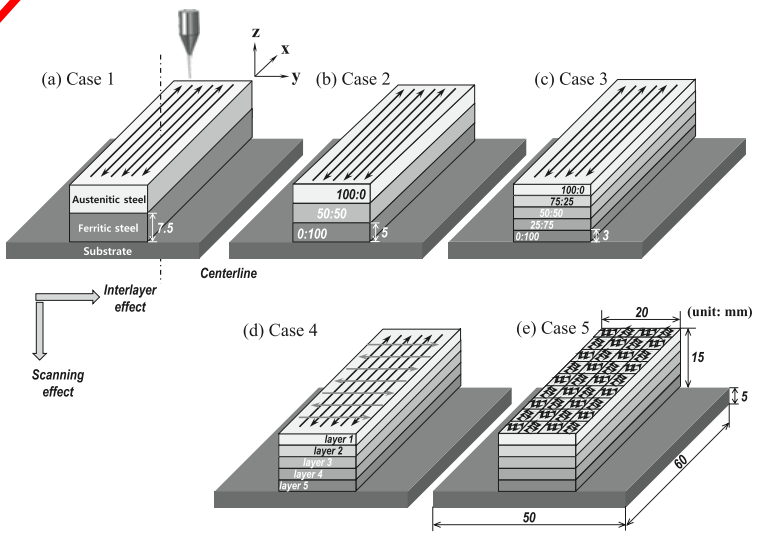
Fig. 2. SEM image of the alloy powders manufactured by (a) PREP (b) RA and (c) GA process [52]. Comparison of shape of powders fabricated by (d) GA and (e) WA process [50]. IN 718 component fabricated using (f) GA [54] and (g) PREP powder [54].

[DebRoy et al., Prog. Mat. Sci.,2018]

Some limitations / processes

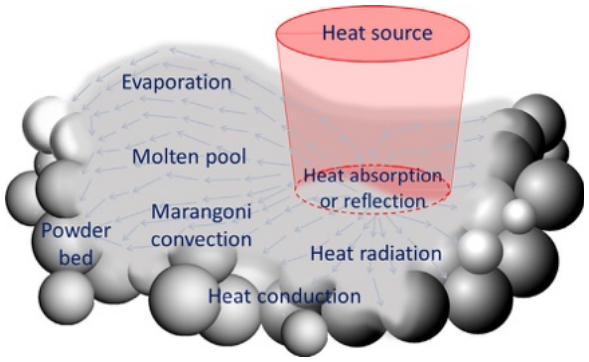
	DED	L-PBF
Puissance laser, P_0 (W)	200 à 2 000	20 à 200
Vitesse de balayage, V_0 (mm.s^{-1})	2,5 à 25	100 à 1 500
Diamètre du faisceau laser, D_0 (µm)	1 500	50
Diamètre moyen des poudres, d_{50} (µm)	25 à 125	5 à 25
Hauteur de cordons, H_{app} (µm)	500	50
Largeur de cordons, e_{app} (µm)	2 500	250
Temps d'interaction (= D_0/V_0), t_{int} (ms)	60 à 600	0,03 à 0,3
Densité de puissance laser, I_0 (W.mm^{-2})	≈ 10^2 à 10^3	≈ 10^4 à 10^5
Énergie linéique (= P_0/V_0), E_L (J.mm^{-1})	8 à 800	0,04 à 4
Énergie volumique, $E_V = I_0/V_0$ (J.mm^{-3})	≈ 4 à 400	≈ 20 à 2 000
Vitesse de solidification, Vs (cm.s^{-1})	≈ 10^{-1} à 10^0	≈ 10^2 à 10^3
Vitesse de refroidissement, $\dot{T}$ (K.s^{-1})	≈ 10^2 à 10^4	≈ 10^5 à 10^8

Approx. minimum thickness



Layer by layer manufacturing

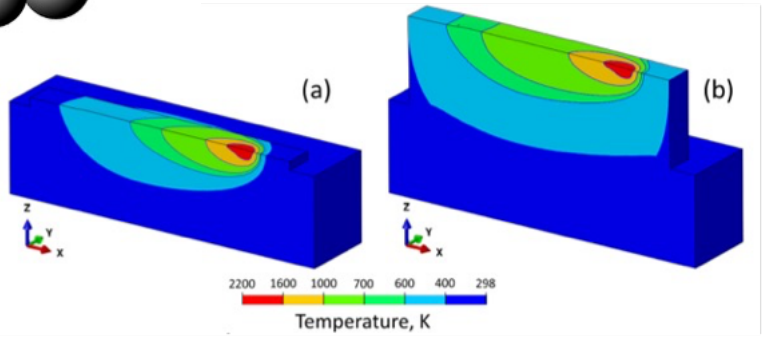
- Building direction, lasing strategy, etc: thermomechanical complex cycles, thermal gradients



Porosities
Unmelted powder

Microstructures
Residual stresses

Interfaces
Roughness



[DebRoy et al., Prog. Mat. Sci.,2018]

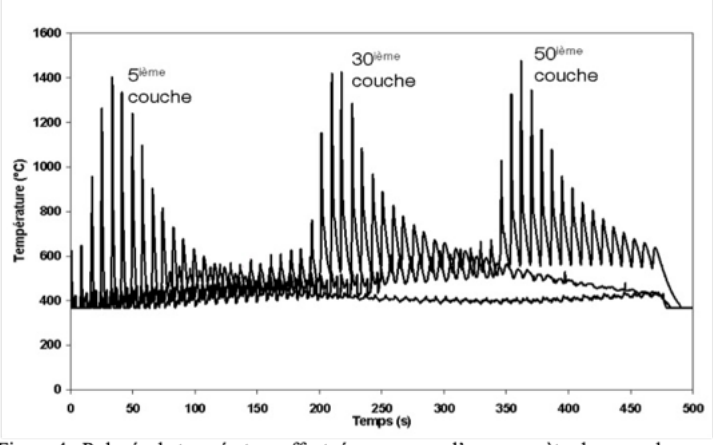


Figure 4. Relevés de température effectués au moyen d'un pyromètre laser sur la cinquième, trentième et cinquantième couche d'un mur de soixante couches

[Maisonneuve et al.,2006]

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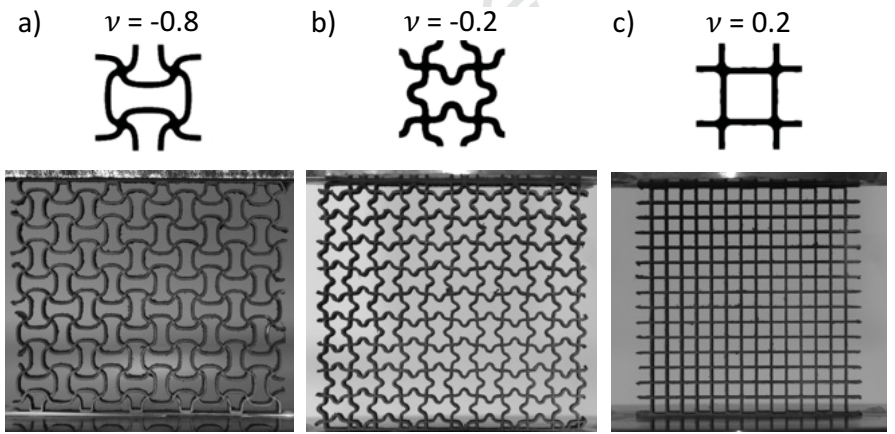
Briefly

- Geometrical variations / ideal: variabilities
- Roughness: some possible post-treatment
- Porosities: some possible post-treatment
- Local microstructure: : some possible post-treatment

Metallic AM lattices

(a) (b) (c)

E-PBF @ SIMaP (TA6V)



DED @ LMS (316L)

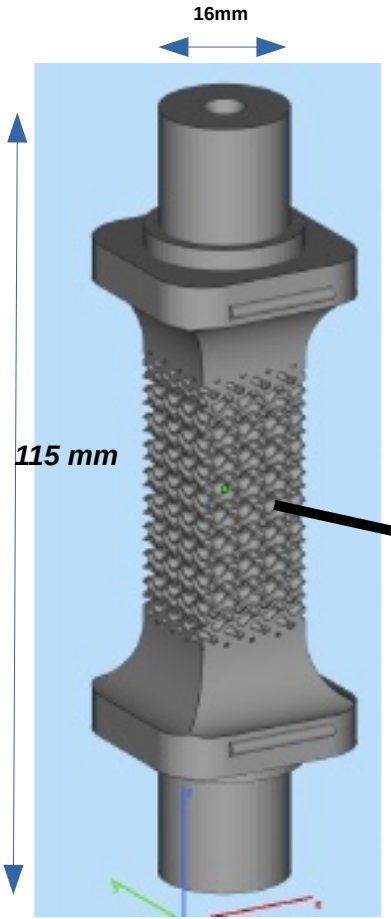
[Balit et al. (2021) Mech. Mat.]

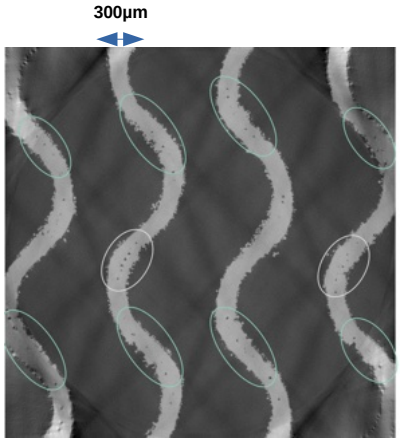
As-built lattices: roughness

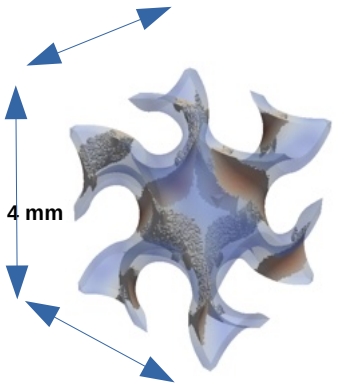
- Roughness: a tens of microns (similar as bulk specimens)

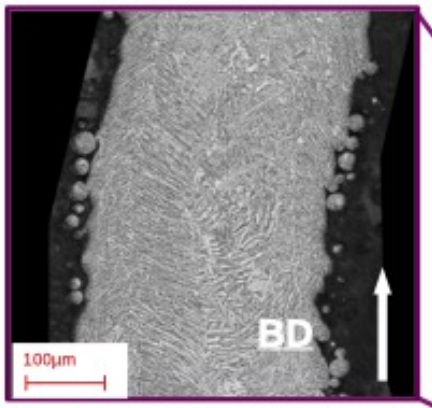
E-PBF @ SIMaP (TA6V)

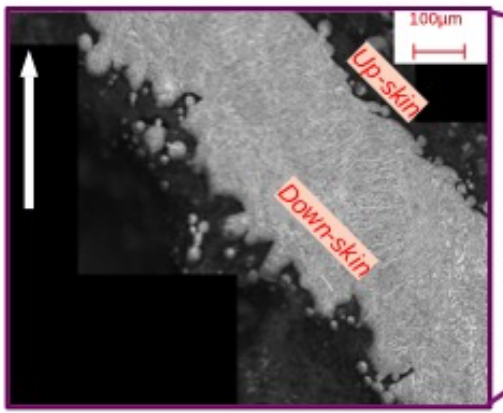
Geometrical variabilities: gyroids









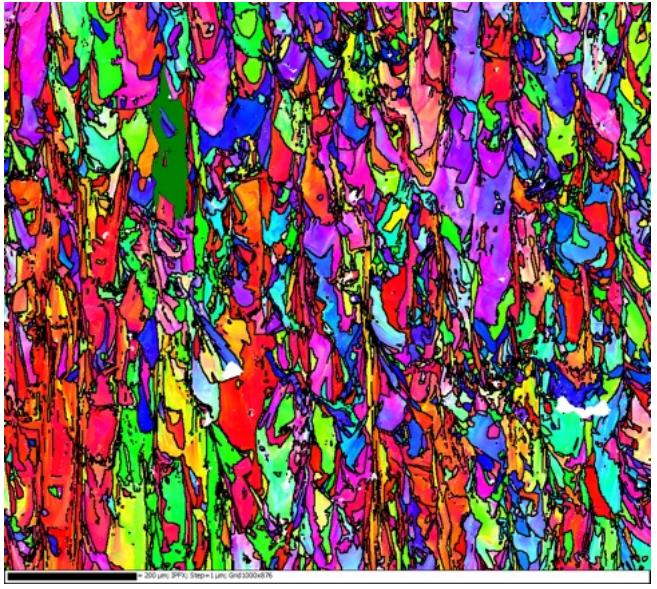


[M. Pirotais, PhD, I2M, Bordeaux]

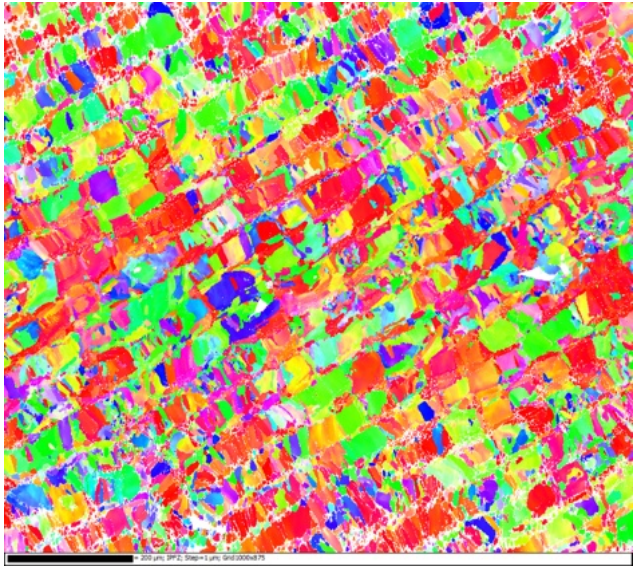
Bulk microstructures

Bulk 316L from L-PBF

building direction



building direction ⊗



[N. Khailov, PhD, LMS, Palaiseau]

Gyroids: microstructures and defects

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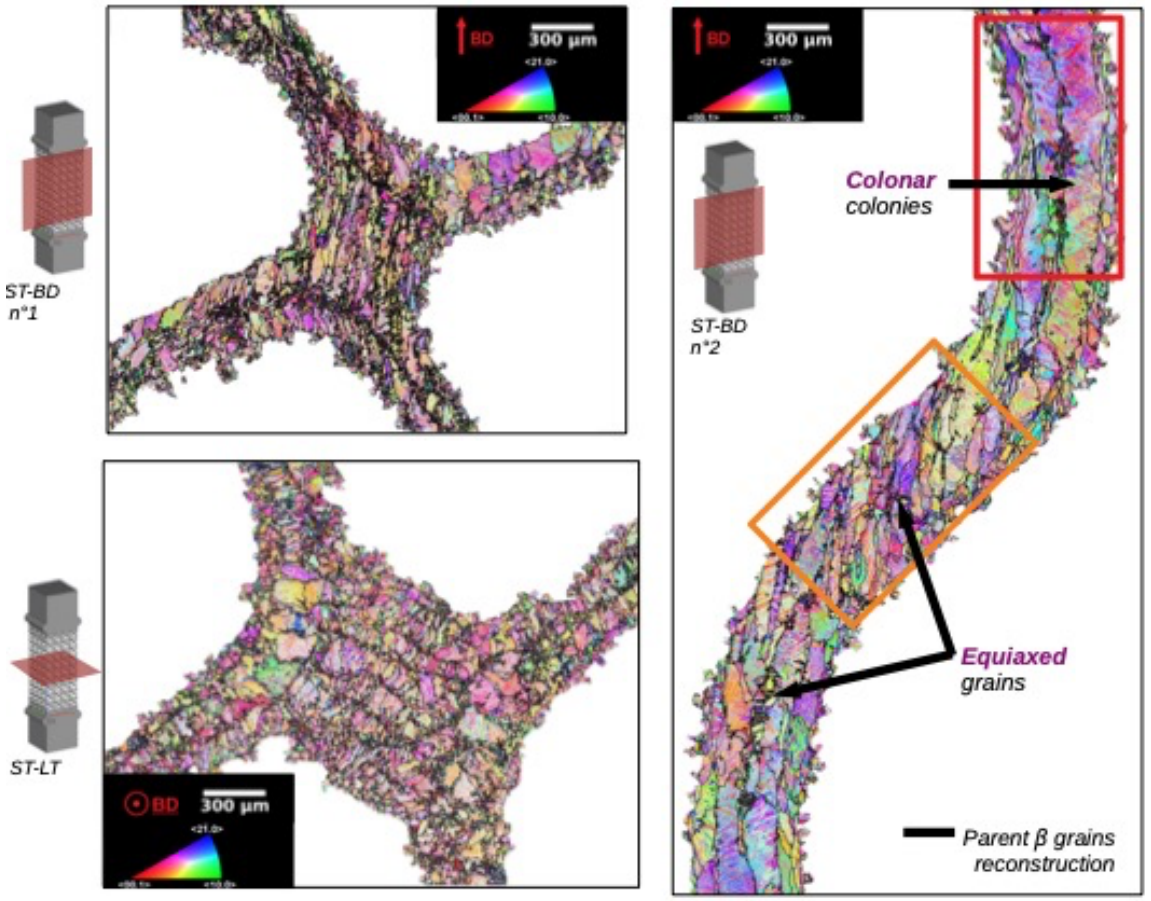
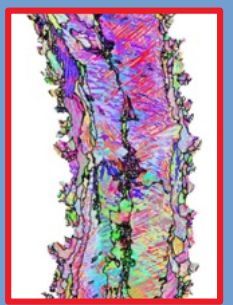


TA6V from L-PBF

Analyses EBSD

BD-oriented

Elongated colonies



45°/BD – oriented

Tilted crossing colonies

[M. Pirotais, PhD, I2M, Bordeaux, 2022]

Porosities: as-built

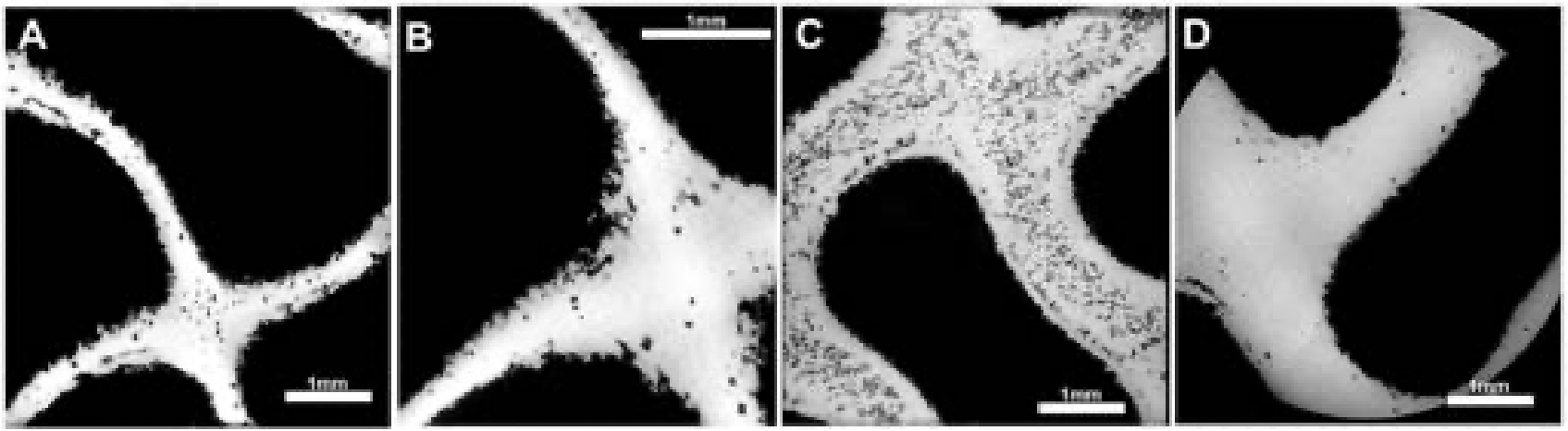
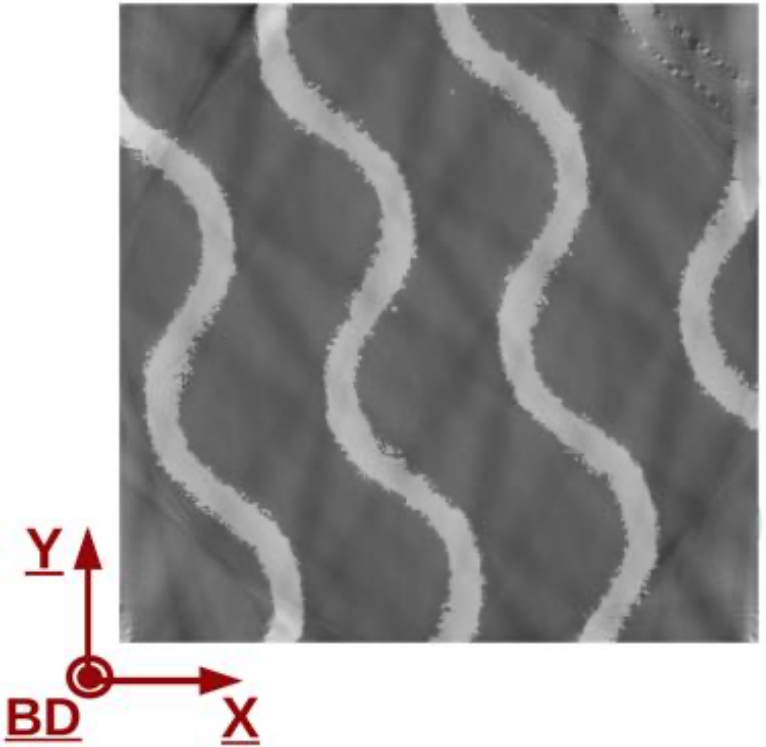


Figure 2.52 – Tomographie RX d'une SL gyroïde fabriquée par SLM : parois d'épaisseur (A,B) 250µm ou (C,D) 1000µm, imprimées avec une stratégie aux paramètres (A,C) standards ou (B,D) optimisés [Kelly *et al.*, 2019b].

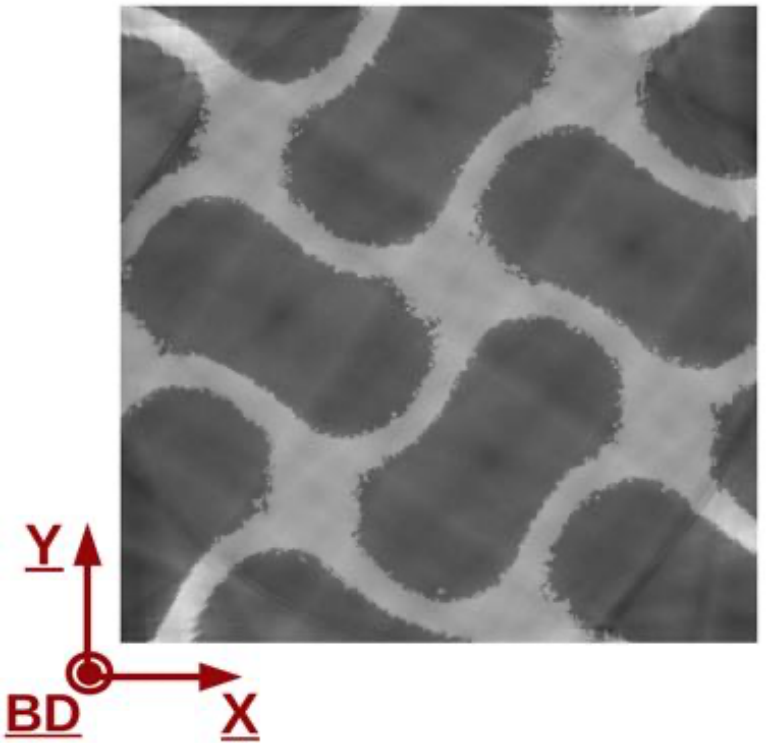
Porosities: after HIP

TA6V from L-PBF + HIP (approx. 1000°C + 1000 bars)

!! Effect depends on the material



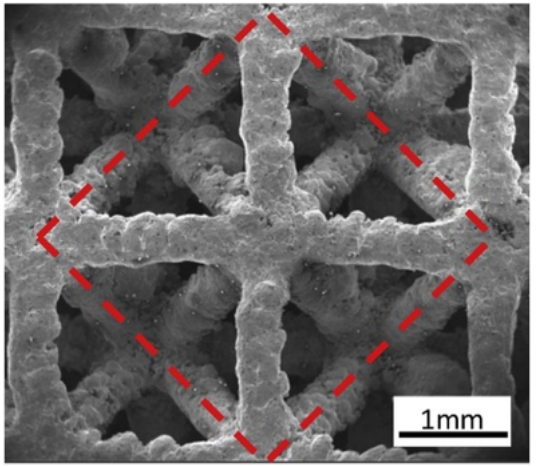
(b) Coupe 1



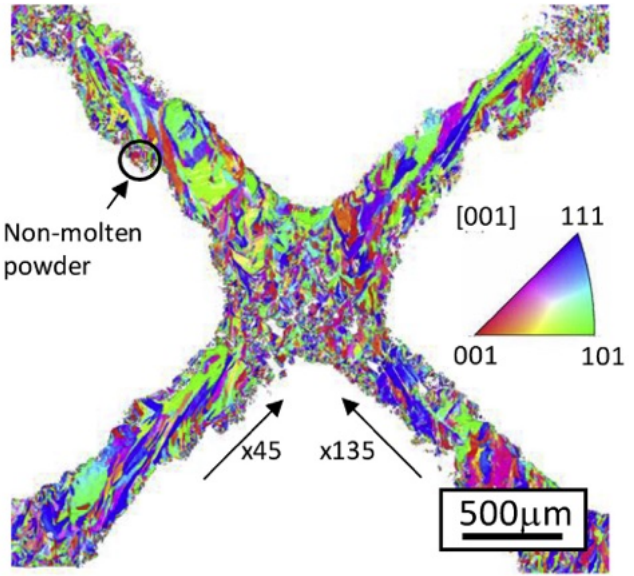
(c) Coupe 2

[M. Pirotais, PhD, I2M, Bordeaux, 2022]

Geometrical var. and microstructure: octets



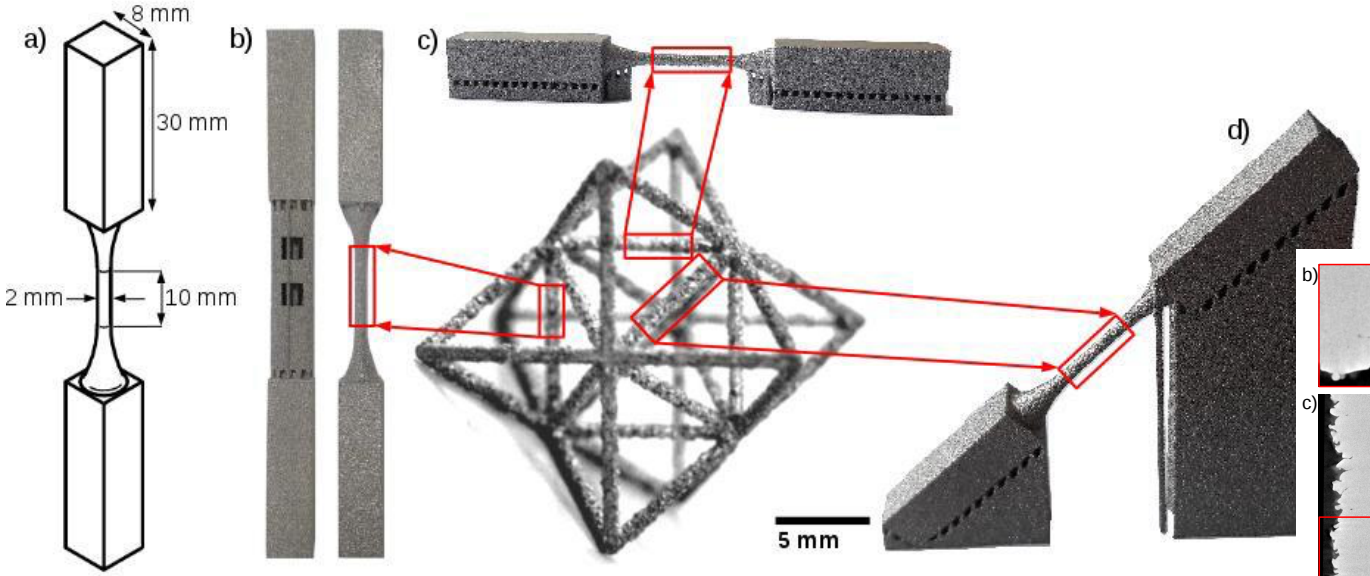
316L from L-PBF

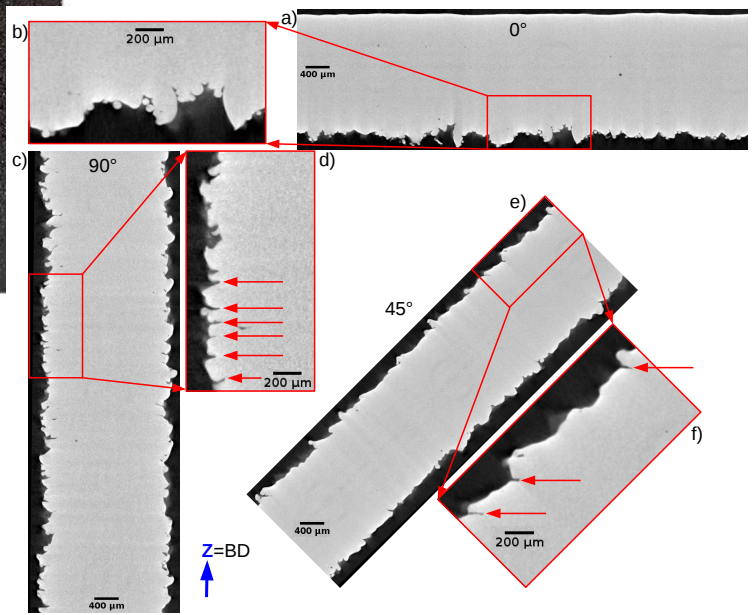


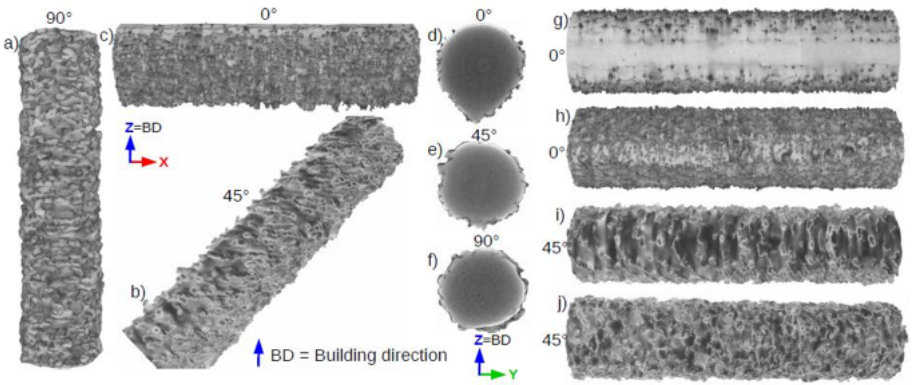
[Tancogne et al. (2016) Acta Mat]

Geometrical var. and microstructure: octets

E-PBF @ SIMaP (TA6V)



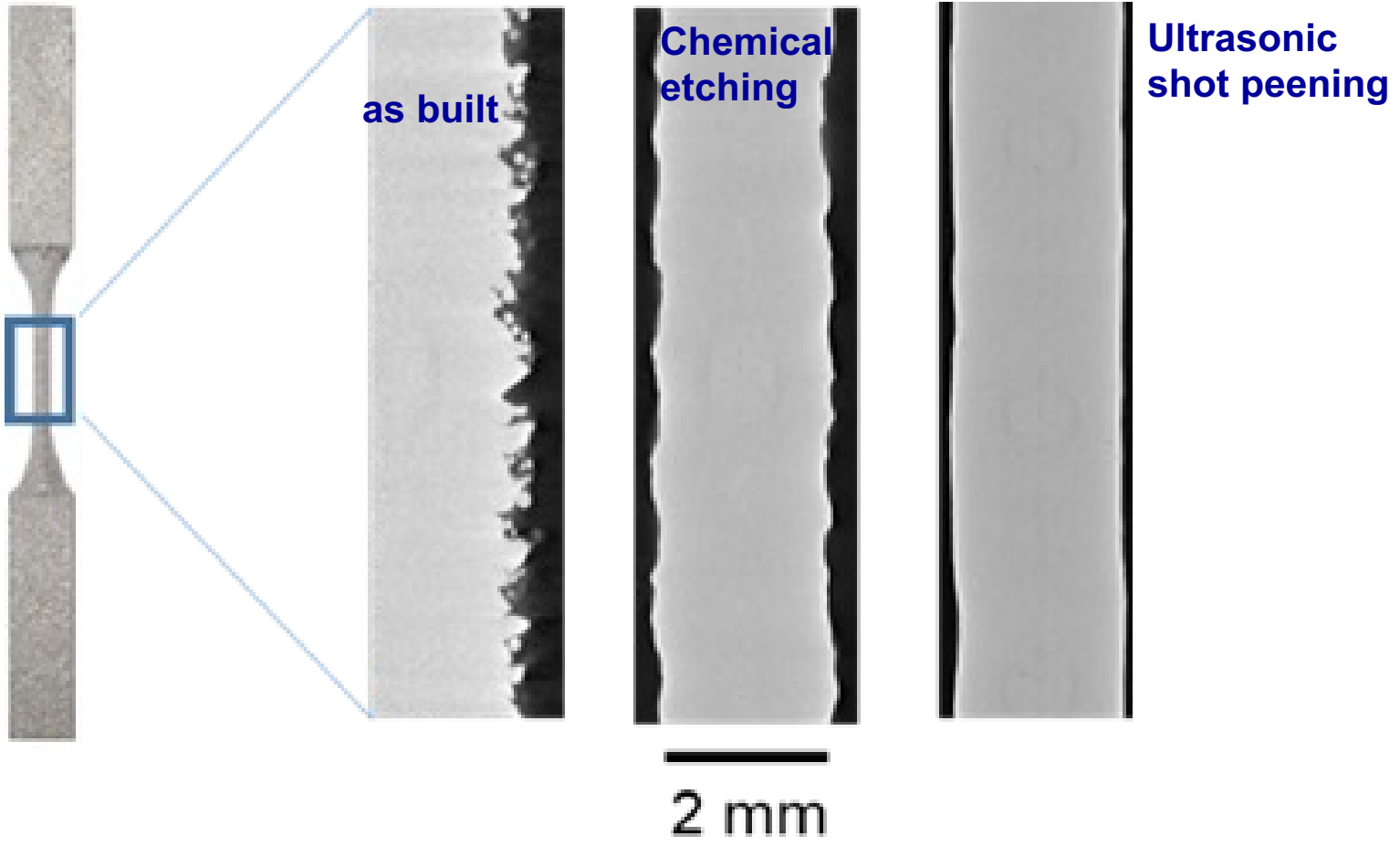




[T. Persenot, PhD, Grenoble-Lyon, 2018]

How to decrease roughness

E-PBF @ SIMaP
(TA6V)



PhD Théo Persenot (2018) coll. SIMAP / MATEIS

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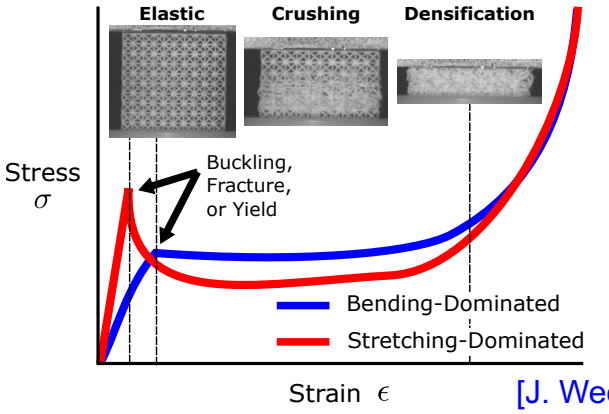
- Conclusions and open questions

Briefly

- Static compression: lots of works, lots of materials, lots of lattice types, etc
- Fatigue: recent works (N. Saintier, I2M, J.Y. Buffière, Mateis, R. Dendievel, SIMaP)
- Dynamic loading, impacts, blast, etc: under progress
- Depend on:
  - Materials and post-treatment
  - Lattice type
  - Loading
  - etc

!! Process parameters dependant !!

Static compression



[J. Weeks, PhD, CalTech, 2022]

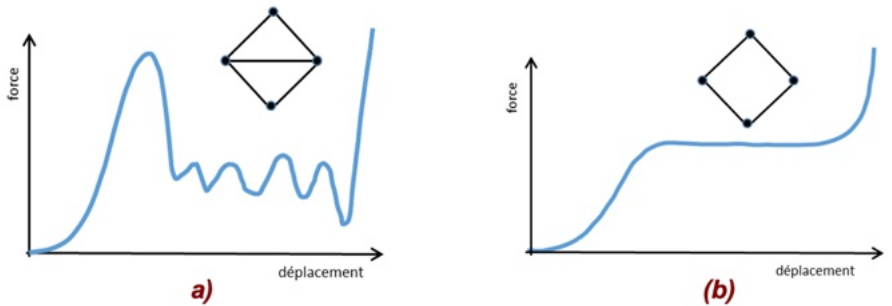


Figure 7.5.4 : *Comportement schématique d'une structure lattice en compression pour une topologie a) stretching dominated - b) bending dominated (inspiré de (Leary, 2019)).*

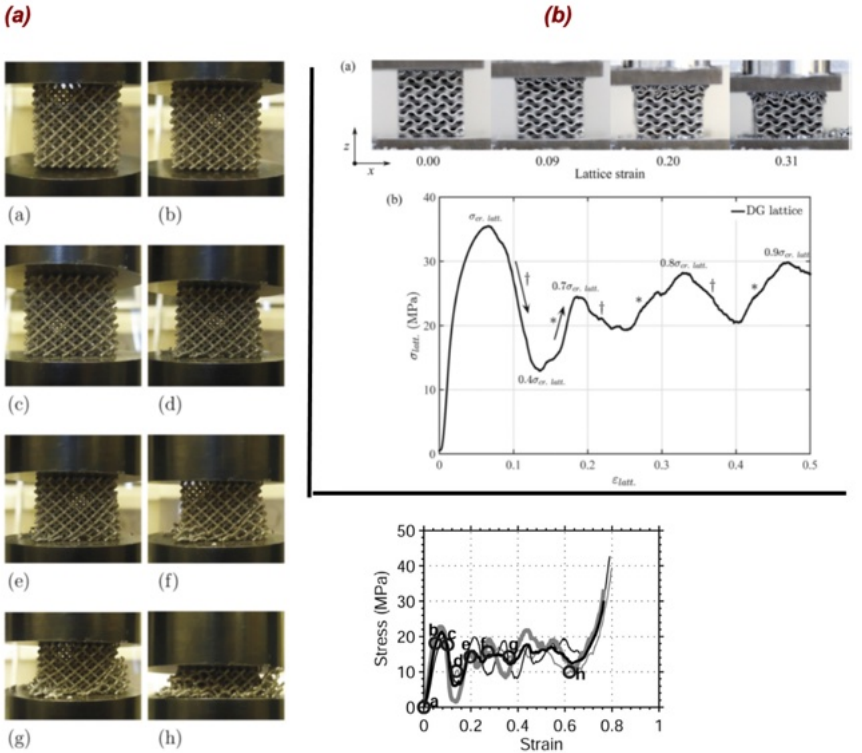
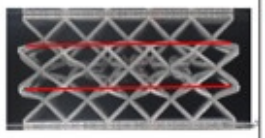
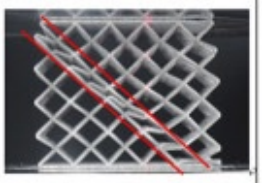
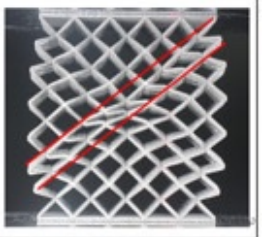
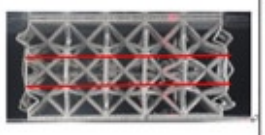
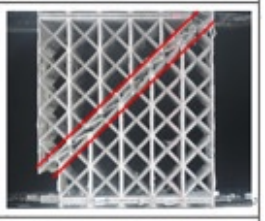
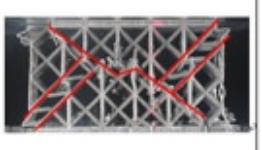
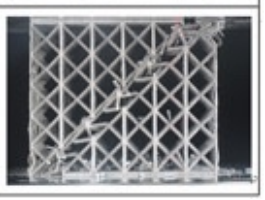
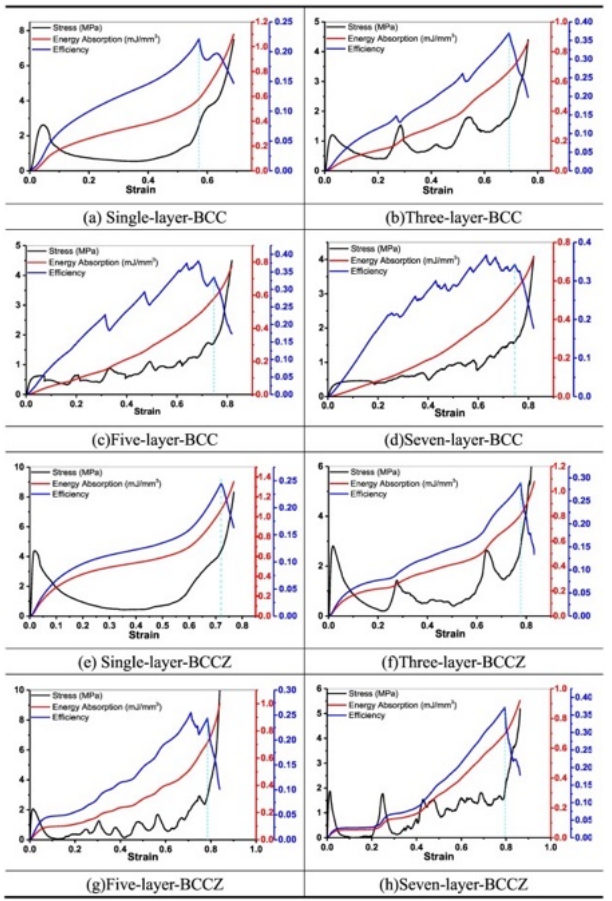


Figure 7.5.5 : *visualisations et courbes expérimentales correspondantes d'un essai de compression quasi-statique a) d'une structure « diamant » en Ti-6Al-4V fabriquée par E-PBF (Ozdemir et al., 2016) et b) d'une structure gyroïde en Al-Si10-Mg fabriquée par L-PBF (Maskery, 2017).*

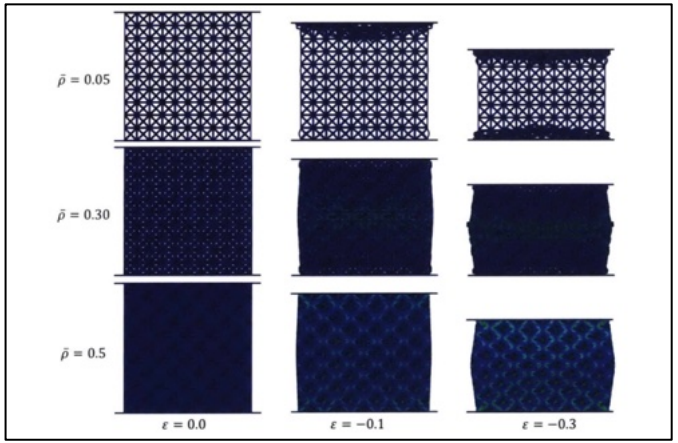
Localization mechanisms

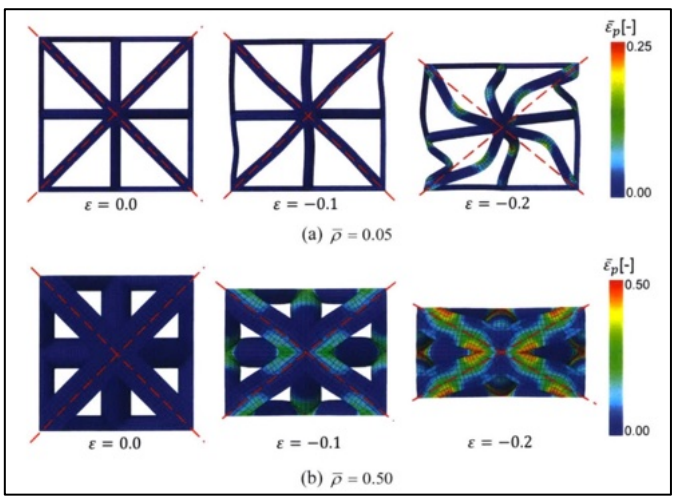
Strain	Type	Single-layer	Three-layer	Five-layer	Seven-layer
0.2	BCC				
	BCCZ				
0.4	BCC				
	BCCZ				

[Lei et al., Mat. Des., 2019]

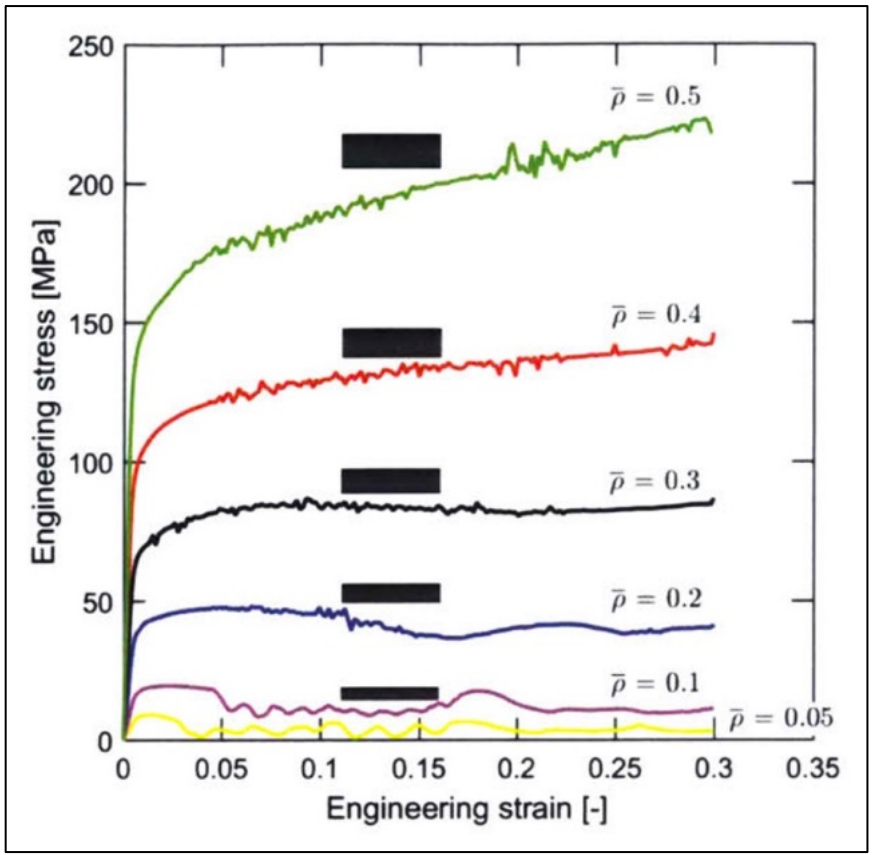


Density





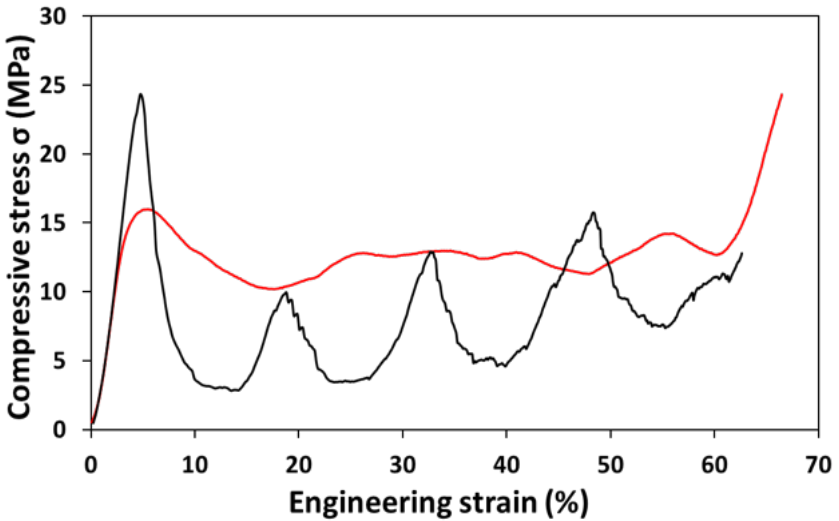
Bulk 316L from L-PBF



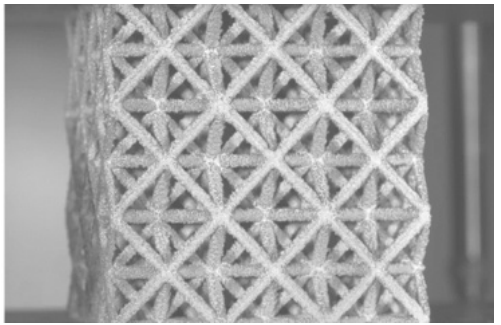
[Tancogne et al., PhD, MIT, 2014]

Material / microstructure

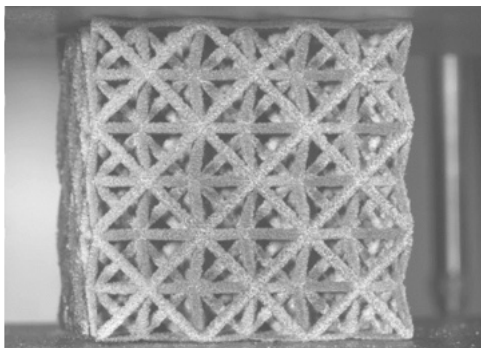
Ti-14Mo alloy by EBM => as built = typical α+β
=> 900°C /30 min => β-metastable => Twinning



α+β (as-built)



β-metastable
(Heat Treated)



[Duport et al., Scripta Materialia 219, 2022]

E-PBF @ SIMaP

Material / microstructure

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ARCHI-META
Architectured Metamaterials

Aluminum alloy AS10Mg

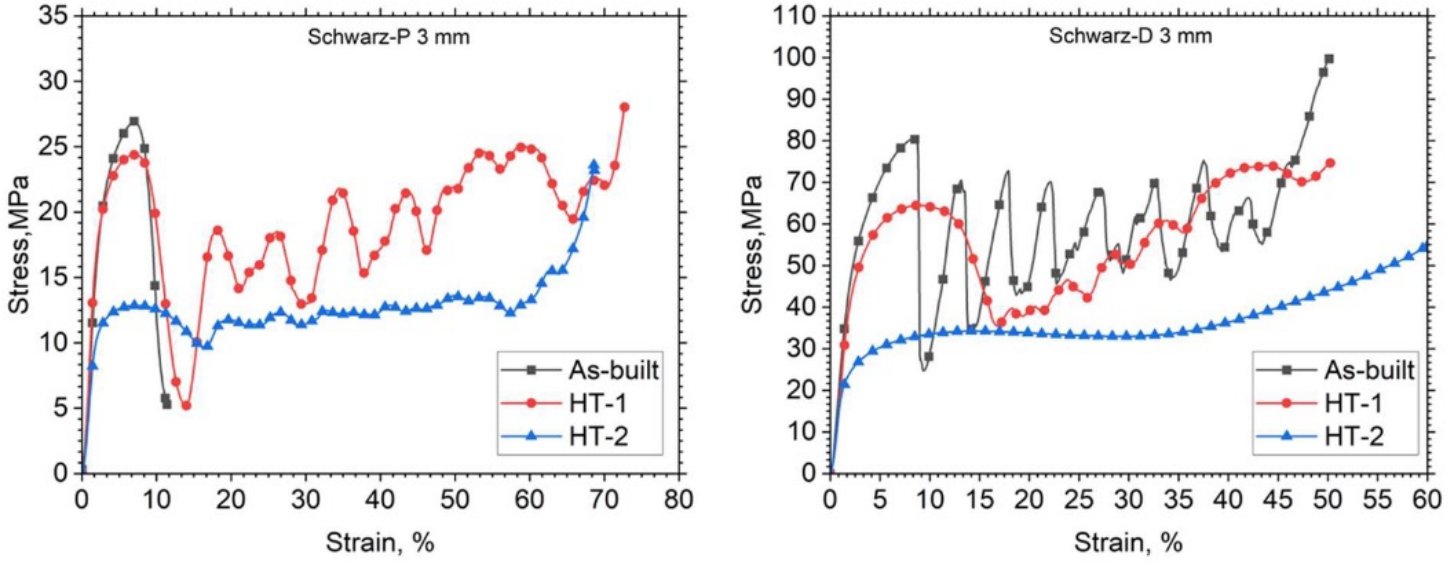
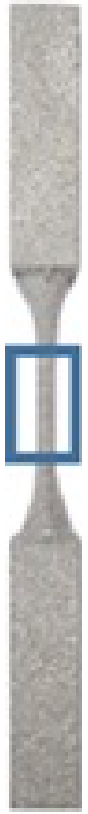
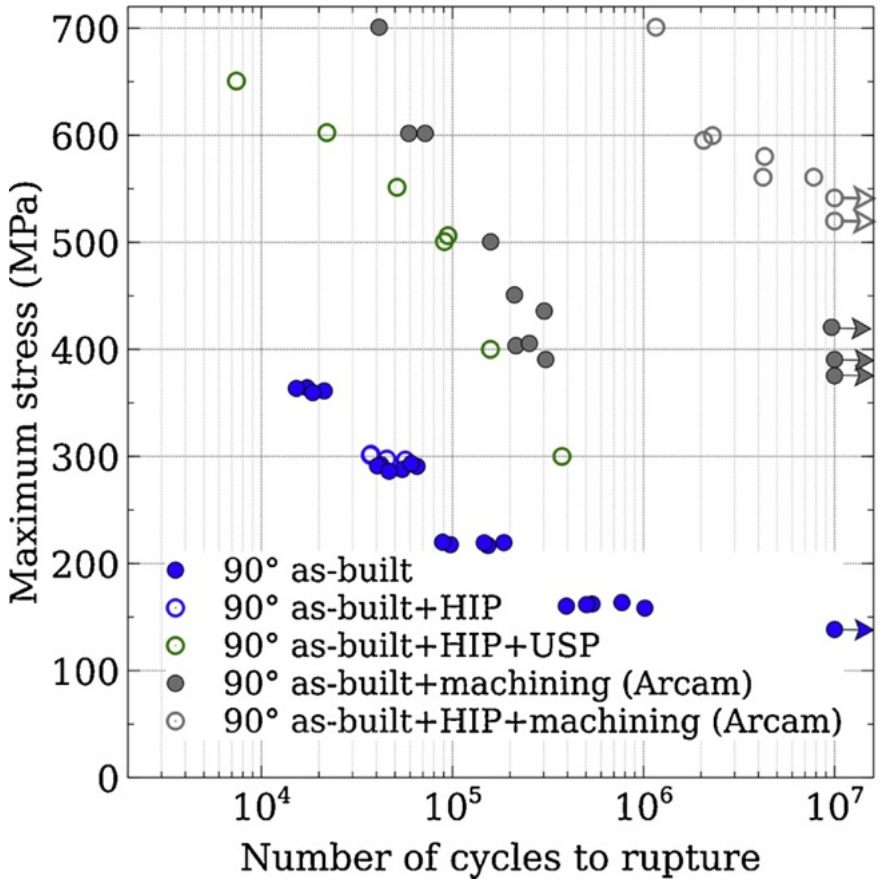


Fig. 12. Comparison of compressive stress-strain plots for as-built vs. HT-1 vs. HT-2 treated TPMS lattice structures with 3 mm unit cell and 0.2 mm wall thickness.

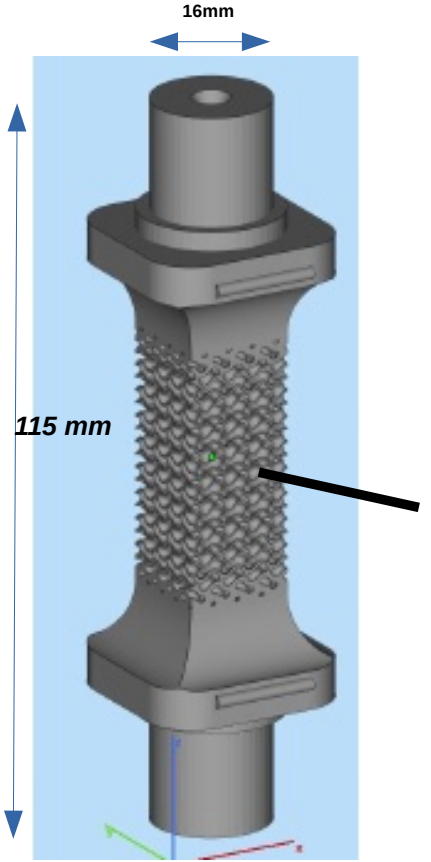
Fatigue: under progress

E-PBF @ SIMaP
(TA6V)





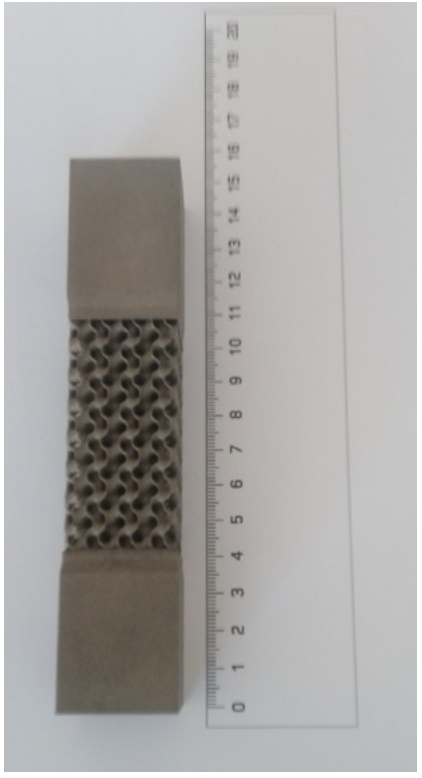
[Persenot et al.,Add. Manuf., 2019]

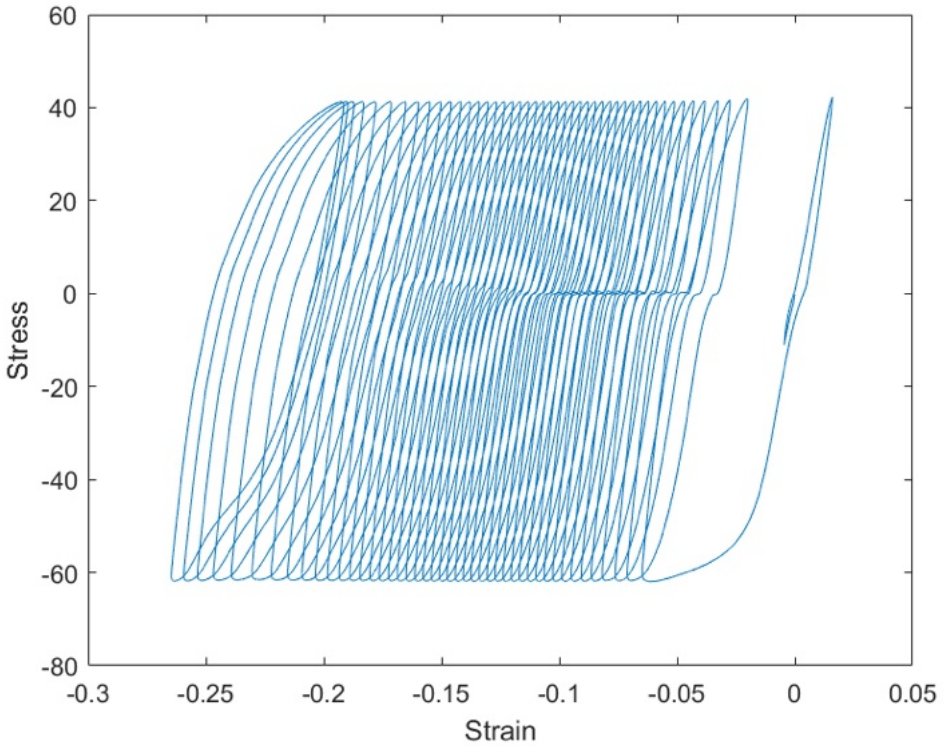


[M. Pirotais, PhD, I2M, Bordeaux, 2022]

Fatigue: under progress

316L from L-PBF





[N. Khailov, PhD, LMS, Palaiseau]

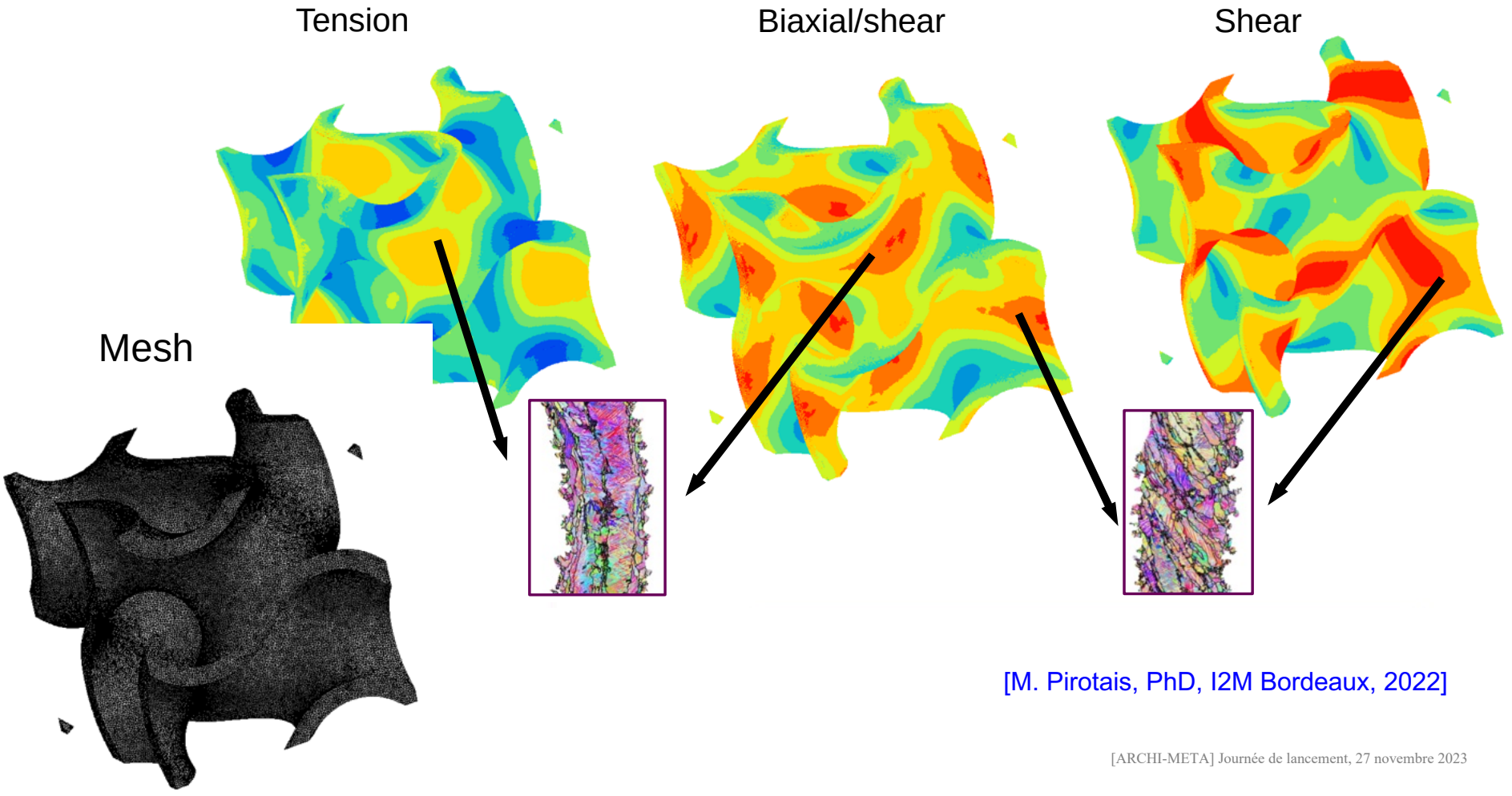
Index

- Some generalities on metallic Additive Manufacturing (AM)
- Materials, microstructures, defects : some variabilities
- Mechanical characterization
- Numerical simulations
- Conclusions and open questions

Briefly

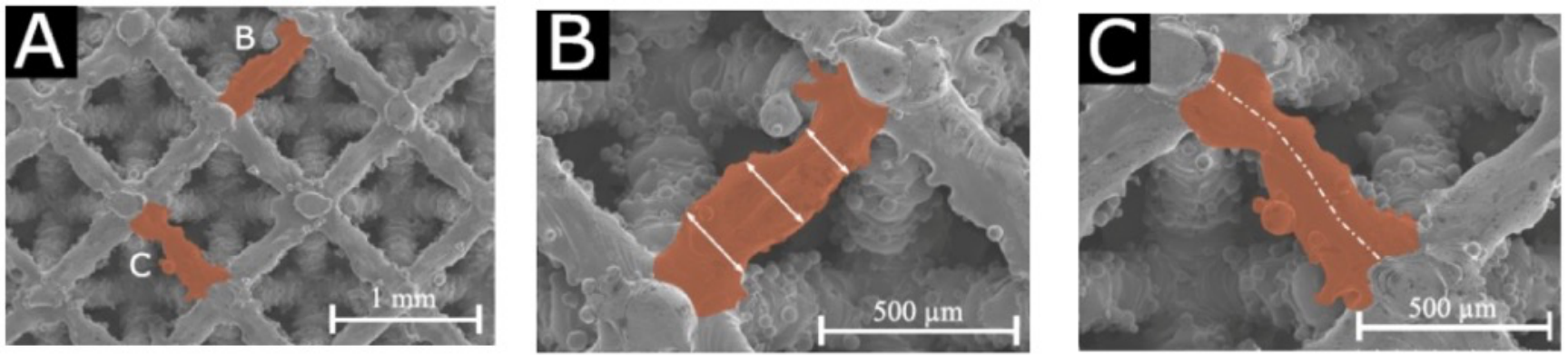
- 3D calculations: generally limited to unit cell studies
- Introducing variabilities in simulations requires:
  - Variabilitiy characterizations
  - Simpler models (beams, shells, plates)

3D simulations: local loadings



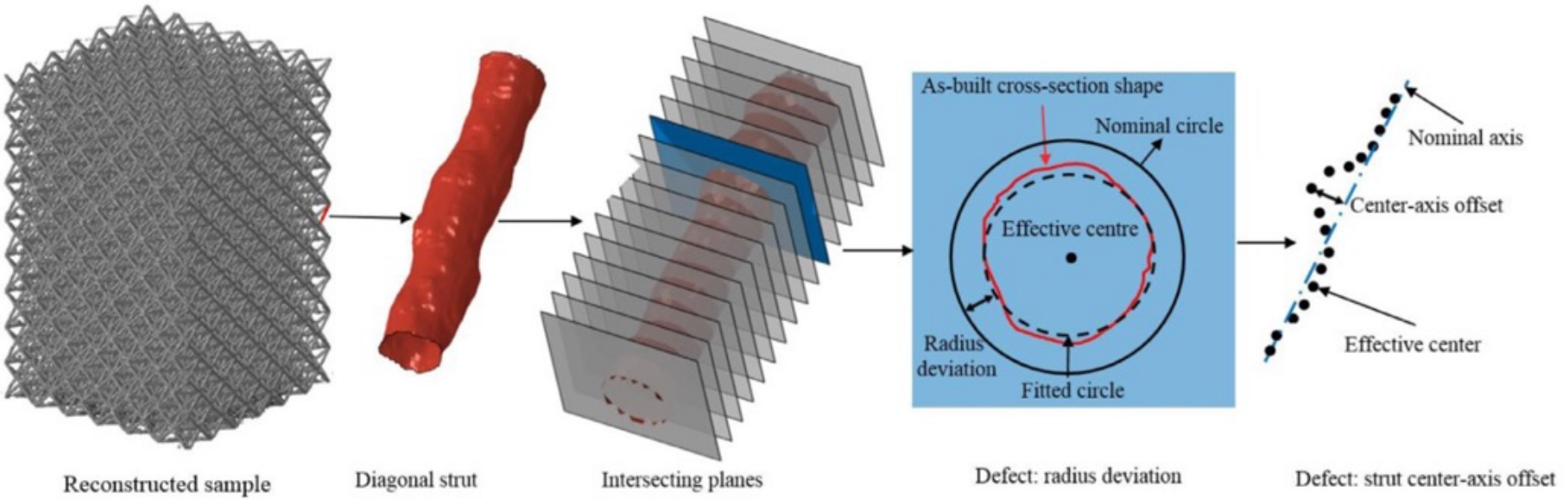
[M. Pirotais, PhD, I2M Bordeaux, 2022]

Variabilities: tomography



[Melancon et al., 2017]

Ideal versus realistic simulations



[Liu et al., JMPS, 2017]

Ideal versus realistic simulations

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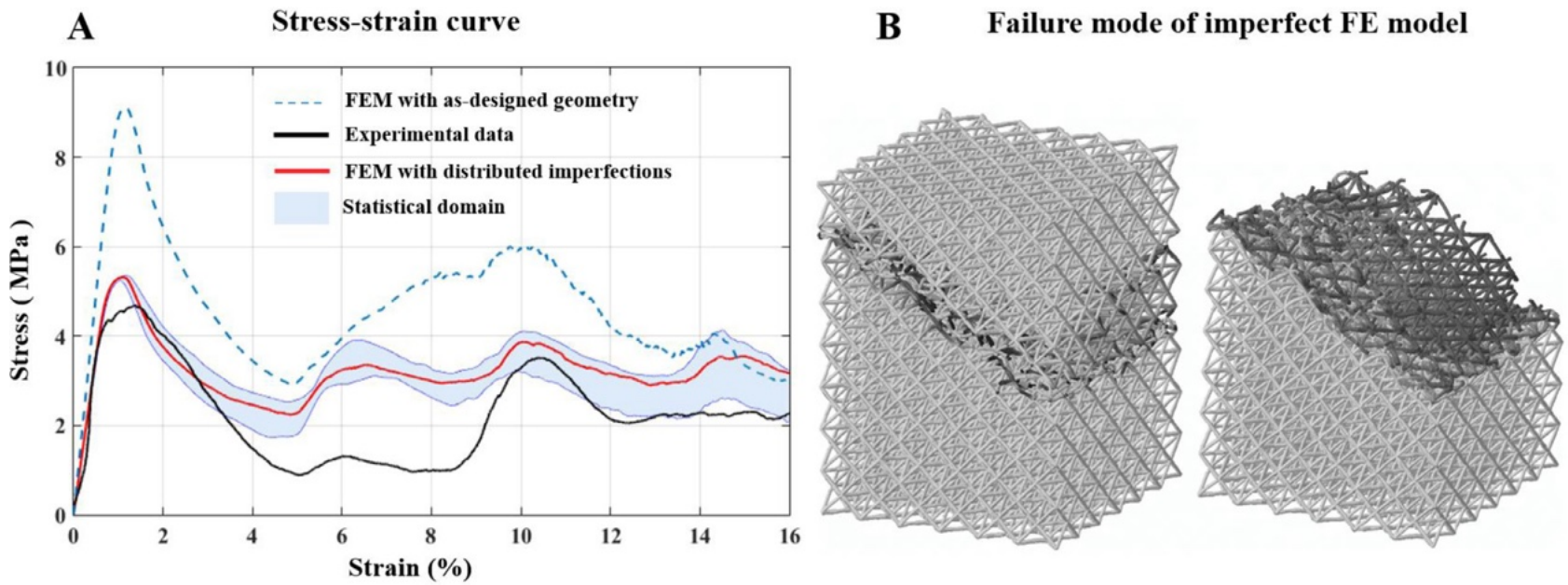
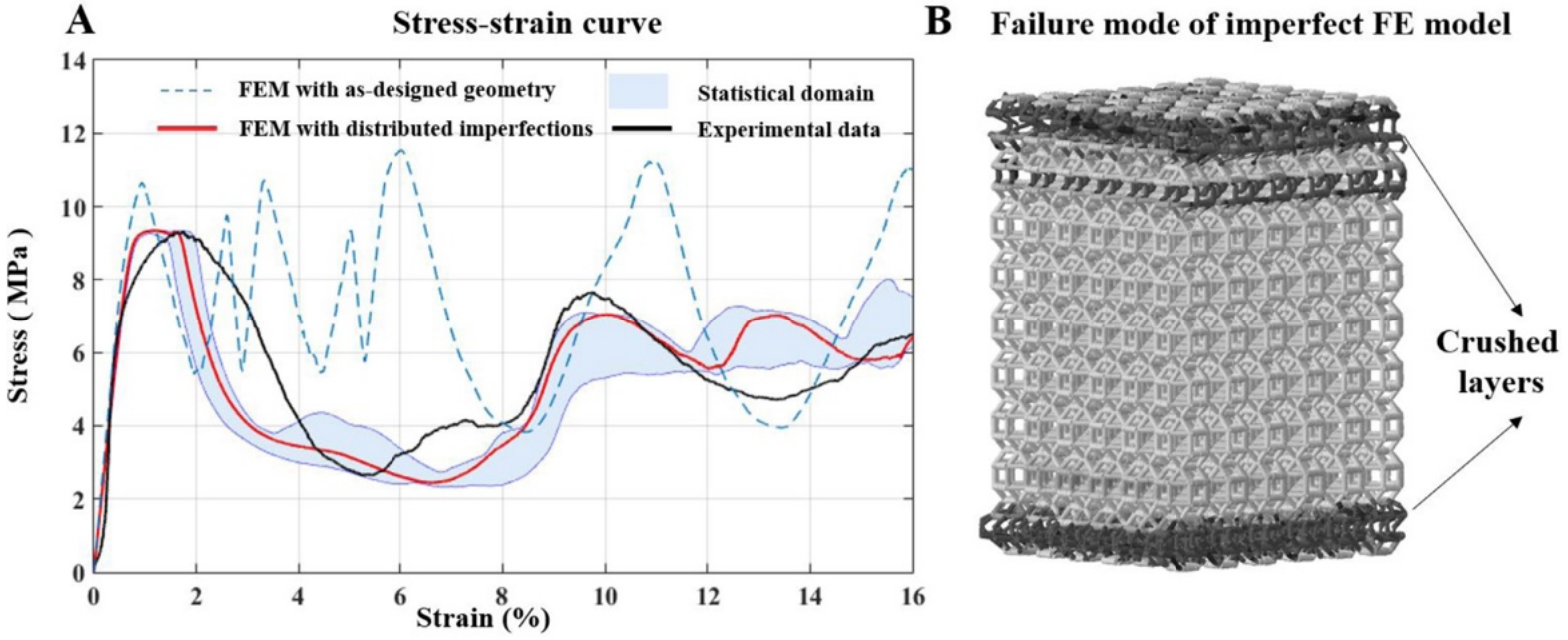
Regular octet lattice



[Liu et al., JMPS, 2017]

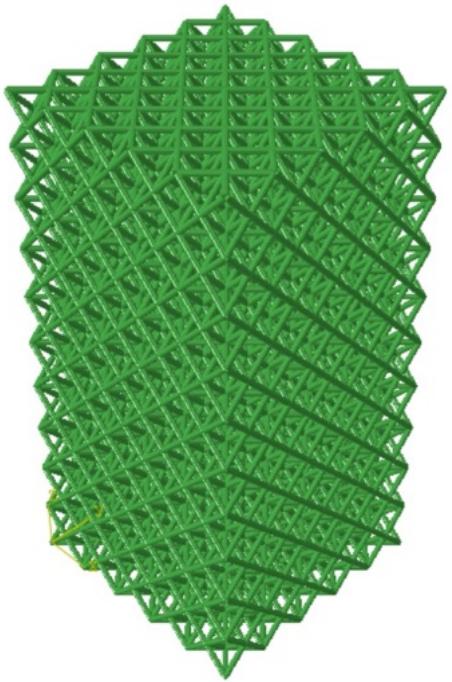
Ideal versus realistic simulations

Rhombicuboctahedron lattice

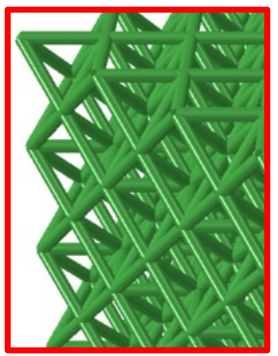


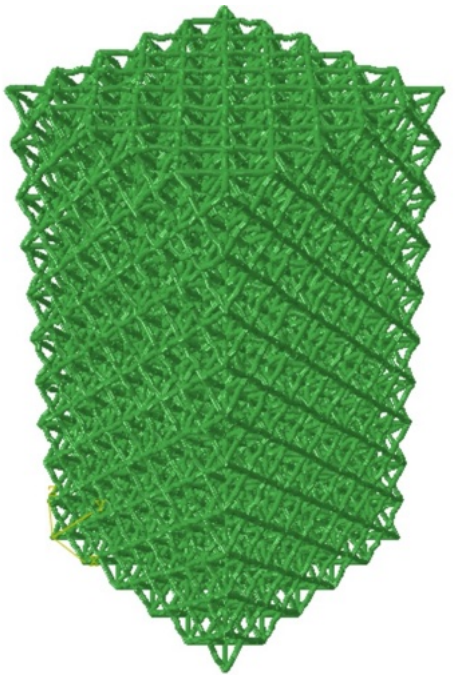
[Liu et al., JMPS, 2017]

Ideal versus realistic simulations

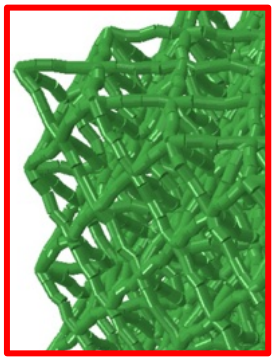


ideal



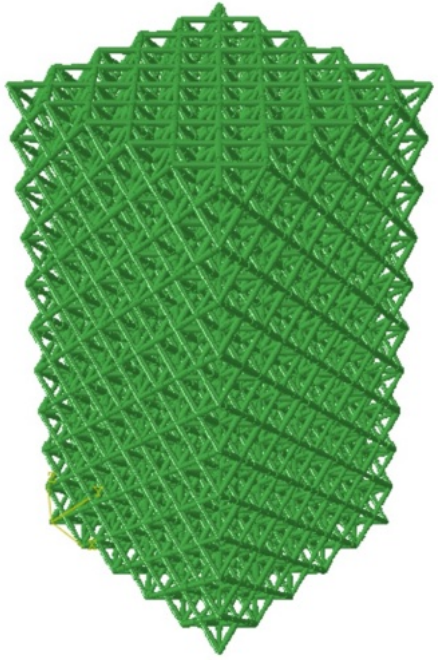


waviness

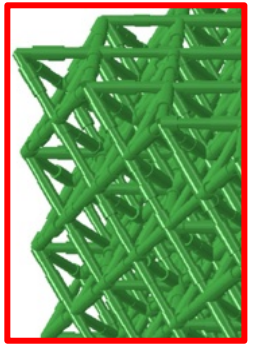


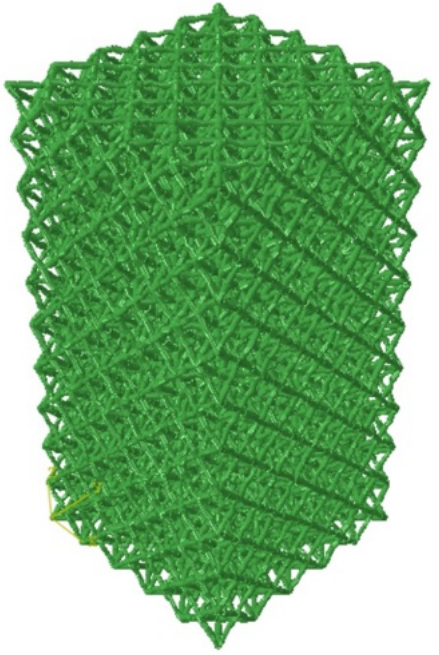
[N. Khailov, PhD, Palaiseau]

Ideal versus realistic simulations

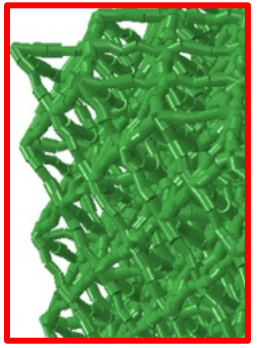


sections





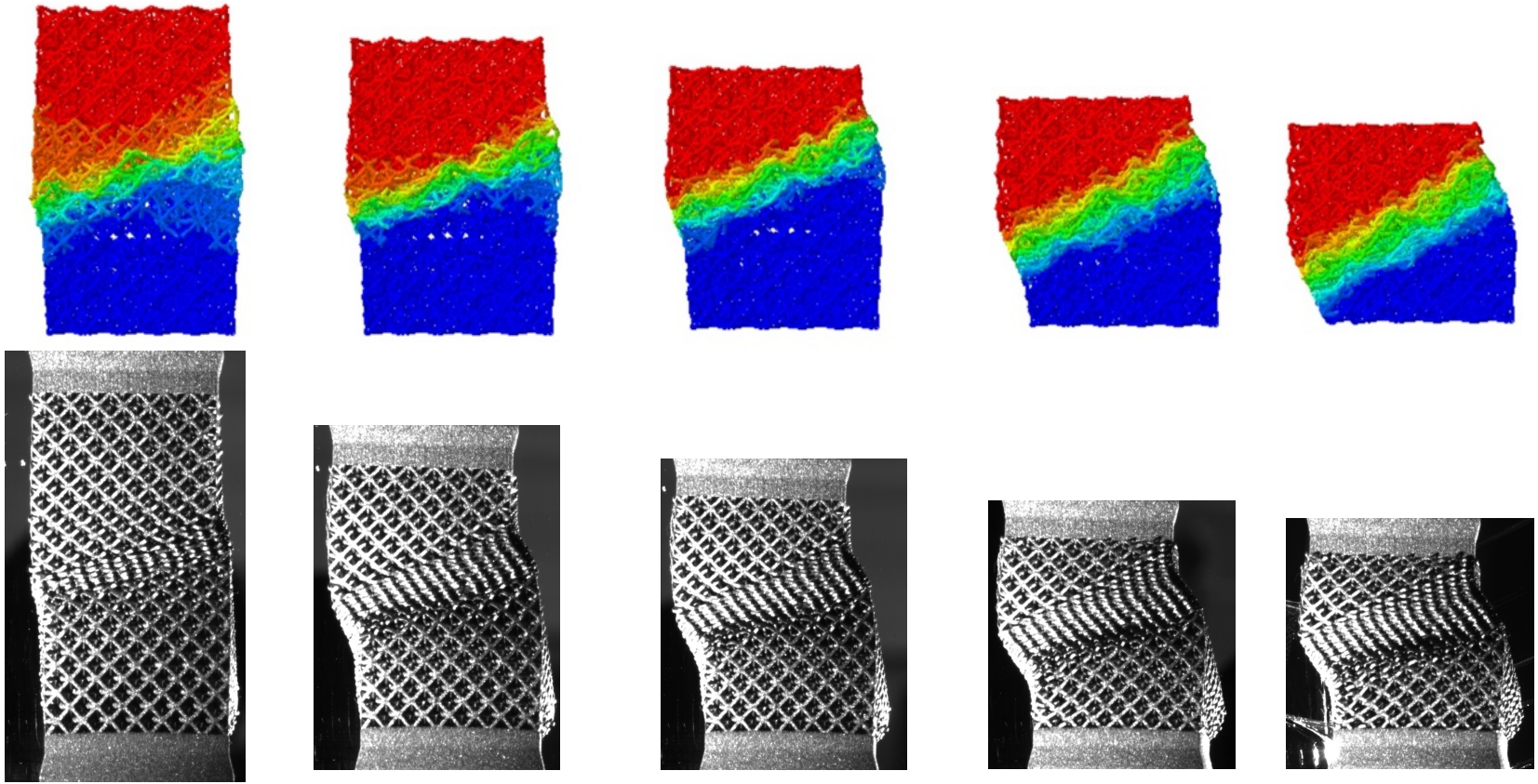
full



[N. Khailov, PhD, Palaiseau]

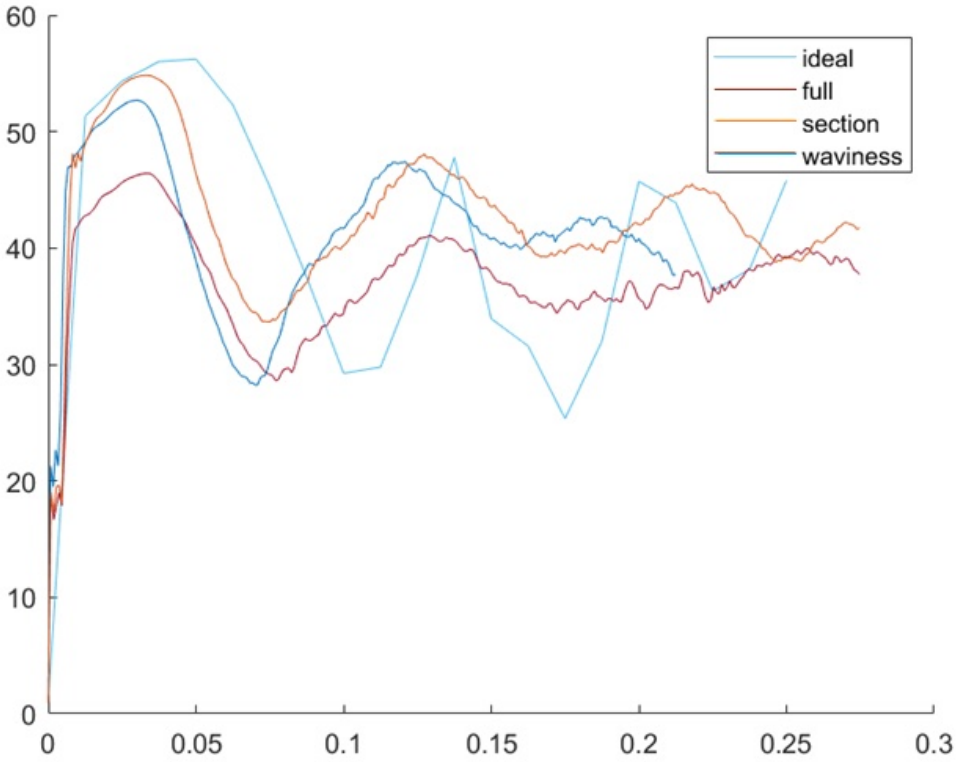
Ideal versus realistic simulations

full

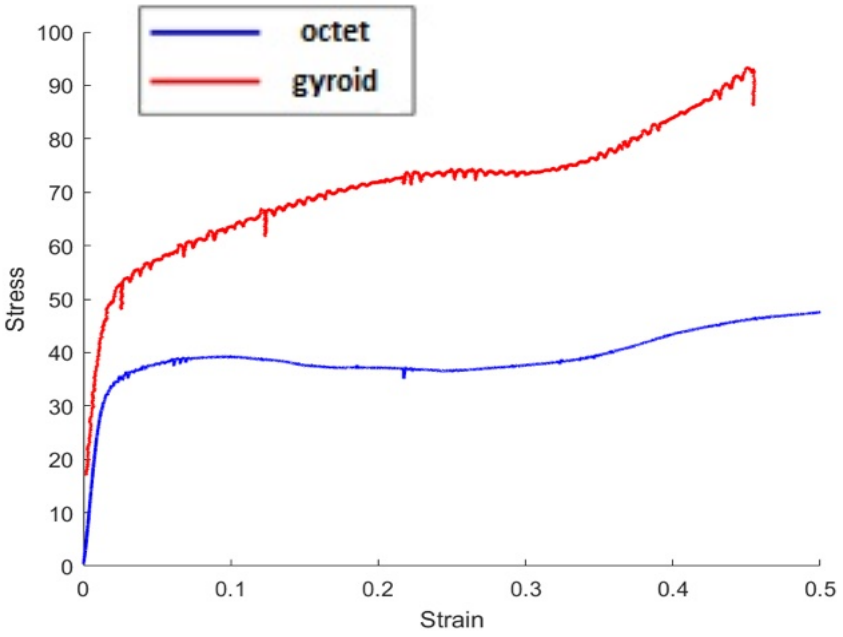


[N. Khailov, PhD, Palaiseau]

Ideal versus realistic simulations



316L from L-PBF



[N. Khailov, PhD, Palaiseau]

Index

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Conclusions and open questions

GDR Groupement de recherche ARCHI-META Architectured Metamaterials

- Importance of variabilities!!!! Real world is not the ideal one!
  - First order on mechanical behavior: instabilities, localization, lifetime
- Open questions:
  - How to model / control / decrease / exploit variabilities?
  - Fatigue: a challenge! How to live with defects?
  - Auxetic structures: recent studies particularly in 2D
  - Optimal lattice for energy absorption? Optimal density? Optimal material?

National structures in metallic AM

cnrs GDR Groupement de recherche
ARCHI-META
Architectured Metamaterials

A collaborative project:

HEAD
Fabrication Additive

A research group:

cnrs GDR Groupement de recherche
ALMA Alliages métalliques
par/pour la fabrication additive

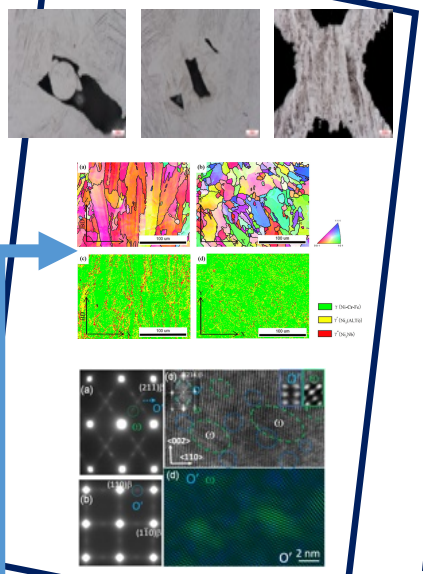
Int. Res. Project (IRP) on AM lattices / fatigue

Groupement de recherche ARCHI-META Architectured Metamaterials

Contact: N. Saintier (I2M, Bordeaux)

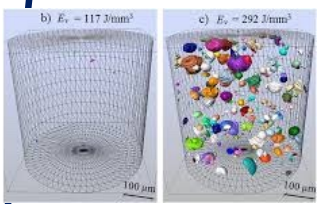
IRP AMHELIE Fatigue of Architectured Materials

Manufacturing – Microstructure evaluation

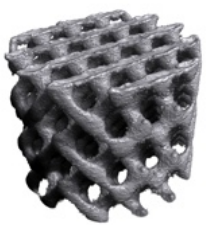


Post-Process

HIP

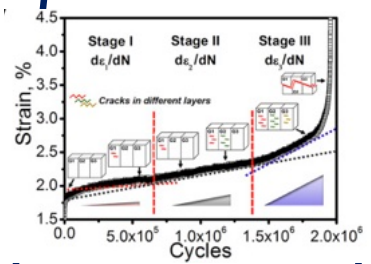


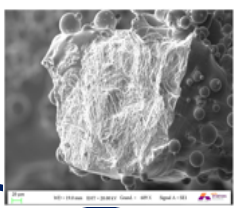
Etching



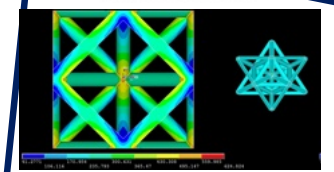
Fatigue damage

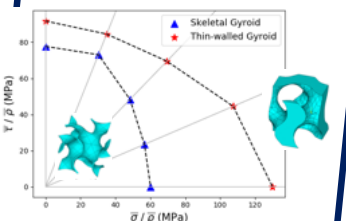
Damage – deformation mechanisms and kinetics



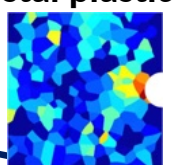


Numerical strategy





Crystal plasticity



Thank you!

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remy.dendievel@phelma.grenoble-inp.fr

nicolas.saintier@ensam.eu