Mechanical behaviour of additively manufactured materials

ION Congress 2018

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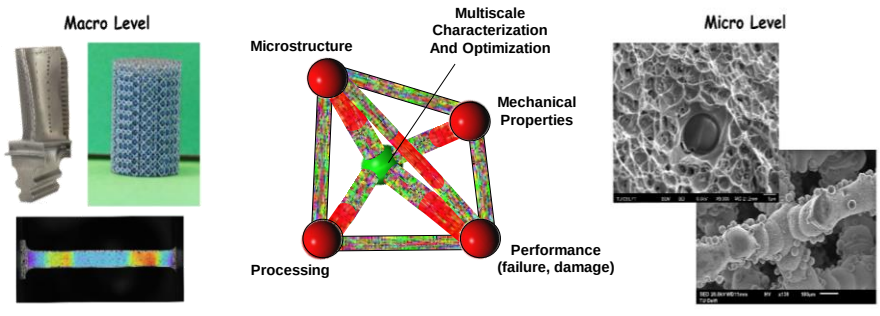
Outline

- **Who we are: AM research activities at TUDelft**
- **Introduction: General concepts**
- **Nickel-based super alloys**
  - Mechanical properties and microstructural design
  - Effect of heat treatment
  - Design for high temperature applications
- **Titanium alloys**
  - Surface engineering, microstructural design & Fatigue
- **Where we go: future research activities**

Research activities:

Mechanical behaviour of additively manufactured materials



- Understanding and control of mechanical behaviour
- Development of multifunctional materials
- Surface engineering and post-processing
- Multi-scale modelling of mechanical response

Dr. Vera Popovich, v.popovich@tudelft.nl
https://www.tudelft.nl/en/3me/organisation/departments/materials-science-and-engineering/research/mechanical-behaviour/

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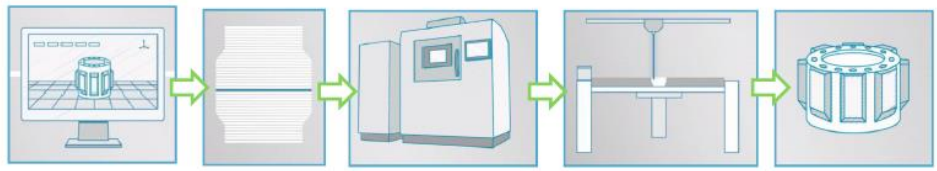
AM Definition

Additive Manufacturing is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer (Definition by ASTM).



Courtesy of Voestalpine Additive Manufacturing Center

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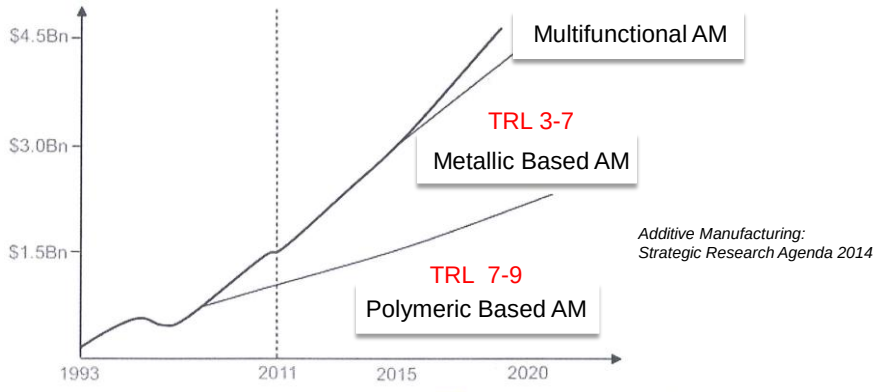
Introduction Additive Manufacturing Technologies
Factories of the Future

Rapid Prototyping, Rapid Manufacturing, 3D printing,
Freeform Fabrication, E- Manufacturing……



Additive Manufacturing:
Strategic Research Agenda 2014

In **2016**, 3D-Printing market grew by **$1 billion** to a total of **$5.1 billion,**
In 2018, total of $12.8 billions, In **2020**, the market is expected to reach **$21.2 billion**

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Additive manufacturing of metals

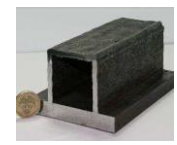
Weld based Additive Layer Manufacturing - METALS

Powder based

- Low deposition rate (0.1-0.2 kg/h)
- Low material efficiency (10-60 %)
- High level of design complexity

Wire based

- High deposition rate (few kg/h)
- High material efficiency (90 %)
- Low level of design complexity



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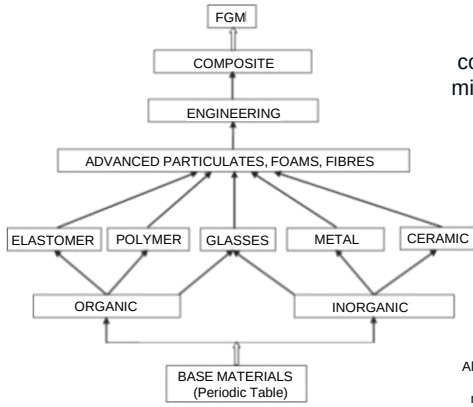
Introduction to functional grading

Modern Material Hierarchy

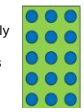


Functionally Graded Materials (FGM)

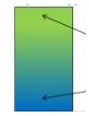
composite materials whose composition and/or microstructure vary in 3D space, which allows to tailor properties and performances.

Composite

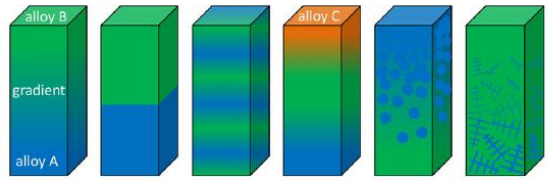
All the part is thermally conductive, but the matrix lost hardness



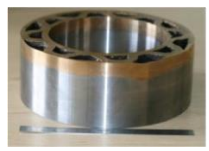
FGM

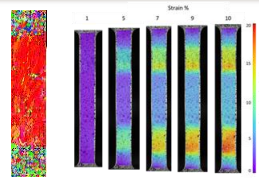


Introduction to functional grading via AM



Composition	Microstructure	Topology
- gradually changing chemical composition	- structural gradient	- controlled porosity Lattice structures





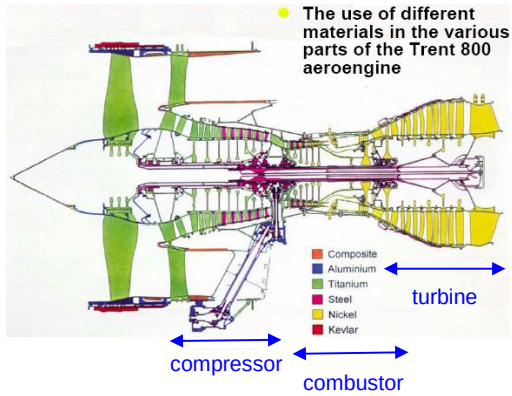
Microstructural design by AM

AM offers a unique opportunity to generate material with site-specific properties or FGM

D.C. Hofmann et al.: Compositionally graded metals: A new frontier of additive manufacturing, 2014

Nickel-based Super alloy: Inconel 718

oxidation-corrosion-resistant material well suited for service in extreme environments subjected to pressure and heat.



Conventional Casting and Forging

- Difficult to machine and weld
- Design and shape limitation
- Material waste

Additive Manufacturing (AM), such as Selective Laser Melting (SLM)

- More convenient and efficient
- High geometrical complexity
- Dimensional accuracy
- Reduction of production steps
- Low material consumption
- Unique and superior properties

Attracted a lot of attention in aerospace industry

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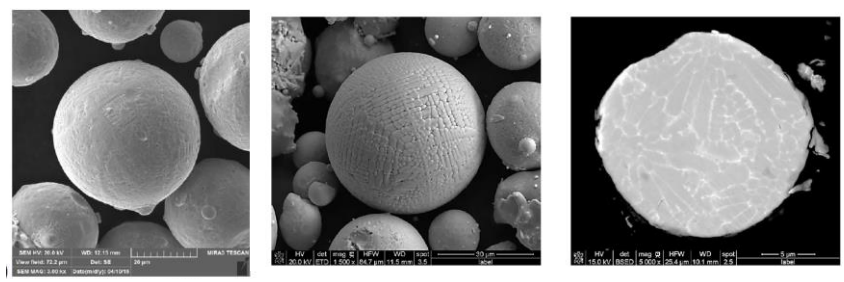
What kind of microstructure can be obtained via AM?

Gas atomized **Inconel 718** powder (d_{10} = 20 µm to d_{90} = 64 µm) .

Element	Ni	Cr	Fe	Nb	Mo	Ti	Al	Co	Mn
Content, %.	51.45	19.38	18.49	5.3	3.4	1.04	0.72	0.1	0.12



Powder particle showing the internal microdendritic structure.

V.S. Sufiarov et al. / Procedia Engineering, 2017

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What kind of microstructure can be obtained via AM?

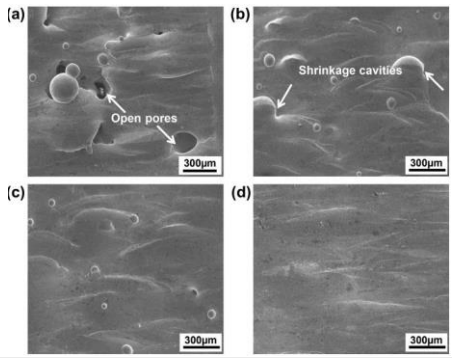
Effect of SLM Process Parameters

- ✓ Layer thickness
- ✓ Laser Power
- ✓ Scanning Speed
- ✓ Distance between passes
- ✓ Scanning strategy ……

Energy density

$$E_V = \frac{P}{v \cdot \delta \cdot h} \left[\frac{J}{mm^3}\right]$$

P = laser power
v = scan velocity
δ = layer thickness
h = hatch distance



Morphology of Inconel 718 (a) with 180 J/m (b) 275 J/m (c) 300 J/m (d) 330 J/m,

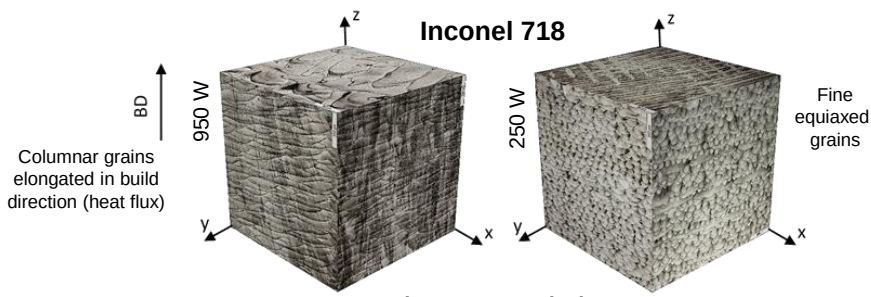
When the energy density is at 330 J/m, the material density increase to 98.4% as compared to 73.6% at 180 J/m.

Q. Jia, et al, Journal of Alloys and Compounds, 2014.

Microstructural design via AM

What kind of microstructure can be obtained?
→ SLM Solutions 280^{HL} → 400W/1000W laser sources

Laser Power (W)	Laser Scanning Speed (mm/s)	Hatch distance (mm)	Layer thickness (μm)	Beam diameter (distribution type), (μm)	Energy density (J/mm³)
250	700	0.12	50	80 (Gaussian)	59.5
950	320	0.5	100	100 (Flat Top)	59.4

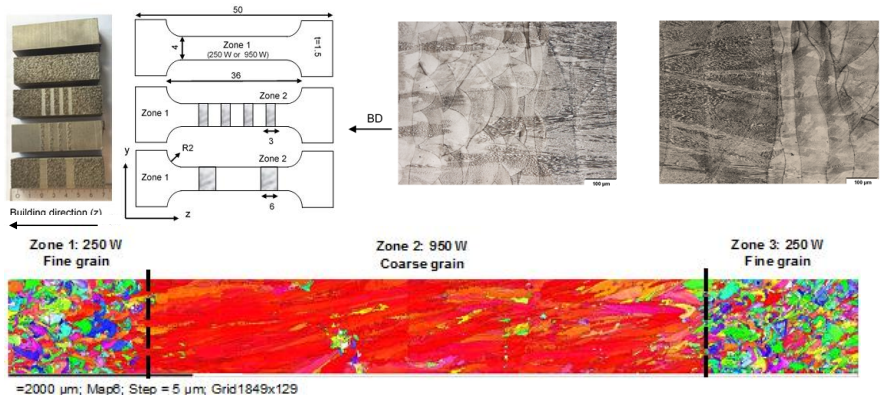


Microstructure design
(Grain Size and Texture) as a tool for functional grading

V.A. Popovich, et al, "Functionally graded Inconel 718 processed by additive manufacturing: crystallographic texture, anisotropy of microstructure and mechanical properties", Materials and Design 14, 2017.

Microstructural design via AM

Development of novel graded materials via grain growth control via AM process



Strong texture
Microstructurally tailored
Load-adapted design

Functionally graded by microstructure design

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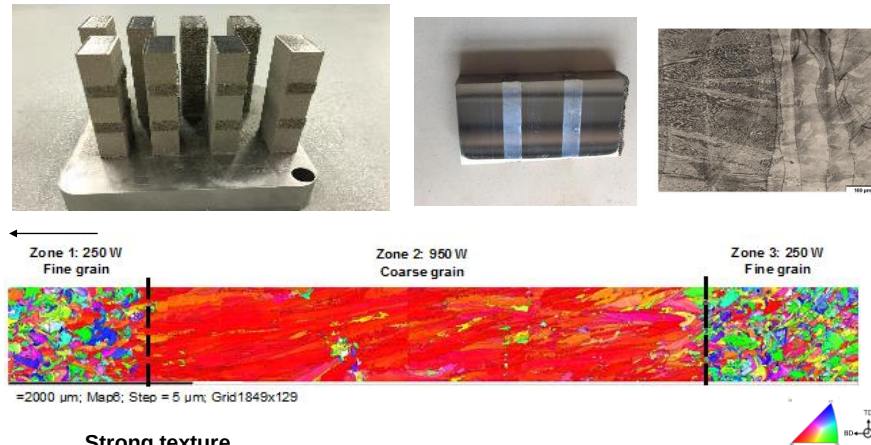

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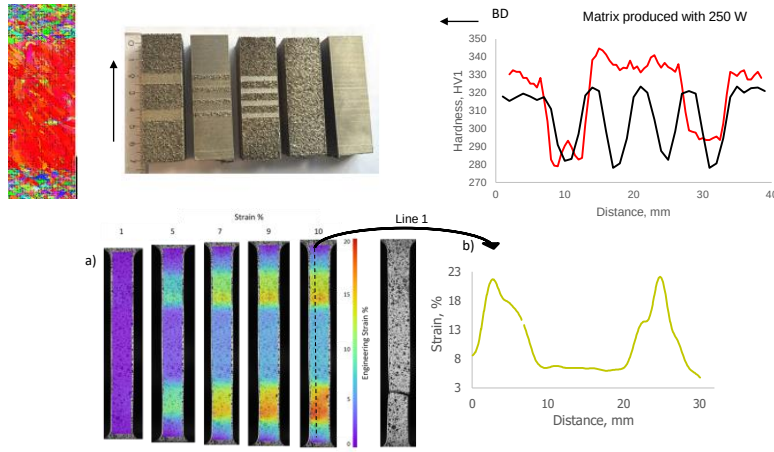


Anisotropy of mechanical properties is highly dependent on the texture.
User-defined functional performance at different locations within a single component.

Not only tailored **mechanical properties**, but **corrosion, electrical and thermal properties**, etc.

V.A. Popovich, et al, "Functionally graded Inconel 718 processed by additive manufacturing: crystallographic texture, anisotropy of microstructure and mechanical properties", Materials and Design 14, 2017.

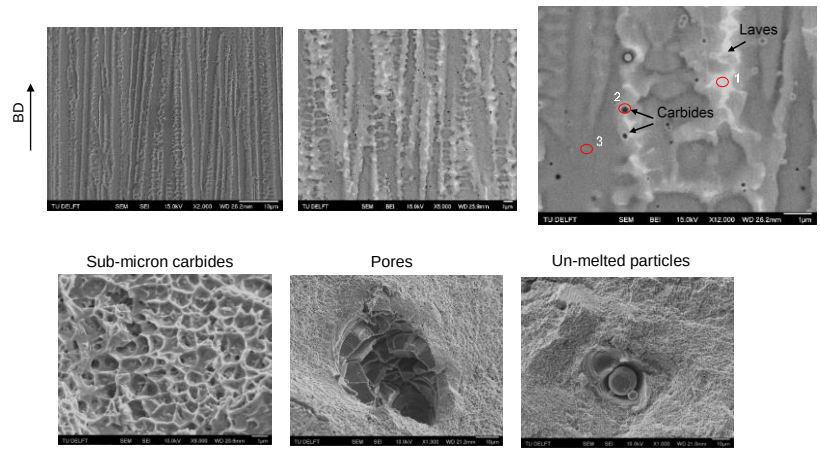
Microstructural design via AM

Samples name and laser source	Yield Strength (MPa)	Young's Modulus (GPa)	Elongation to failure (%)	Tensile Strength (MPa)	Hardness, 250 W / 950 W HV_{1kgf}		Porosity 250 W / 950 W %	
Conventionally processed Inconel 718								
Cast	488	200	11	786	353		-	
Wrought	916	200	17	1055	353		-	
SLM processed Inconel 718								
250 W	668 ± 16	173 ± 13	22 ± 2	1011 ± 27	320		0.11	
950 W	531 ± 9	113 ± 3	21 ± 7	866 ± 33	287		0.27	
Graded SLM processed Inconel 718								
Graded Material 1: Zone 1 - 250 W Matrix and Zone 2 - two lines of 950 W								
As Processed	574 ± 6	136 ± 13	13 ± 2	873 ± 14	330	285	0.09	0.2

- Superior to Cast material mechanical properties
- Primarily dependant on the grain size, texture and process-induced defects
- Coarse grains elongated along the (001) direction will be beneficial for high temperature properties, such as thermomechanical fatigue (TMF) and creep.

V.A. Popovich, et al, "Functionally graded Inconel 718 processed by additive manufacturing: crystallographic texture, anisotropy of microstructure and mechanical properties", Materials and Design 14, 2017.

Microstructural design via AM



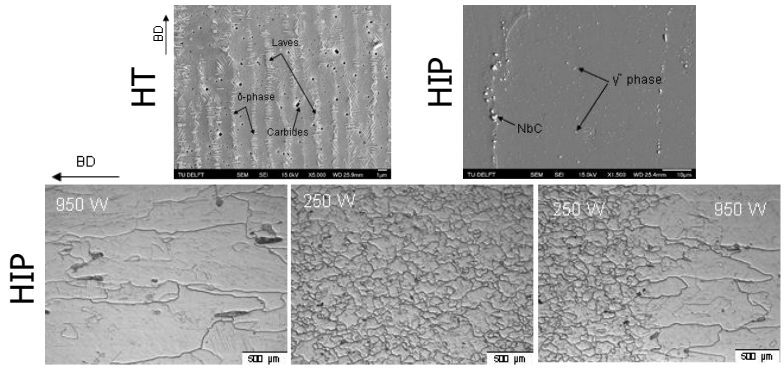
Increased porosity and the formation of undesirable Laves phases results in a reduction of mechanical performance

→ Thermal post-processing is required

V.A. Popovich, et al, "Functionally graded Inconel 718 processed by additive manufacturing: crystallographic texture, anisotropy of microstructure and mechanical properties", Materials and Design 14, 2017.

Impact of heat treatment

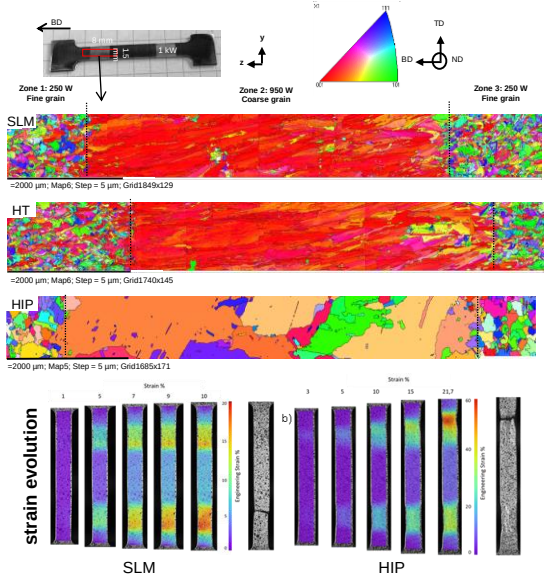
Designation	Heat Treatment	Details (AMS 5664E)
HT	Annealing Heat Treatment	850 °C / 2h / air cooling (AC)
HIP	Hot Isostatic Pressing	1180 °C / 3h at 150 MPa pressure. Furnace cooling (FC)
HIP + H/T	Hot Isostatic pressing + homogenization + aging	HIPed + 1065 °C/1 h/ AC + 760 °C /10 h / FC at 55 °C/h to 650 °C / 8 h / AC



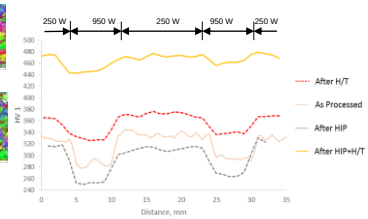
Grain coarsening, but desired grain morphology/grading is preserved

V.A. Popovich, et al, "Impact of heat treatment on microstructure and mechanical properties of functionally graded Inconel 718", Materials & Design 131, 2017.

Impact of heat treatment



Hardness gradient



Desired grain morphology is preserved

V.A. Popovich, et al, "Impact of heat treatment on microstructure and mechanical properties of functionally graded Inconel 718", Materials & Design 131, 2017.

Impact of heat treatment

Tensile properties at 650 ºC

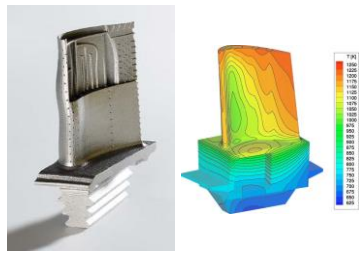
Samples name and laser source	Yield Strength 0.2%, (MPa)	Elongation to failure (%)	Tensile Strength (MPa)
Cast	517	13	576
Wrought	955	14	1061
As-processed			
SLM - 250 W	650 ± 11	28 ± 4	845 ± 9
SLM - 950 W	543 ± 2	31 ± 6	782 ± 6
SLM + Hot Isostatic Pressing			
250 W	626 ± 8	29 ± 1	857 ± 14
950 W	479 ± 5	28 ± 2	665 ± 7
SLM + Hot Isostatic Pressing + Heat Treatment			
250 W	942 ± 11	20 ± 2	1078 ± 8
950 W	872 ± 13	17 ± 4	1005 ± 12

By applying post-processing the intended microstructural grading remained and the resulting mechanical properties became superior to those of cast and wrought Inconel 718.

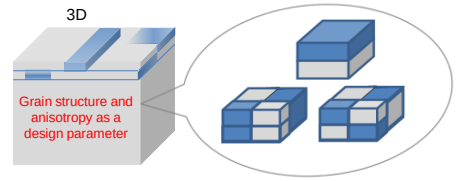
V.A. Popovich, et al, "Impact of heat treatment on microstructure and mechanical properties of functionally graded Inconel 718", Materials & Design 131, 2017.

3D microstructural design for high temperature applications

Temperature distribution



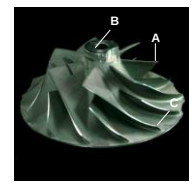
Grading and Microstructural design for improved TMF and creep



- Microstructurally tailored
- Load-adapted design

Design for site-specific properties

Turbine jet engine blisk

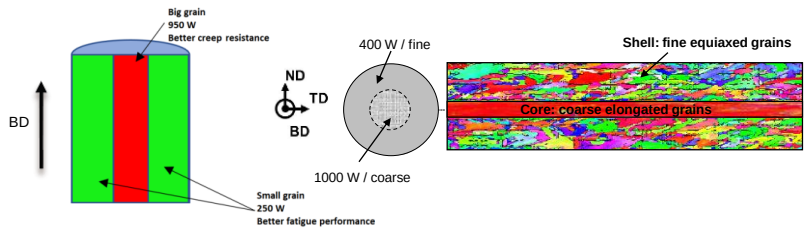


A- high impact resistant
B- fatigue resistant
C - creep

V.A. Popovich, et al, "Creep and Thermomechanical Fatigue of Functionally Graded Inconel 718 Produced by Additive Manufacturing. In: & Materials Society T., The Minerals, Metals & Materials Series. Springer, 2018.

3D microstructural design for high temperature applications

Shell/Core structure via additive manufacturing



- Microstructurally tailored
- Load-adapted design

Design for site-specific properties

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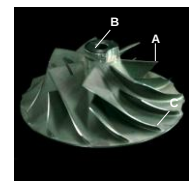

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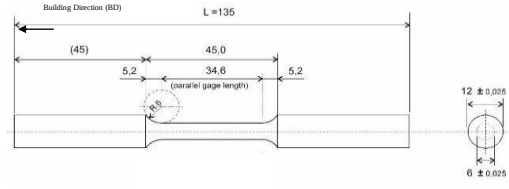
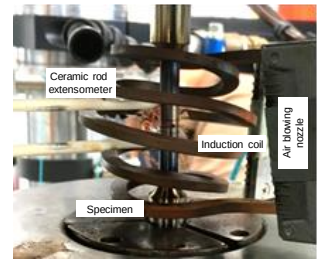
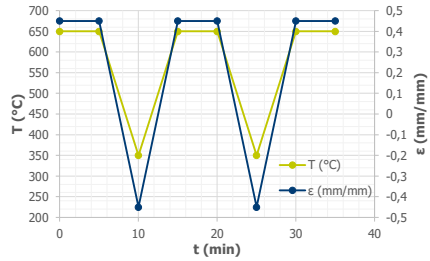
3D microstructural design for high temperature applications

Thermomechanical Fatigue (TMF)





- Strain controlled in-phase thermo-mechanical fatigue (IP-TMF)
- Cycling 350 °C to 650 °C, R = ε_{min} /ε_{max} = -1
- Strain amplitude of ± 0.45 %



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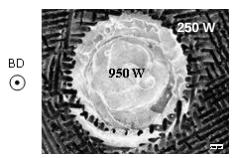
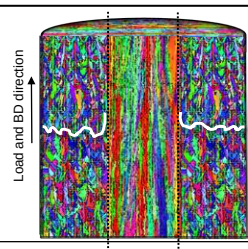
3D microstructural design for high temperature applications

Thermomechanical Fatigue (TMF)

Specimen	Time to failure (h)	Cycles to failure	Porosity (%)	Grain Size, µm	Hardness, HV_3 250 W / 950 W
250 W AP	103.3	621	1.1	50 – 100	303
250 W + HT	207.6	1246	1	50 – 100	446
250 W + HIP+HT	188.3	1853	0.05	150 – 300	478
950 W AP	0.7	2	4.5	500 – 1000 (in BD)	290
950 W + HT	1.9	12	4.1	500 – 1000	415
950 W + HIP+HT	122.4	1470	0.5	1000 – 2000	462
FGM AP	98.5	608	0.3	-	312 / 294
FGM HT	**407.2**	**2244**	**0.4**	-	449 / 426
FGM HIP+HT	283	1595	0.3	-	
Conventional Wrought Inconel 718	340.5	1876	0.2	5 – 10	424

Crack arrest mechanism





Cracks deviate into positions perpendicular to the loading direction → no longer have a driving force to cause crack extension.

Graded interfaces assist crack deflections into positions that cause crack arrest.

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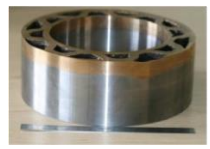
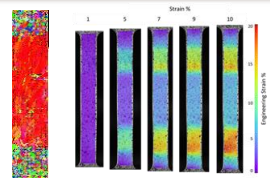
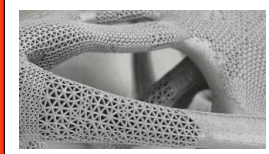
Implants with enhanced fatigue through microstructural design and surface engineering

Composition	Microstructure	Topology
- gradually changing chemical composition	- structural gradient	- controlled porosity in lattice structures





Microstructural design by AM

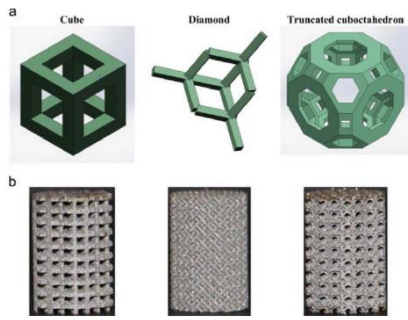


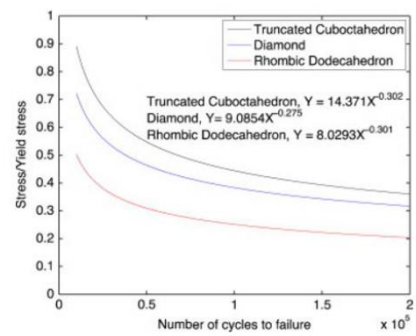
Functional grading via:
Microstructure
Porosity
Composition

⟺ local enhancements in mechanical, structural or other functional properties.

Titanium implants with enhanced fatigue through microstructural design and surface engineering

Porosity/Topology Optimization, cell and material types

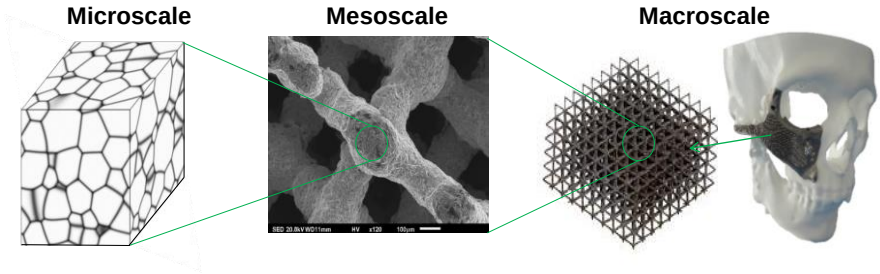




Topology optimization of lattice structures has been extensively studied

Ahmadi, S. M., et al. (2014). "Mechanical behaviour of regular open-cell porous biomaterials made of diamond lattice unit cells." Journal of the Mechanical Behaviour of Biomedical Materials **34**: 106-115.

Titanium implants with enhanced fatigue through microstructural design and surface engineering



Functional grading via:

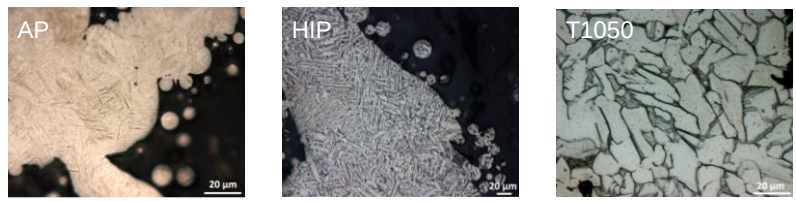
- **Microstructure**
- **Porosity**
- Composition

⟺

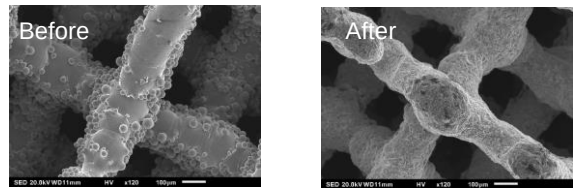
local enhancements in mechanical, structural or other functional properties.

Titanium implants with enhanced fatigue through microstructural design and surface engineering

Microstructural Design

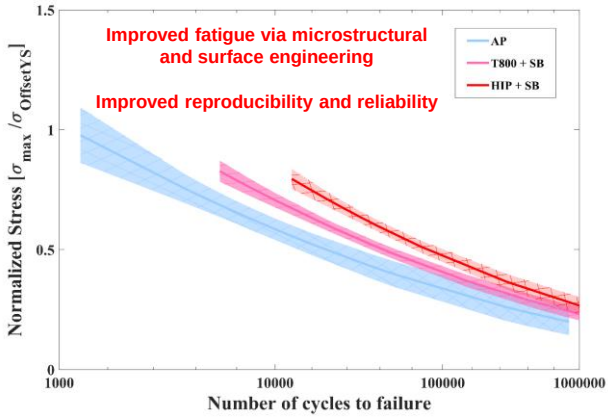


Surface engineering

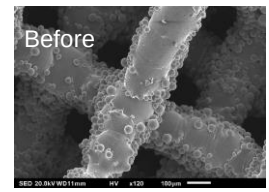


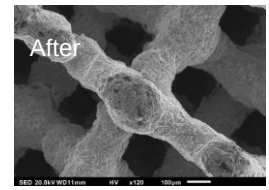
S.M. Ahmadi, A.A. Zadpoor, C. Ayas, V.A. Popovich, "Effects of heat treatment on microstructure and mechanical behaviour of additive manufactured porous Ti6Al4V", 2017
S.M. Ahmadi, R. Kumar, E.V. Borisov, R. Petrov, S. Leeflang, R. Huizenga, C. Ayas, A.A. Zadpoor, V.A. Popovich, "From microstructural design to surface engineering: a tailored approach for improved fatigue life of additive manufactured porous titanium", Acta Biomaterialia, 2018

Titanium implants with enhanced fatigue through microstructural design and surface engineering



Surface engineering

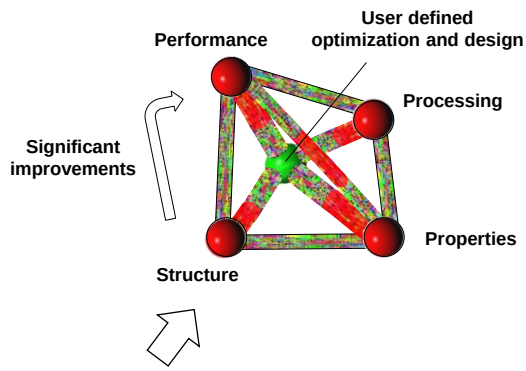




AM lattice structures exhibit high degree of anisotropy, process induced porosity and surface defects

S.M. Ahmadi, A.A. Zadpoor, C. Ayas, V.A. Popovich, "Effects of heat treatment on microstructure and mechanical behaviour of additive manufactured porous Ti6Al4V", 2017
S.M. Ahmadi, R. Kumar, E.V. Borisov, R. Petrov, S. Leeflang, R. Huizenga, C. Ayas, A.A. Zadpoor, V.A. Popovich, "From microstructural design to surface engineering: a tailored approach for improved fatigue life of additive manufactured porous titanium", Acta Biomaterialia, 2018

Future Research Activities

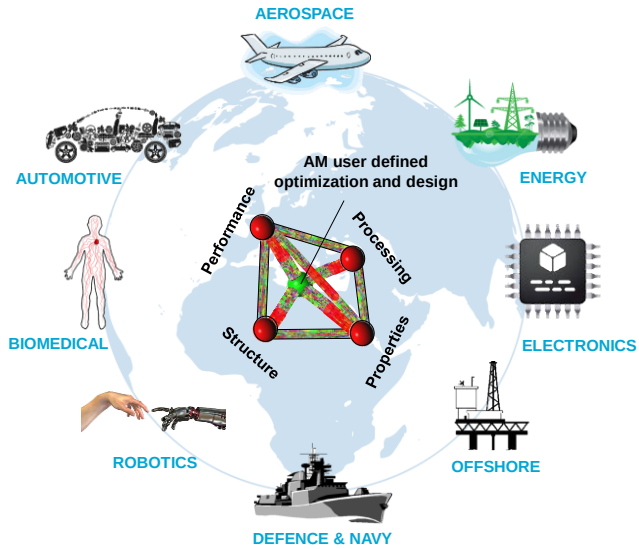


Additive manufacturing is suitable for microstructure manipulation and design freedom

- Grain size & shape
- Texture & anisotropy
- Surface optimization

→ Fundamental research and in-depth understanding is required

Thank you for your attention



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