

**UNIVERSITY  
OF OULU**

KERTTU SAALASTI INSTITUTE

## **Metallin 3D-tulostus: Toiminnalliset rakenteet ja väsymättömät ratkaisut**

Metal 3D Printing: Functional Structures and Fatigue-Free Solutions

**3D-tulostus Oulu 25.3.2025**

Tutkimusjohtaja Antti Järvenpää  
[antti.jarvenpaa@oulu.fi](mailto:antti.jarvenpaa@oulu.fi)

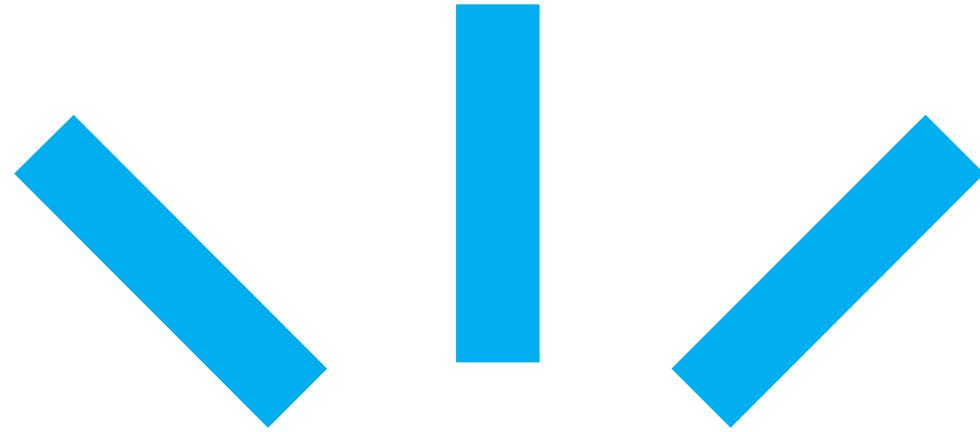
**FMT**  
FUTURE MANUFACTURING  
TECHNOLOGIES



# Content

1. Introduction
2. Material quality
3. Functional structures and META-materials
4. Summary

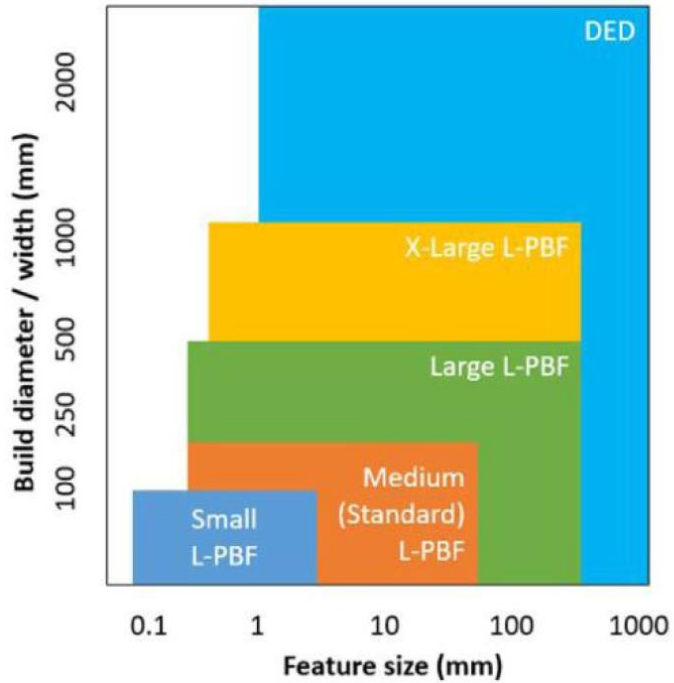




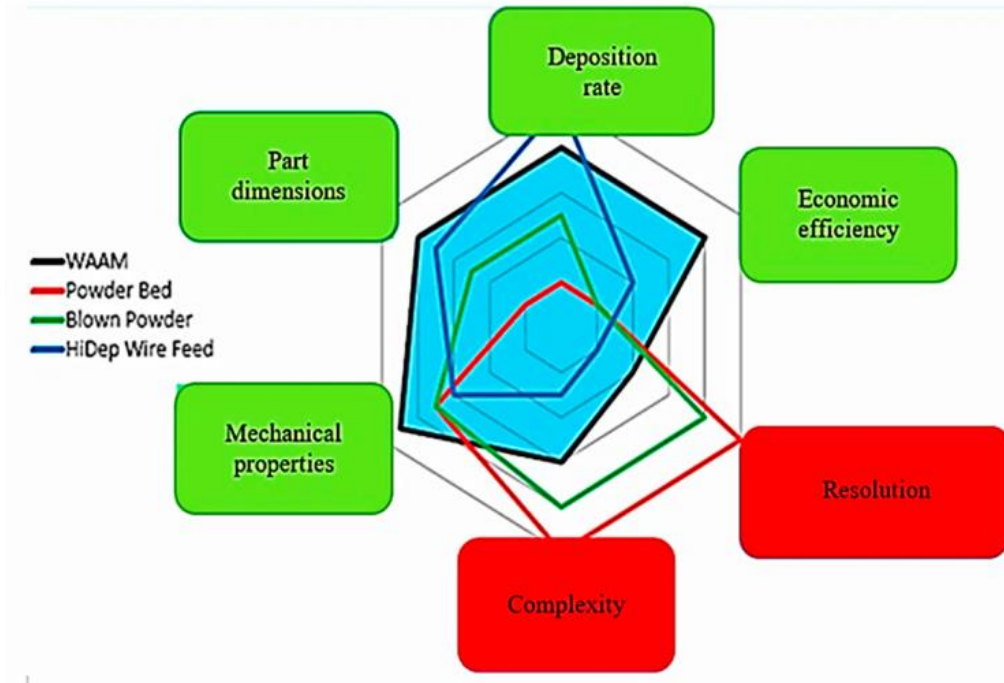
# 1. Introduction



# Size matters in AM !!



Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components, <https://doi.org/10.1007/s11665-022-06850-0>

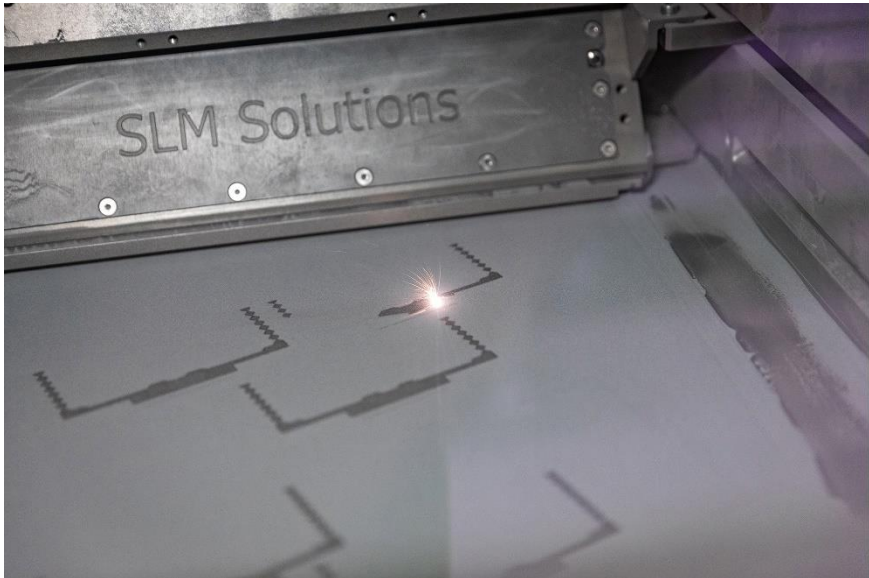
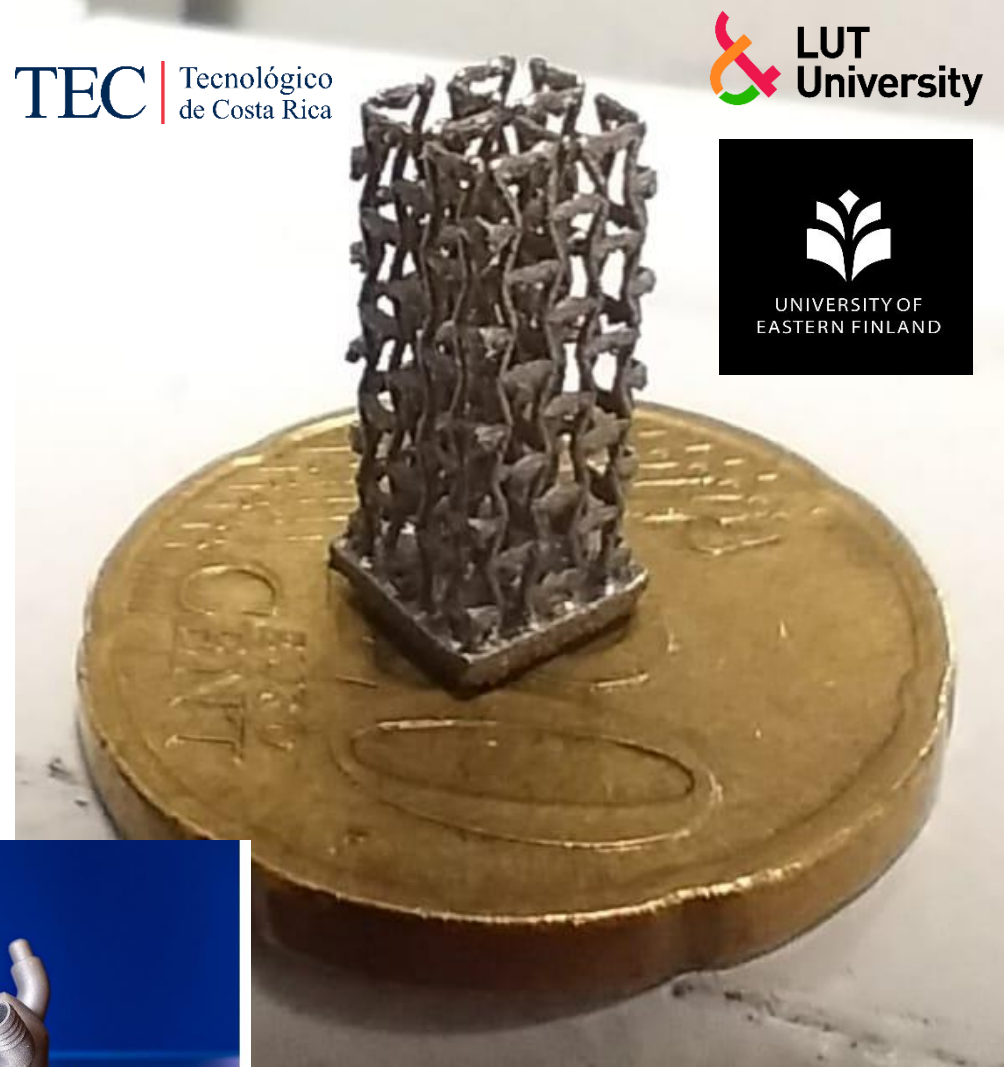




# Jauhepetitulos

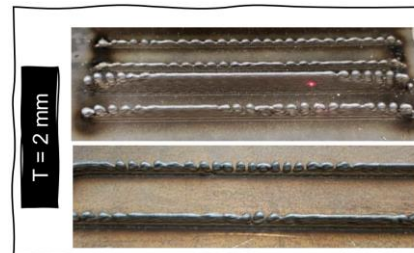
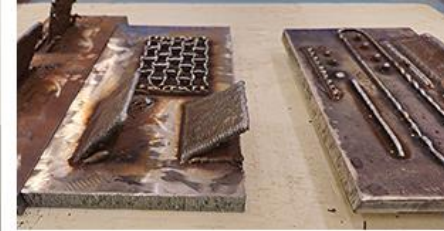
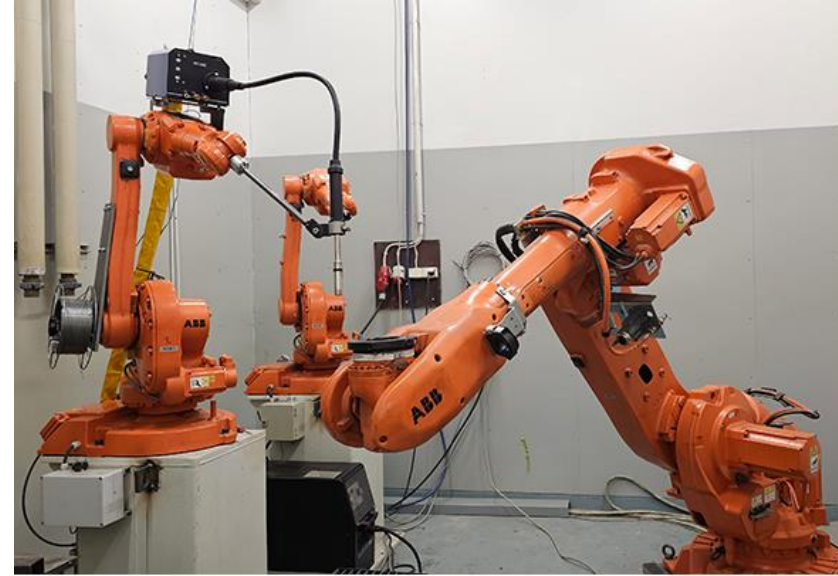
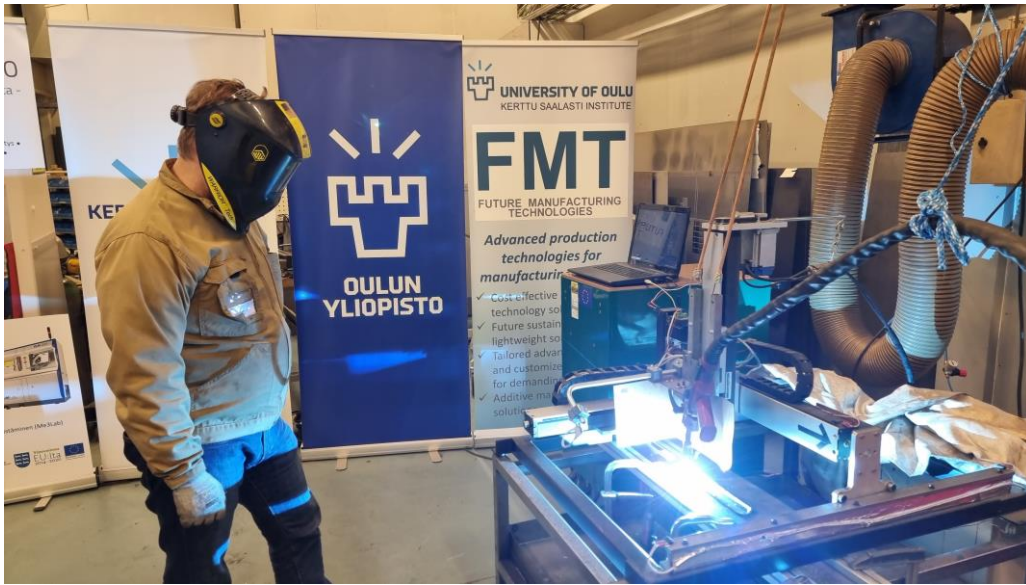
TEC | Tecnológico de Costa Rica

LUT University





# WAAM (MIG/MAG-wire) equipment





Nano ( $10^{-9}$ )

Mikro ( $10^{-6}$ )

Milli ( $10^{-3}$ )

Metri (1)

Materiaalin mikrorakenteen optimoiminen

Kennorakenteet

Uudet ekologiset teräkset

Mikro- ja makrorakenteen optimointi

Tuotteet

Induktio ja lasertekniikka

Huokosrakenteet

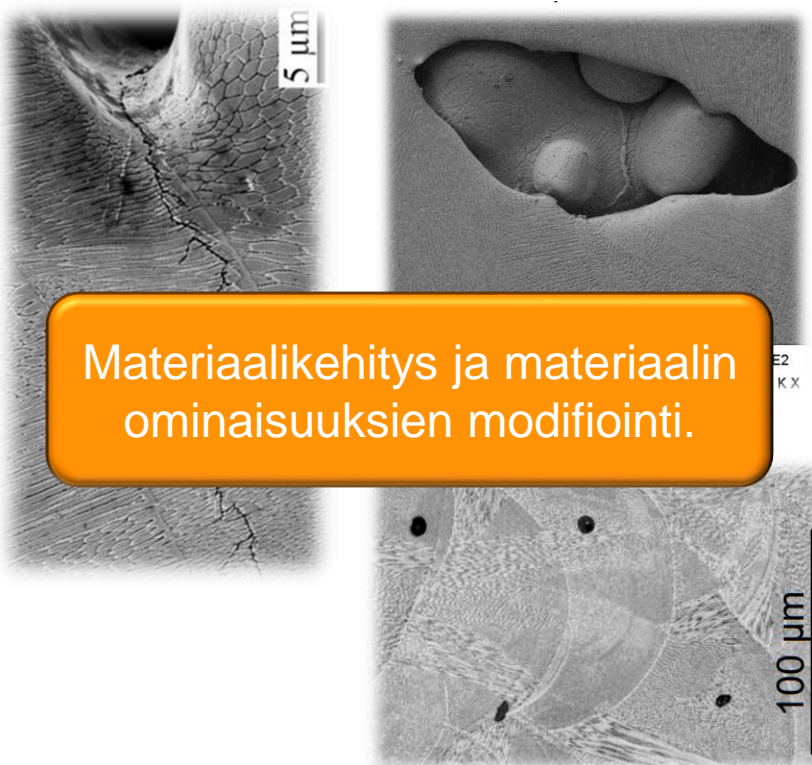
Suunnittelun ja valmistuksen optimointi

3D tulostus

Induktio ja lasertekniikka

Suunnittelu ja prototyyppi

Materiaalin testaus

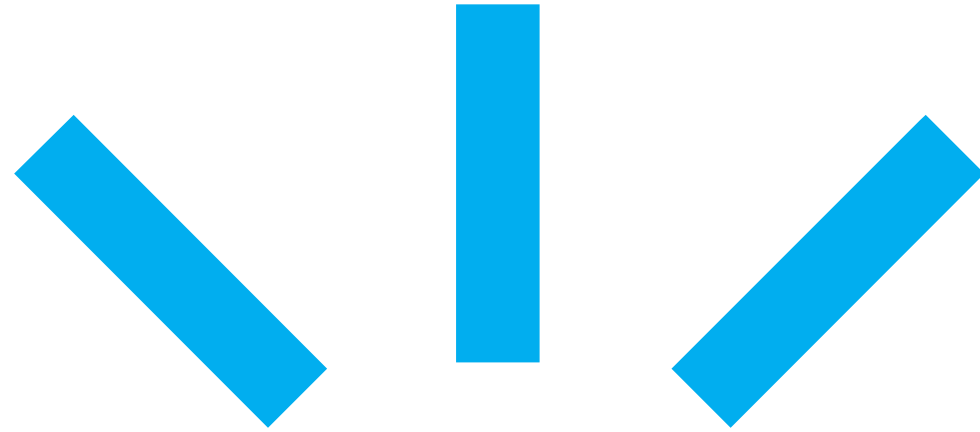


Materiaalikehitys ja materiaalin ominaisuuksien modifiointi.



Optimoidut mikro- ja makrokokoluokan rakenteet samassa komponentissa/tuotteessa.

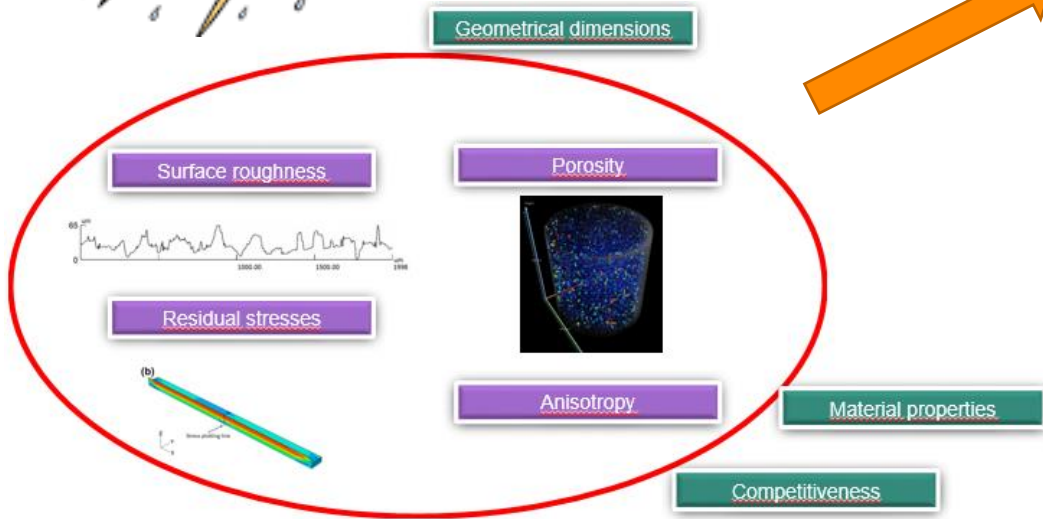




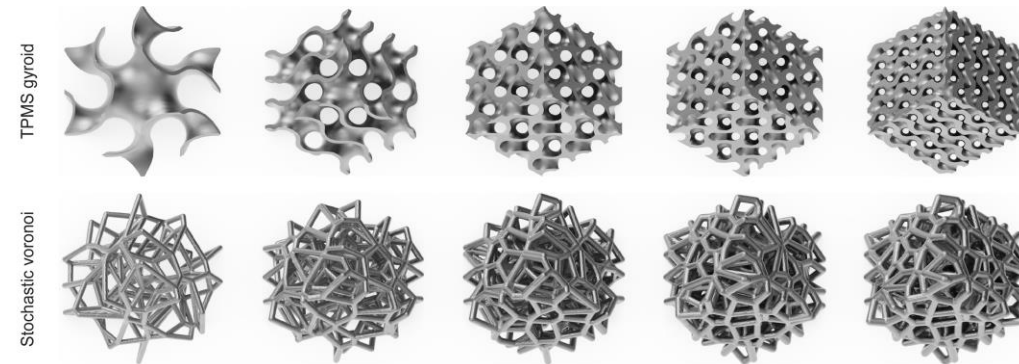
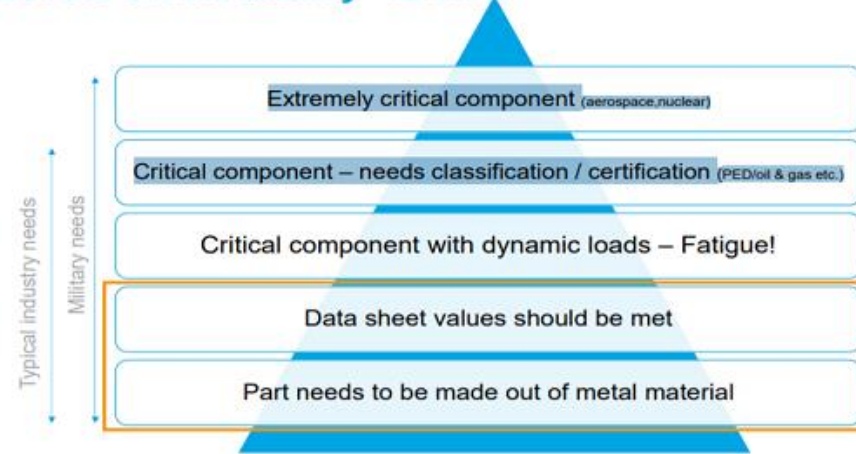
## 2. Material quality



# 1. AM material quality



## Levels of AM Quality - LAMQ



	0.1	0.2	0.3	0.4	0.5
Relative Density ( $\rho/\rho_s$ )	0.1	0.2	0.3	0.4	0.5
Strut / wall thickness ( $\mu\text{m}$ )	200	225	250	275	300

## Additive manufacturing



Various commercial LPBF machines and technics were used to manufacture the test specimens.

### LPBF processing:

LPBF machine (SLM280HL, SLM500, EOS, 3D systems, Metal fab)

Typical parameters: Layer thickness [ $\mu\text{m}$ ], laser power [W], scanning speed and hatch space.  $\rightarrow$  parameter sets are coded typically based on the layer thickness so the layer thicknesses are presented in this database.

## Heat treatments



Argon and vacuum atmospheres were applied in furnace treatments.

### Heat treatments

Austenitic stainless steels: (600 °C/120min, 900 °C/30min, 1100 °C/180min, slow cooling until RT, Ar atmosphere)

AlSi10Mg: 300 °C / 120min

Ti6Al4V: (Vacuum treatment 1, HT1 in Ar, HT2 in Ar) 800 °C / 120min

In718: Three distinct solution treatment at 980, 1080, and 1180 °C, followed by air cooling and water quenching to study the effect of cooling rates after treatment. Two aging treatment follows a standardized two-step cycle, comprising a heating phase up to 720-760 °C for 8 hours (stabilizing treatment), followed by an 8-hour cooling phase within the furnace at 620-650 °C (precipitation hardening treatment), and subsequently allowed to cool in ambient air.

## Surface engineering



### Electropolishing - GPA Innovations – DryLyte HF100+

Electropolishing media:

Steel-04 for carbon steels

SSL-01 for stainless grades and Inconel

Ti-01 for Ti6Al4V

Al-03 for AlSi10Mg

SSL-22 MSA G L130 for tool steels and special alloys

### Shot peening

A six-axis industrial robot

Spherical martensitic chromium media (STELUX C40)

Media size range 0.30–0.85 mm and hardness of 36 HRC

Blasted with an operating pressure of 7.4 bar and 70 mm from the SP nozzle

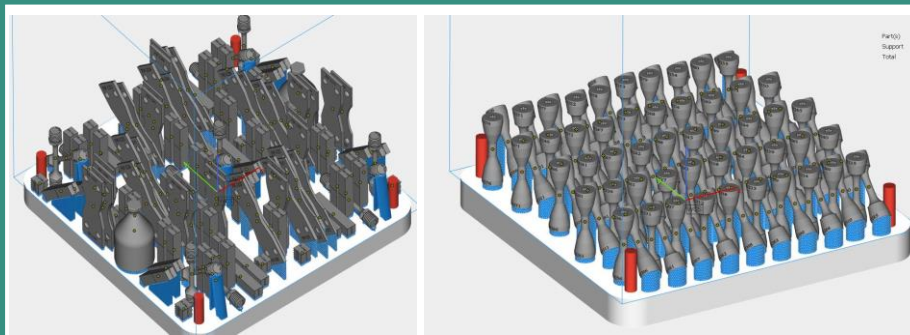
Almen intensity was determined with type A strips using a range of passes from 1 to 22 at the speed of 50 mm/s

Almen intensity from 260 to 358A

# TEST SAMPLES & PLATFORMS



## "Standard" test process (2 platforms)



Standard test process includes two separate platforms where the 1st platform contains impact toughness, tensile, bending fatigue and microstructural specimens. The second platform contains the axial fatigue specimens..

### Impact toughness testing:

The effect of sample location: 50 vertical impact toughness specimens (0°C and -40° test temperatures)

The effect of build orientation: 10 horizontal and 10 diagonal impact toughness specimens (0°C and -40° test temperatures, 5 samples per T)

### Fatigue

Both the bending and axial fatigue tests (stress ratio -1) were performed using two build orientations (vertical and diagonal) and two surface conditions (as built and polished) → in total four test conditions.

**Bending fatigue:** 40 test specimens (10 samples for each condition)

**Axial fatigue:** 100 test specimens (25 samples for each condition)

### Tensile tests

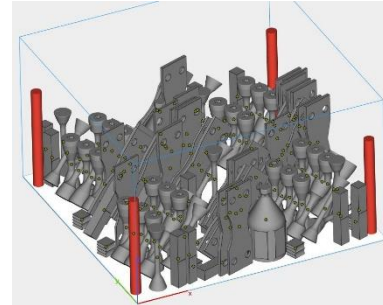
15 tensile test specimens, 5 on each orientation: horizontal, vertical, diagonal

### Metallography

15 cubes for microstructural and porosity analysis

Additional failure analysis has been performed for the selected samples

## "Lighter" test process (1 platform)



Lighter test process includes only one platform with total of 136 specimens (limited amount of impact toughness and axial fatigue test specimens)

### Impact toughness testing:

The effect of build orientation: 6 horizontal, 6 vertical and 6 diagonal impact toughness specimens (0°C and -40° test temperatures, 3 samples per T)

### Fatigue

Both the bending and axial fatigue tests (stress ratio -1) were performed using two build orientations (vertical and diagonal) and two surface conditions (as built and polished) → in total four test conditions.

**Bending fatigue:** 40 test specimens (10 samples for each condition)

**Axial fatigue:** 48 test specimens (12 samples for each condition)

### Tensile tests

15 tensile test specimens, 5 on each orientation: horizontal, vertical, diagonal

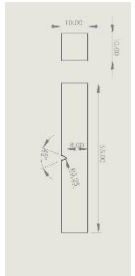
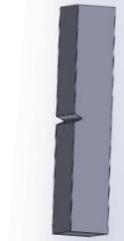
### Metallography

15 cubes for microstructural and porosity analysis

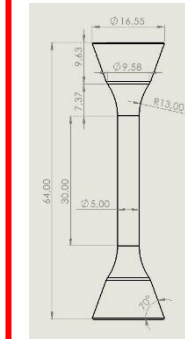
Additional failure analysis has been performed for the selected samples

## Test specimen types

### Impact toughness testing:

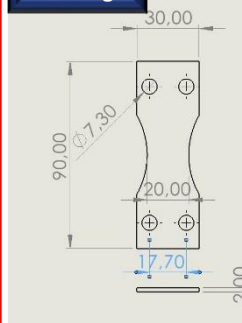


### Tensile test testing:

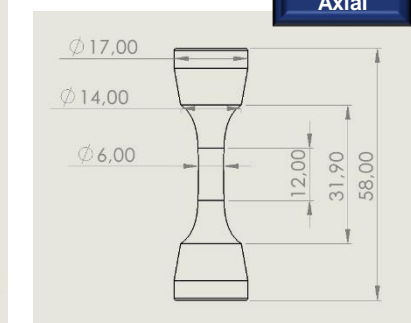


### Fatigue testing:

#### Bending



#### Axial

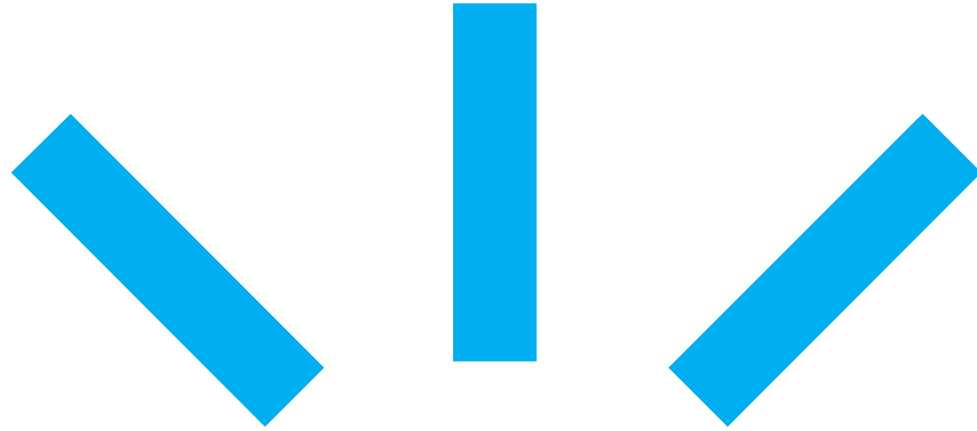


# DATA INSTRUCTIONS FOR SERIES NUMBERS

- 1<sup>st</sup> Column – Material**
- 2<sup>nd</sup> column – Printer type and manufacturer**
- 3<sup>rd</sup> column – Layer thickness**
- 4<sup>th</sup> column – Heat treatment parameters**
- 5<sup>th</sup> column – Series numbers to find the correct excel tab (see next slide)**

3D-step →  
3D formtech →  
Delva →  
Amexci →  
3D formtech →  
Amexci →

1 <sup>st</sup> column	2 <sup>nd</sup> column	3 <sup>rd</sup> column	4 <sup>th</sup> column	5 <sup>th</sup> column
Material	Printer	Layer thickness [µm]	HT	Series numbers
316L (HT+SSP study)	SLM 280HL	30	2h@600, 30min@900, 3h@1100	56-63
316L (polishing study)	SLM 280HL	30	2h@600	41-44, 93, 94, 178, 724
316L (HT study)	EOS	40	2h@600, 30min@900, 3h@1100	175, 306, 284, 231-233, 155, 259,
316L references	sheet metal/wrought	-	-	723, 725, 686, 891, 747, 748, 97, 746
316L	BJ	50	-	174, 176, 177, 281,282, 236
316L	MEX	150	-	260
316L	EOS	40	2h@900	360-374
316L	EOS	80	2h@900	343-358
316L without axials	SLM	60	no HT	705-714
316L axial	SLM	50	no HT	682-685
316L	EOS	40	2h@900	263-280
316L virgin powder	EOS	80	0,5h@900	378-393
316L used powder	EOS	80	0,5h@900	394-409
316L	EOS	40	0,5h@900	988-1003
316L	EOS	40	2h@900	1113-1128
316L	MetalFAB	60	2h@900	946-963
MS1	3D Systems	40	6h@480 (+1h@820 before)	85-87, 89, 90, 105, 256, 485-500
MS1	SLM	50	none compared to 6h@495	582-585, 636-639
Ti64	SLM 280HL	30	vacuum 2h@800°C	118-131
Ti64	SLM	30	none	136-145
Ti64	SLM	60	none	586-598
Ti64		40		1246-1261
Ti64		80		1262-1277
AlSi10Mg	SLM	30,60,90	none	81-83, 112, 113, 187
AlSi10Mg	SLM500	90	2h@300	728-745
AlSi10Mg	SLM500	60	2h@300	550-567
AlSi10Mg	SLM	60	2h@300	749-766
AlSi10Mg	SLM	60	none	767, 874-890
AlSi10Mg	SLM	60	90min@270	926-943
2024-RAM2C	SLM	40	manufacturer standard	1145-1162
Almgty90	SLM 280 HL	60		156-172
Inconel 718 (3 platforms)	EOS	40	2h@960+8h@720+8h@620	209-226, 503-516, 517-532
Inconel 718	EOS	40	2h@960+8h@720+8h@620	533-548
Inconel 718	EOS	40 HiPro	2h@960+8h@720+8h@620	894-909
Inconel 718	EOS	80 HiPro	2h@960+8h@720+8h@620	910-925
IN625-RAM2	EOS		manufacturer standard	1163-1180
H13	SLM	60	Tempered at 650 °C	965-982
H13	SLM	60	Tempered at 550 °C	1207-1224



## 3. Functional structures



# Why META-materials ?

## What advantages lattice structures offer ?

Controlled elasticity

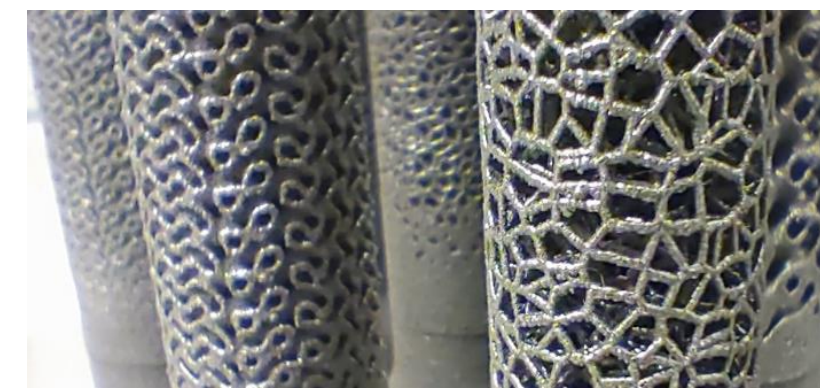
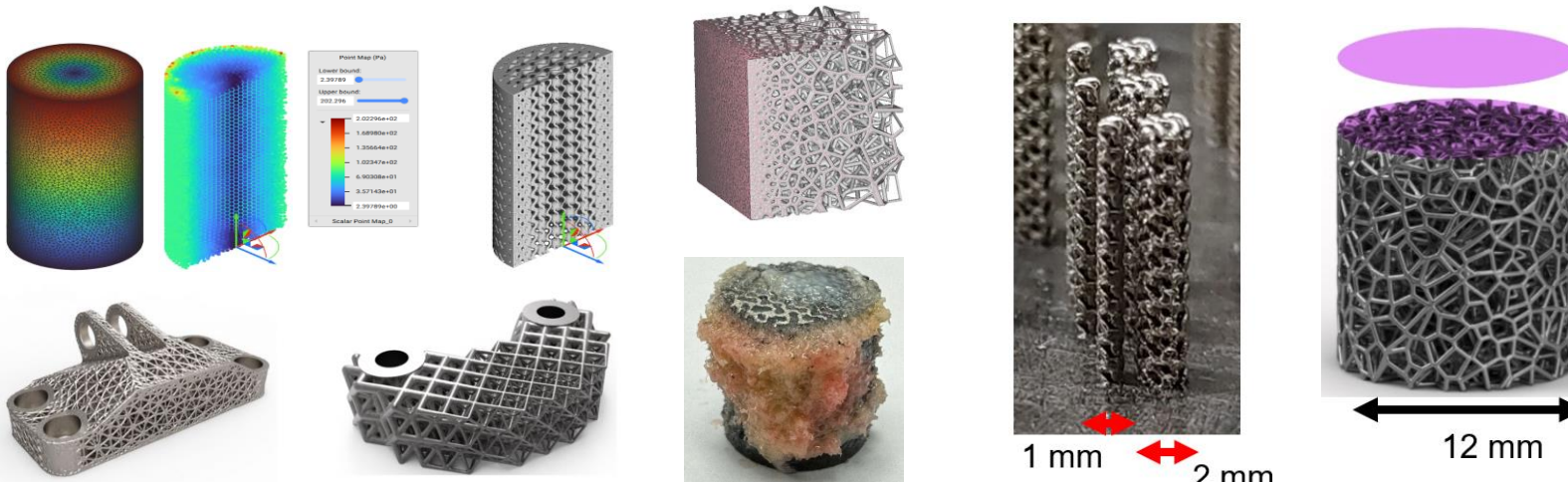
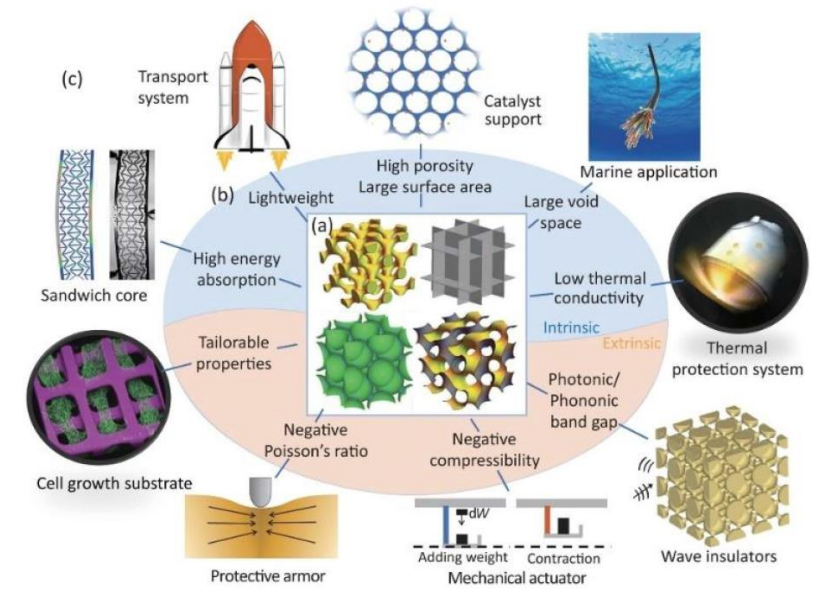
Spring-like structures, medical applications...

Weight reduction

Strongest low-density metals available, hot spot elimination...

Functional features

Liquid and gas flow, osseointegration, electronics, integrated engines...





# Future solutions / Heat exchangers, dampers, protection, etc.

## JUSTIA Patents

### AUXETIC TEXTILE STRUCTURES

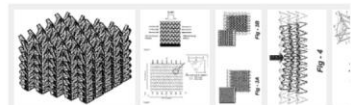
Aug 24, 2023

#### Three-dimensional auxetic structures and applications thereof

##### Abstract

Negative Poisson's ratio (NPR) or auxetic structures, including three-dimensional auxetic structures, are disclosed and applied to various applications. One such structure comprises a pyramid-shaped unit cell having four base points A, B, C, and D defining the corners of a square lying in a horizontal plane. Four struts of equal length or different lengths extend from a respective one of the base points to a point E spaced apart from the plane. Four tendons of equal length or different lengths, but less than that of the struts, extend from a respective one of the base points to a point F between point E and the plane. In three-dimensional configurations, a plurality of unit cells are arranged as tiles in the same horizontal plane with the base points of each cell connected to the base points of adjoining cells, thereby forming a horizontal layer. A plurality of horizontal layers are then stacked with each point E of cells in one horizontal layer being connected to a respective one of the points F of cells in an adjacent layer. Particularly for typical applications, the structure may further include a pair of parallel plates made sandwiching a plurality of horizontal layers of unit cells.

##### Images (8)



US20100119792A1  
United States

Download PDF Find Prior Art Similar

Inventor: Zheng-Dong Ma  
Current Assignee: MKP Structural Design Associates Inc.

Worldwide applications

2008-11-10

Application US12/267,867 events

2008-11-10 • Application filed by Individual

2008-11-10 • Priority to US12/267,867

2010-05-13 • Publication of US20100119792A1

2011-03-22 • Application granted

2011-03-22 • Publication of US7910193B2

Status: Expired - Fee Related

2029-07-05 • Adjusted expiration



(19) Bundesrepublik Deutschland  
Deutsches Patent- und Markenamt

(10) DE 103 23 367 A1 2004.12.16

#### (12) Offenlegungsschrift

(21) Aktenzeichen: 103 23 367.9  
(22) Anmeldetag: 21.05.2003  
(43) Offenlegungstag: 16.12.2004

(51) Int. Cl.: F16S 1/00

(71) Anmelder:  
Universität Dortmund, 44227 Dortmund, DE

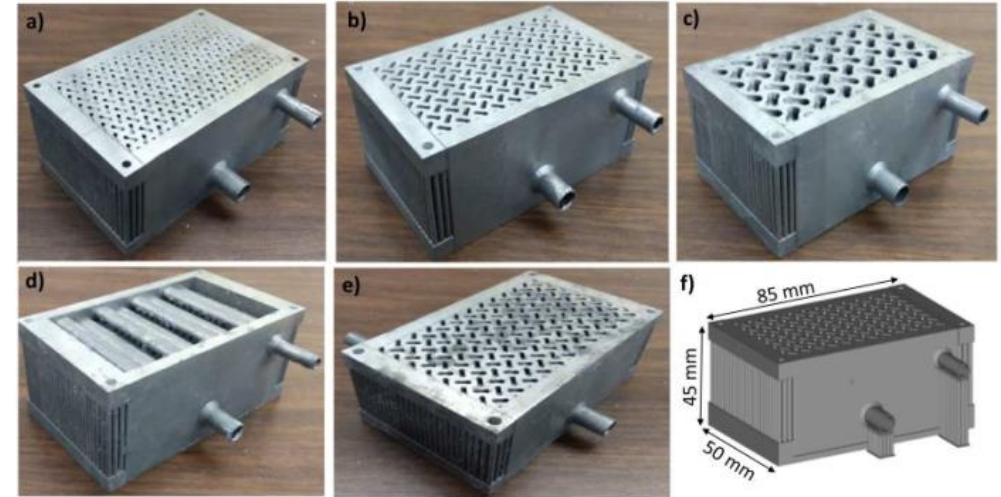
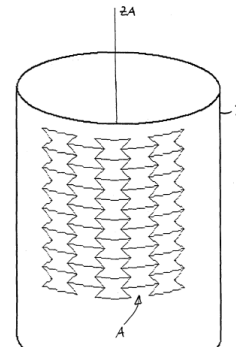
(72) Erfinder:  
Obrecht, Hans, Prof. Dr., 44795 Bochum, DE

(74) Vertreter:  
COHAUSZ DAWIDOWICZ HANNIG & PARTNER,  
40237 Düsseldorf

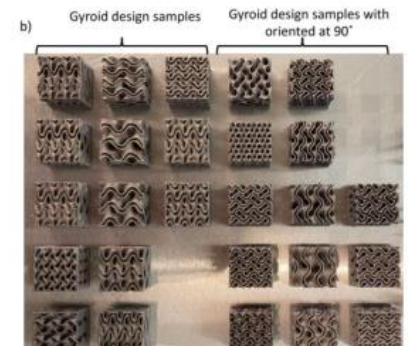
(56) Für die Beurteilung der Patentfähigkeit in Betracht zu ziehende Druckschriften:  
EP 08 265 611

Die folgenden Angaben sind den vom Anmelder eingereichten Unterlagen entnommen.  
Rechercheantrag gemäß § 43 Abs. 1 Satz 1 PatG ist gestellt.

(54) Bezeichnung: Bauelement mit auxetischer Struktur  
(57) Zusammenfassung: Die Erfindung betrifft ein Bauelement, bei dem wenigstens eine Oberfläche des Bauelementes eine auxetische Gitterstruktur aufweist.



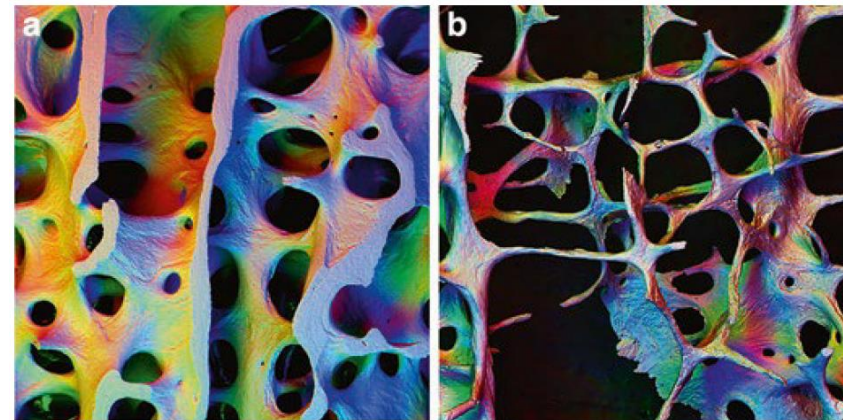
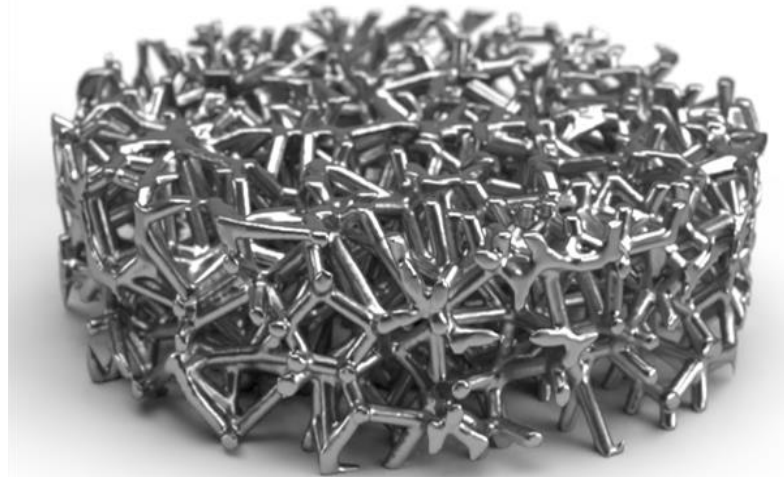
[Enhancement of heat exchanger performance using additive manufacturing of gyroid lattice structures]



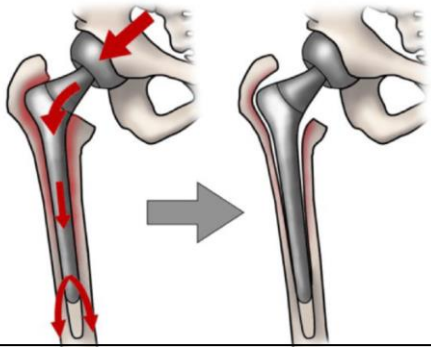
## Development of a Biomechanical and Osseointegration Evaluation System Using Additively Manufactured Mimetic Bone Models for Orthopedic Applications

Thesis submitted for consideration of an evaluating tribunal of the Interuniversity Program of Doctorate in Engineering to opt for the degree of Doctorate in Engineering.

MIGUEL ARAYA CALVO

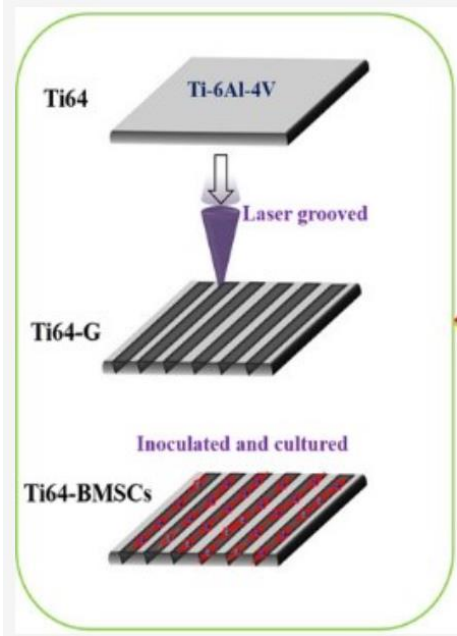


1. Elastic Modulus Mismatch between the implant and bone tissue causes preliminary failures “Stress-shielding effect”
2. Functional possibilities of solid materials are limited

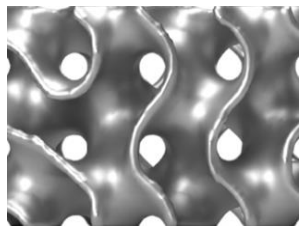


- **Elastic Modulus Mismatch**  
 Traditional solid implants (e.g., titanium Ti64 ~ 110 GPa, stainless steel ~190 GPa, cobalt-chrome ~210 GPa) have a much higher elastic modulus than natural bone.  
 Cortical Bone (Dense Bone): ~10–30 Gpa  
 Trabecular Bone (Cancellous Bone): ~0.1–2 GPa

1. Smooth metallic surface is not optimal for cell growth
2. Solid material only allows cell growth on the surface



1. Elastic Modulus Mismatch → **Porous META-materials to meet the stiffness of different bone tissues**
2. Functional features → bone in-growth, other cells such as blood or nerves cells, biosensors, fixing



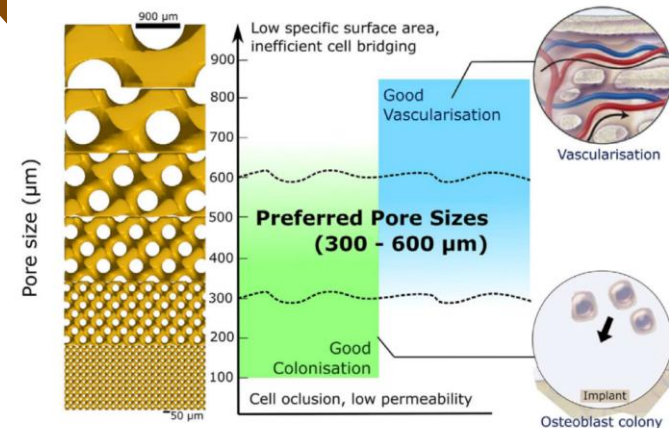
**Triple periodical minimal surfaces (TPMS)**  
 Gyroid structure  
 single cell domain with improved pore connectivity, smoother wall curvature linked to improved bone in-growth

### - Elastic Modulus Mismatch

Young's modulus of 3D-printed titanium lattice structures can be reduced even down to 1 Gpa.

Cortical Bone (Dense Bone): ~10–30 Gpa  
 Trabecular Bone (Cancellous Bone): ~0.1–2 GPa

1. 3D-printed surface is rough → good surface for cells to grow
2. 3D-printed lattice structures are porous → cells growth through the lattice
3. Lattice parameters can be optimized for optimal cell growth

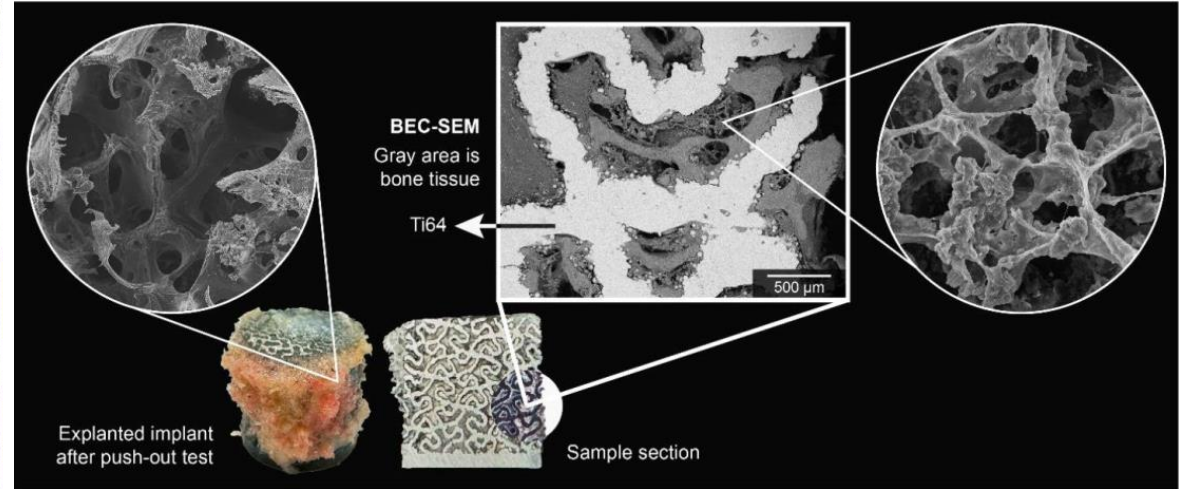


### Research question

1. Can we develop bio-stimulative features by utilizing reduced stiffness
2. Novel lattice structures for enhanced mechanical performance



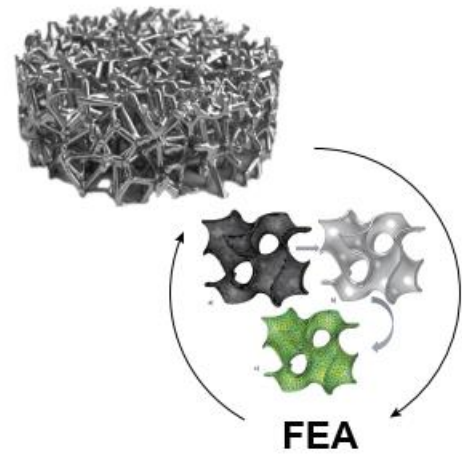
# Clinical testing in Costa Rica





# Future study: Funding being sought

## Additive Manufacturing of Smart Medical Implants with Biocompatible Coatings and Hybrid Metamaterials

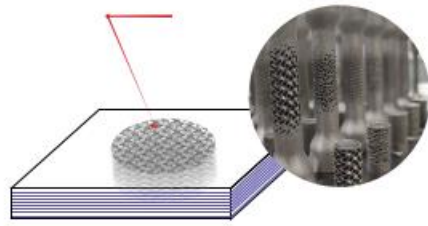


Develop detailed models of the implants with tailored Poisson's ratio and Young's modulus to mimic natural bone properties. Implement iterative FEA and Topology optimization to optimize a Young's modulus that bio-stimulate the bone tissue.

### Lattice design

- Strut based
- Surface based (TPMS)
- Auxetic
- Stochastic

Fabricate implants using Laser Powder Bed Fusion (LPBF), adjusting parameters (**laser power, scan speed, hatch spacing**) to minimize porosity and oxidation.



### Materials

- Ti6Al4V
- Ti13Ni13Zr
- Mg-alloy



### Bioactive coatings

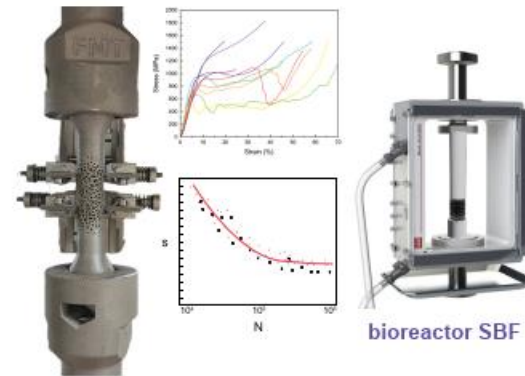
Apply biocompatible coatings to enhance osseointegration and antimicrobial properties:

- Hydroxyapatite for bone growth.
- Bioactive glass for tissue regeneration.
- Silver-based coatings for infection control.

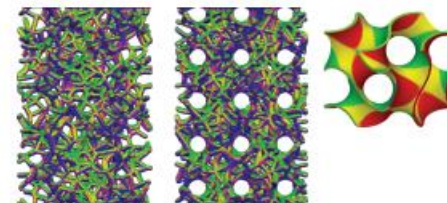
Investigate nanostructured bioinks (PCL + hydroxyapatite + bioglass) for additive bioprinting of coatings.

Conduct mechanical property tests:

- Tension, compression, fatigue, and torsion.
- Corrosion and wear resistance testing.

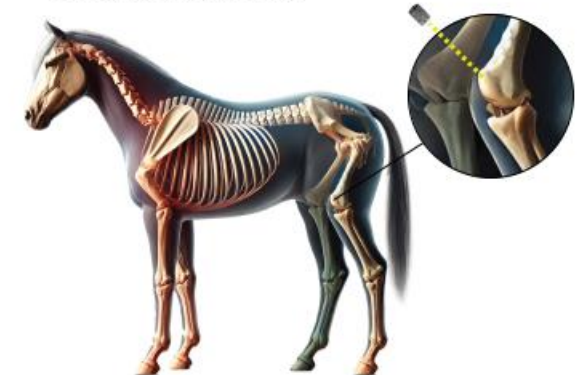


- Use micro-CT imaging to evaluate porosity and verify design integrity.



### Perform in vitro assays

- Cytotoxicity testing to assess biocompatibility.
- Cell adhesion and proliferation studies.
- Antimicrobial testing for biofilm prevention and microbial interaction.
- Utilize body fluid simulators to mimic in-body conditions during testing.



### Conduct in vivo animal studies

- Assess osseointegration, degradation rates, and inflammation response.
- Evaluate long-term biological interactions and implant functionality.
- Conduct ex-vivo biomechanical assessment to evaluate osseointegration.



**UNIVERSITY  
OF OULU**

KERTTU SAALASTI  
INSTITUTE

***Science  
With  
Arctic  
Attitude!***

**Thank you!**

**FMT**  
FUTURE MANUFACTURING  
TECHNOLOGIES

Contact Information:  
Research Director  
Antti Järvenpää  
044 555 1633  
[Antti.jarvenpaa@oulu.fi](mailto:Antti.jarvenpaa@oulu.fi)