UNIVERSITY of DERBY®

IISE
Institute for Innovation in Sustainable Engineering

Additive manufacturing of graded structures in IN718

Workshop at LSU, August, 2019

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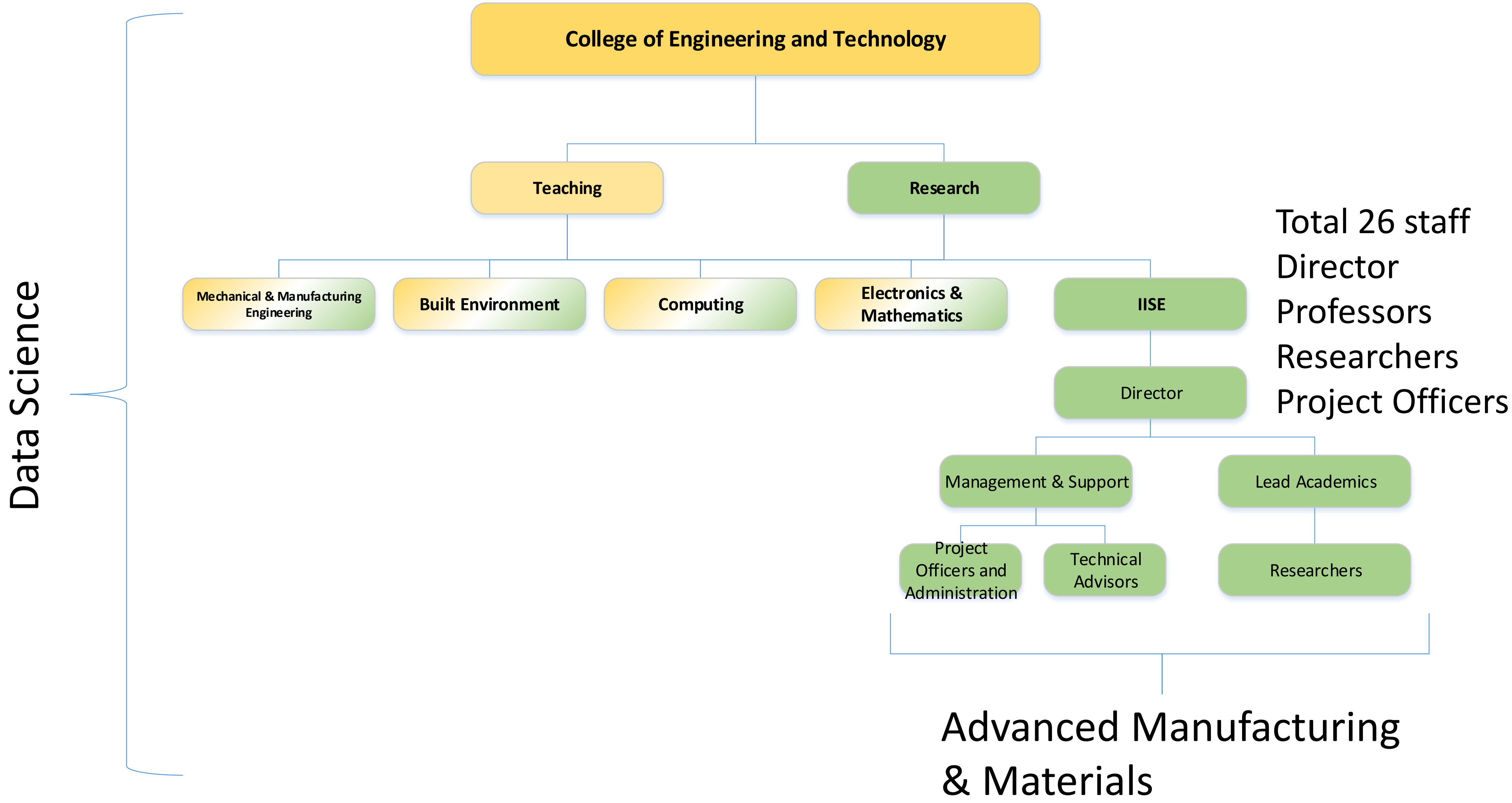
Organisational Chart



Facilities

CNC Tools

- **DMU 40 eVo**: 5axis CNC Machining Centre (18,000rpm)
- **XYZ SLX 1630**: CNC Lathe
- **Dynamometer**: Cutting force/power measurements
- **GF CUT E350: CNC** Wire cut EDM 4Axis, 820x680x250 max work piece

Additive Manufacturing

- **Renishaw AM250**: SLM Machine – 250 x 250 x 300mm
- **Renishaw 5/01**: Vacuum Casting System
- **Stratasys Polyjet 3D Printing**:
  - Objet30 Prime - 294 x 192 x 148.6 mm
  - Connex3 Objet500 - 490 x 390 x 200 mm
- **Mark Forged Composite 3D Printers**
- **Desktop FFF/FDM 3D printing**
- **Desktop SLA 3D Printing**

Facilities

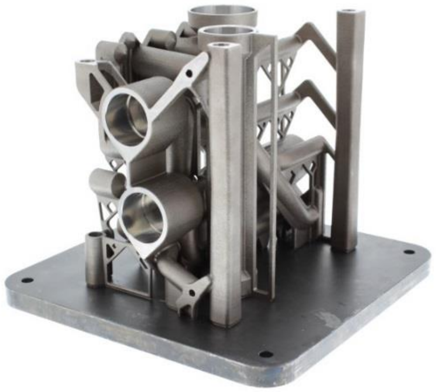
Metrology

- **Eley Metrology Truth ‘S’ CMM**: CNC CMM
- **Renishaw REVO**: 5 Axis Multi-sensor scanning system
- **Argon Heat Treatment Furnace**
- **Shimadzu AGX -Plus** : 100kN Universal Tester
- **Bowers Nexus 3200** : Brinell Hardness Tester
- **Accretech Handysurf E35B** : Portable surface roughness tester
- **3D Scanning & Reverse Engineering**: 9ft articulating measurement arm with blue-light HD 3D scanner

Design For Manufacture Software

- **Autodesk PowerSHAPE**: CAD
- **Autodesk 5-axis PowerMILL**: CAM
- **Abaqus and LS-Dyna:** FEA
- **Renishaw QuantAM**: AM build preparation
- **Solidworks:** CAD
- **Polyworks:** Inspection & Reverse Engineering

Renishaw AM250 Selective Laser Melting



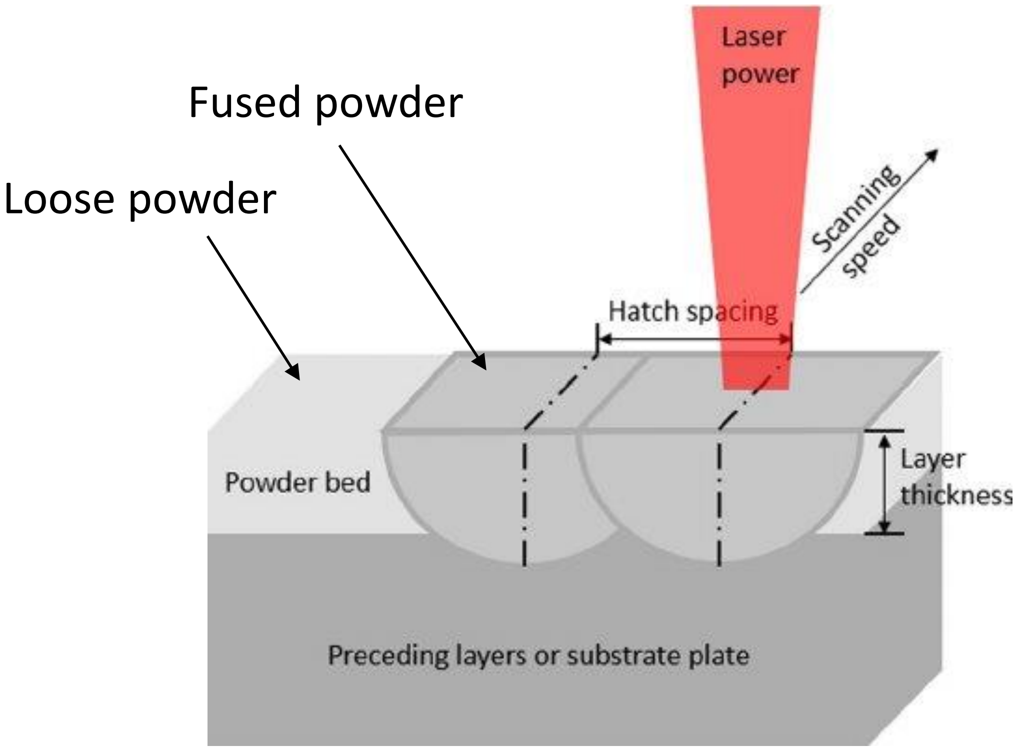
- Powder bed fusion process with laser power 250W
- Build volume (X Y Z)

  250mm x 250mm x 300mm
- Powder particle size as-supplied 15-45 microns
- Layer build resolution

  20µm - 100µm
- Inert build chamber atmosphere using Argon gas

Default SLM Process Parameters to Print Thin-Walled IN718 Structures

$$\text{Energy Density (J/mm3)} = \frac{Power(W)}{Scan\ Speed\ (mm/s) \times Hatch\ distance\ (mm) \times layer\ thickness\ (mm)}$$



Default Build Parameters	
Scan Strategy	Meander
Layer Thickness	30 µm
Focal Point	0 mm (beam focused on powder bed @ 70µm spot diameter)
Beam Compensation	0.06mm
Hatch Distance	0.09mm
Scan Speed	400 to 1000mm/s
Laser Power (Watts)	200
Exposure Time (µs) **(ET)**	20 to 70
Point Distance (µm) **(PD)**	50 to 70
Energy Density (J/mm^2)	**2.2 to 5.5 calculated from scanning speed**
	0.6 to 3.1 calculated from exposure time

Relationship between hatch spacing, point distance and laser spot size to ensure sufficient overlap and minimum porosity

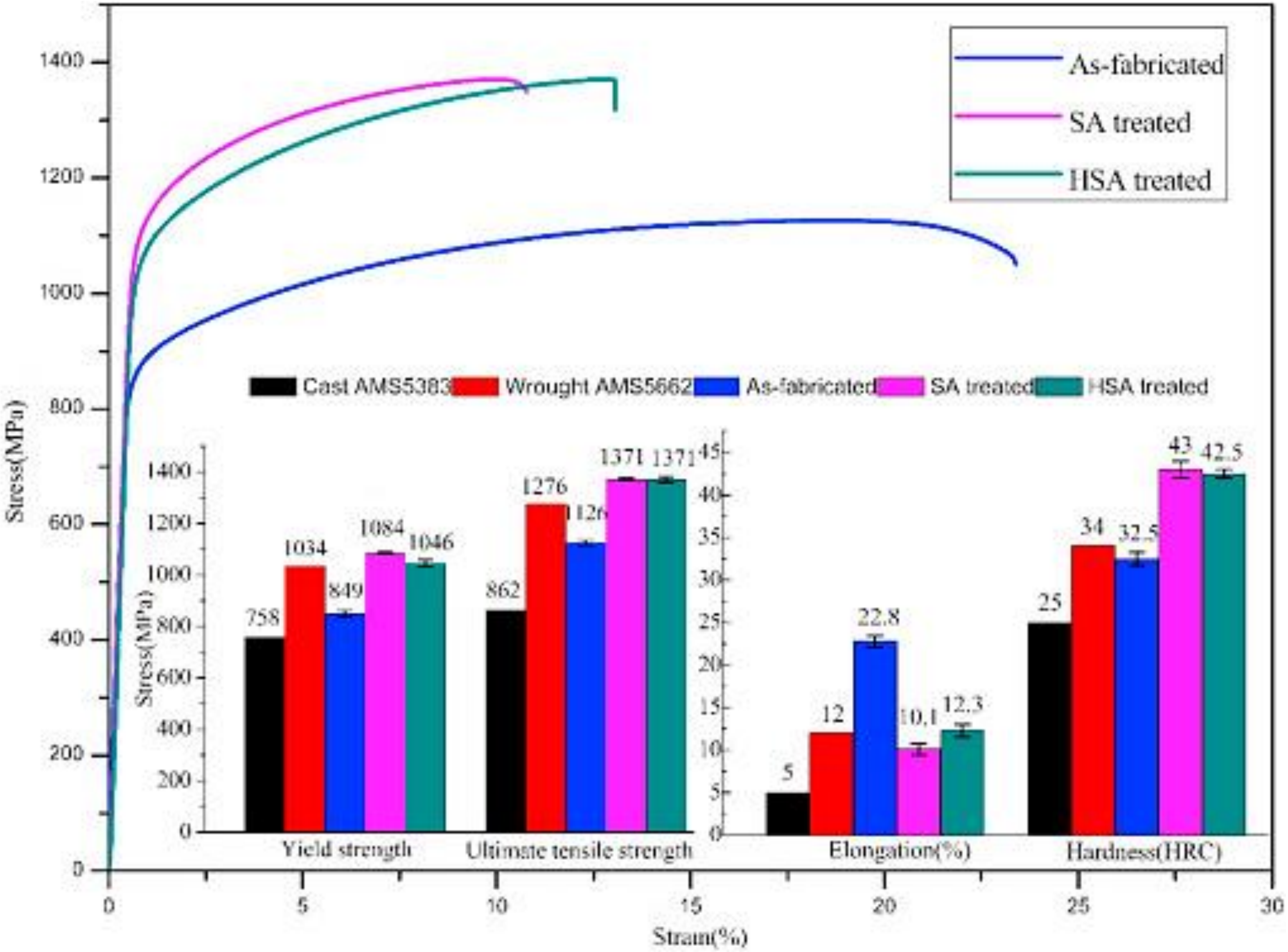
Review of SLM IN718 Process Parameters

Process parameters for SLM IN 718						
Power (W)	Scanning speed (mm/s)	Thickness (mm)	Hatch spacing (mm)	Energy Density (J/mm3)	Energy Density (J/mm2)	Ref
400	7000	0.04	0.08	17.86	0.71	Kuo et al, 2018
285	960	0.04	0.11	67.47	2.70	Seede et al, 2018
285	960	0.04	0.1	74.22	2.97	Wan et al, 2019
400	1000	0.04	0.1	100.00	4.00	Mostafa et al, 2017
175	620	0.03	0.12	78.41	2.35	Tillmann et al, 2017
90	1600	0.025	0.08	28.13	0.70	Choi et al, 2017
200	200	0.05	0.18	111.11	5.56	Konecna et al, 2016
250	700	0.05	0.12	59.52	2.98	Popovich et al, 2017
950	320	0.1	0.5	59.38	5.94	Popovich et al, 2018
100	85.7	0.05	0.16	145.86	7.29	Chlebus et al, 2015
200	200	0.05	0.18	111.11	5.56	Edwards and Ramulu, 2014

$$\text{Energy Density (J/mm3)} = \frac{Power(W)}{Scan\ Speed\ (mm/s) \times Hatch\ \text{distance}\ (mm) \times \text{layer thickness (mm)}}$$

$= 0.7 < E < 7.3$ J/mm^2
(Per unit layer thickness)

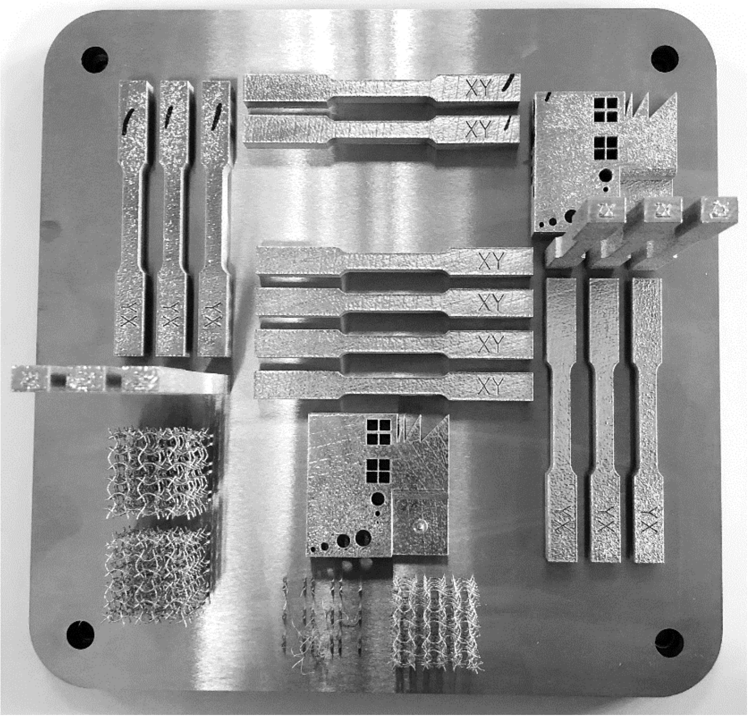
Effect of Heat Treatment on SLM IN718 Static Tensile Properties (in X direction)

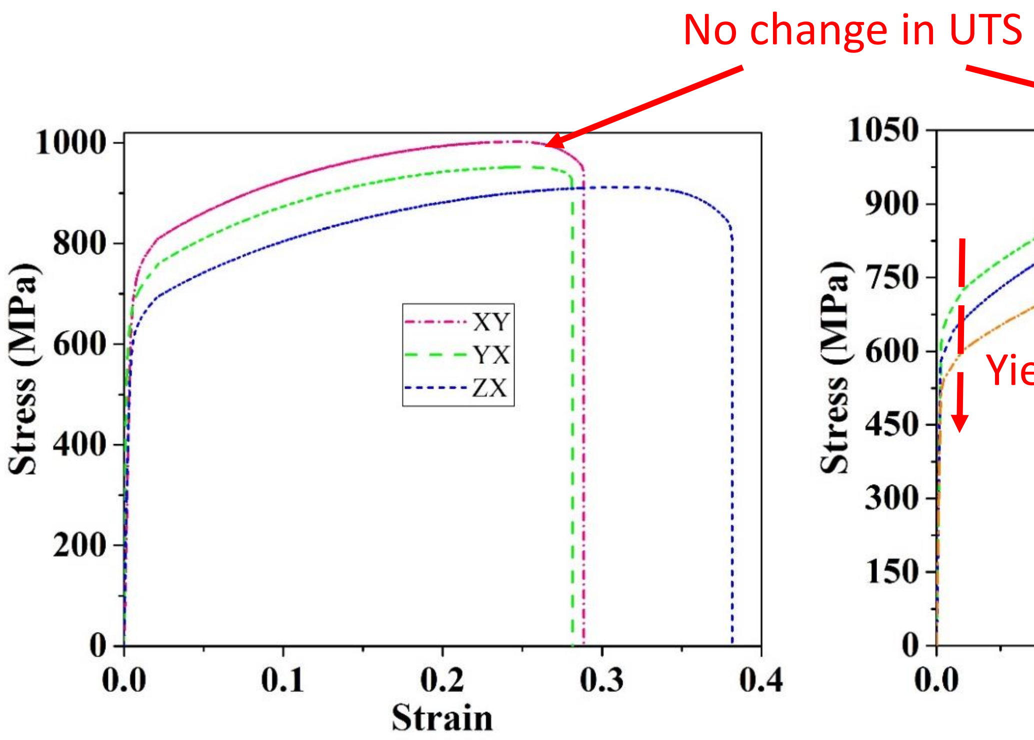


- SA: Solution + Aged
- HSA: Homogenised + Solution + Aged

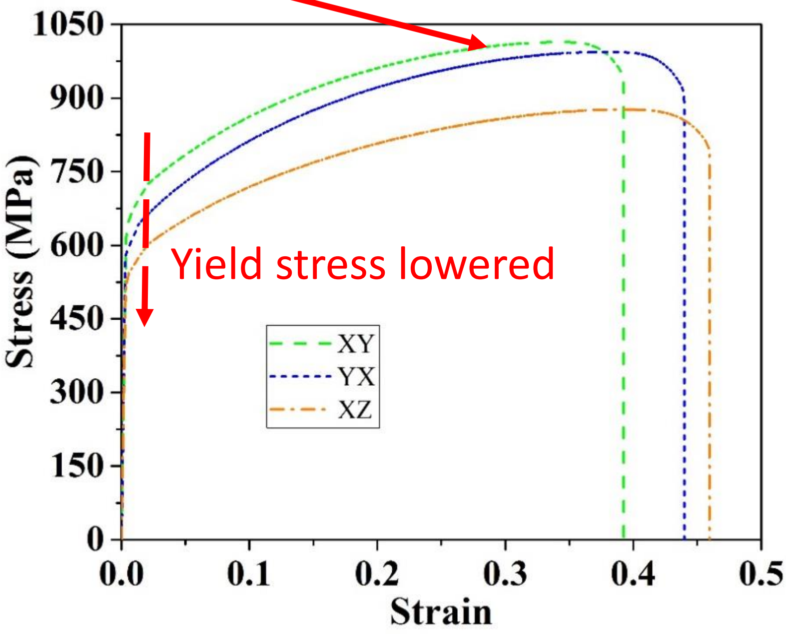
Dongyun Zhang, Wen Niu, Xuanyang Cao, Zhen Liu, Effect of standard heat treatment on the microstructure and mechanical properties of selective laser melting manufactured Inconel 718 superalloy, Materials Science and Engineering: A, Volume 644, 2015, Pages 32-40

SLM IN718 Static Tensile Properties (X, Y, Z direction)





As printed without stress relief

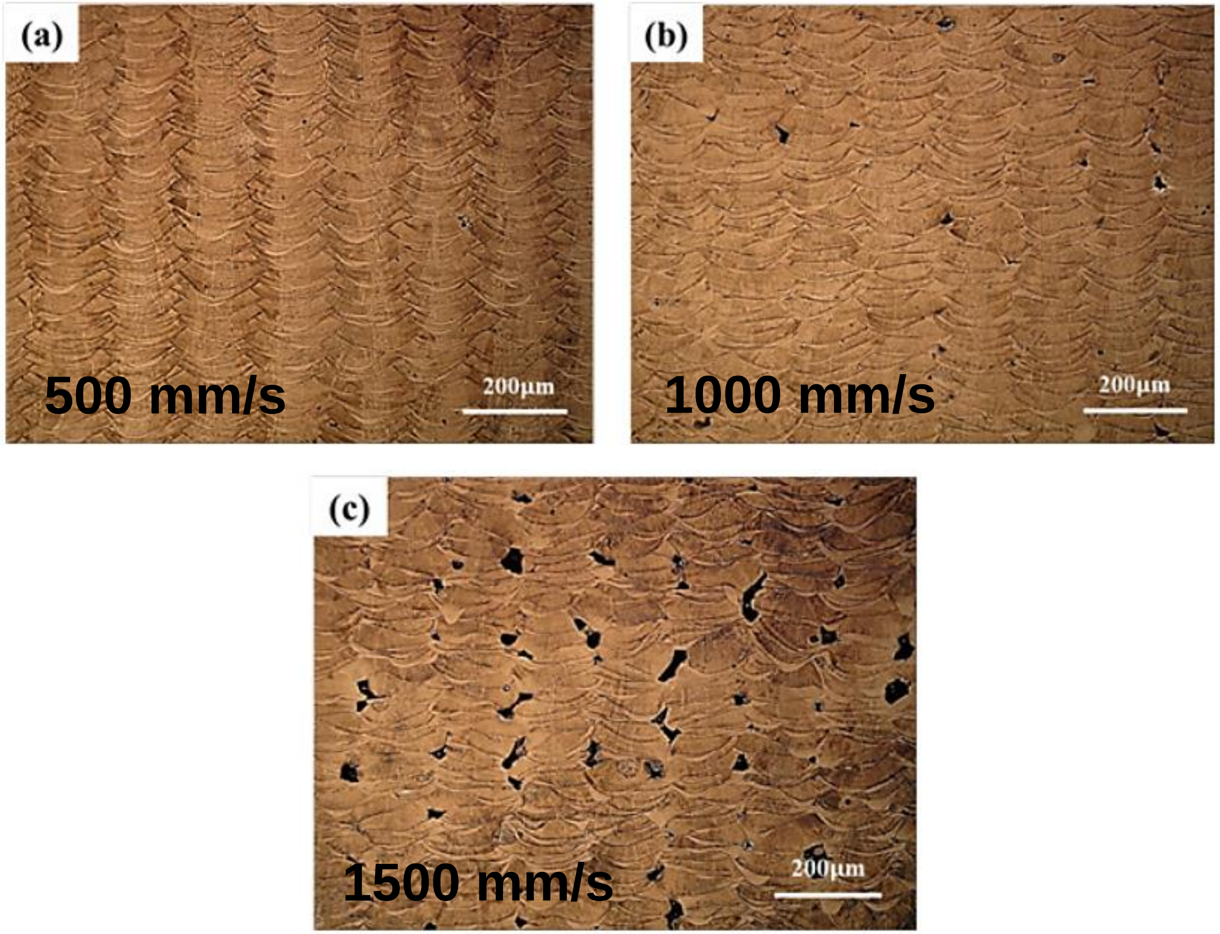


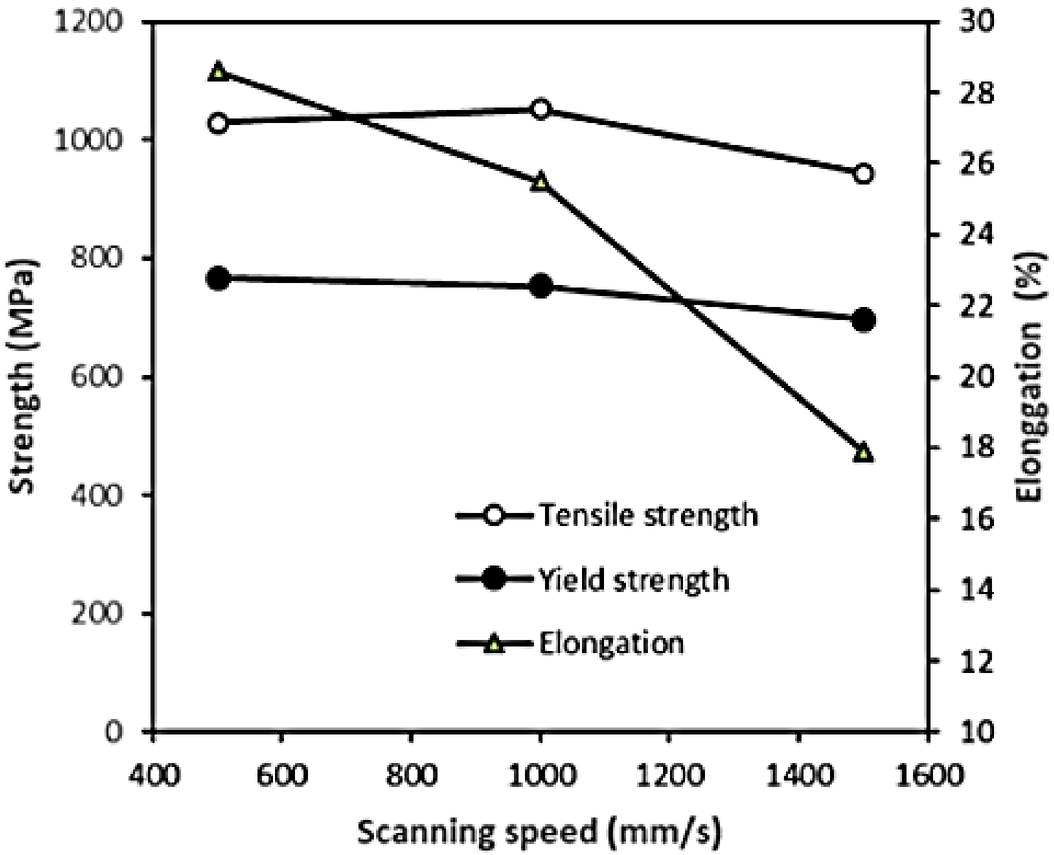
Stress-relief condition on build plate:

1) Annealed for 1 hours at 982º C.
2) Slow cool to room temperature in furnace

	XY		
	Break strain (%)	Yield stress (MPa)	UTS (MPa)
As Built	26.7 - 30.1	706 - 718	1002 - 1008
Stress Relieved	39.2 - 40.2	651 - 653	1014 - 1015

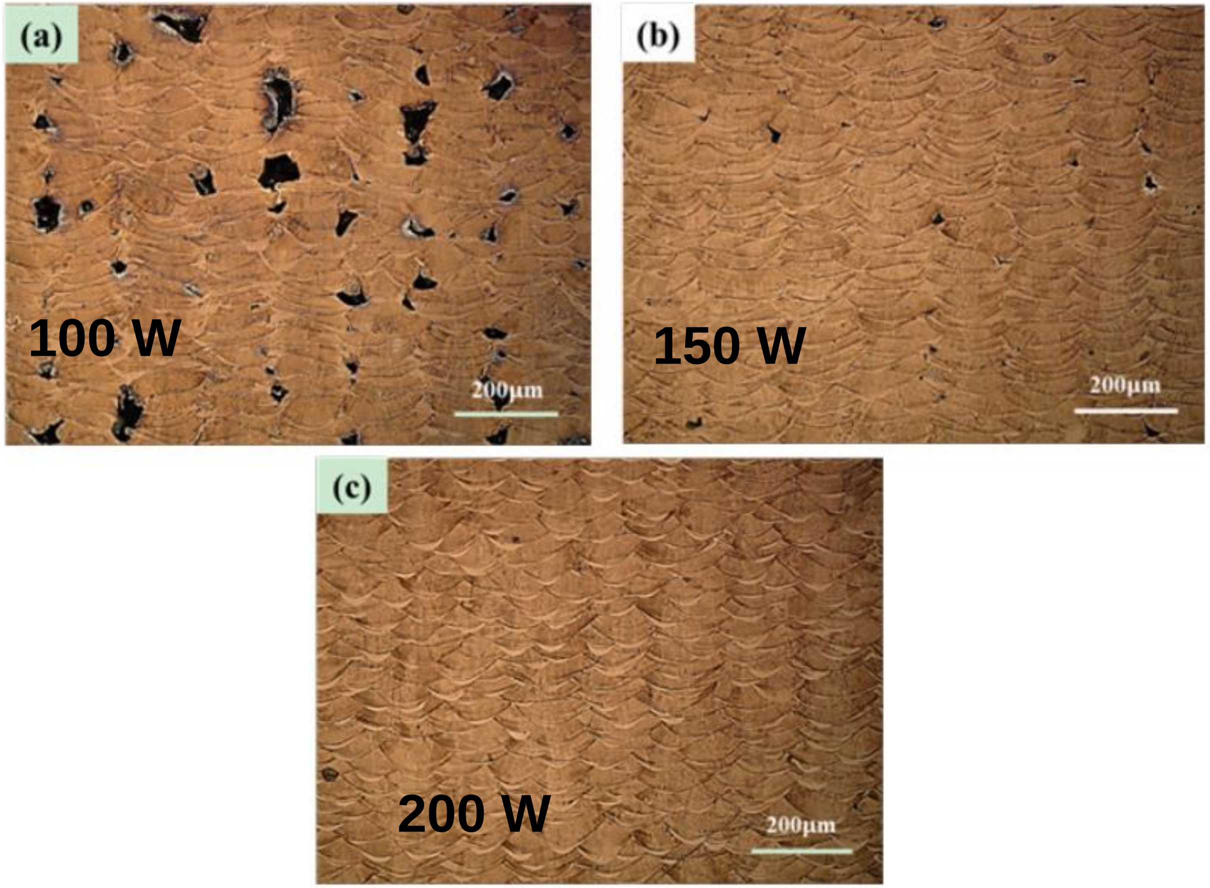
SLM IN718 : Effect of Scanning Speed on Microstructure and Properties Using 150 W Laser Power

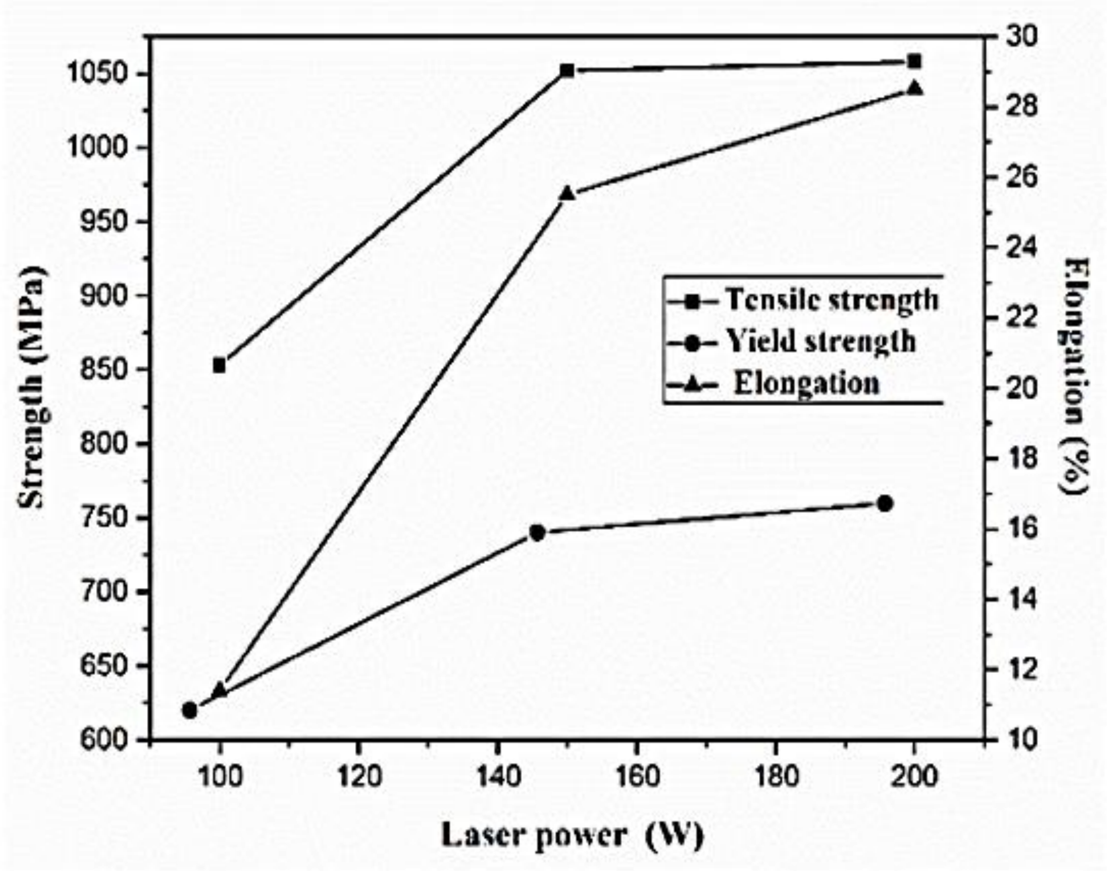




Kang JW, Yi JH, Wang TJ, et al. Effect of laser power and scanning speed on the microstructure and mechanical properties of SLM fabricated Inconel 718 specimens. Material Sci & Eng. 2019;3(3):72–76. DOI: 10.15406/mseij.2019.03.0009

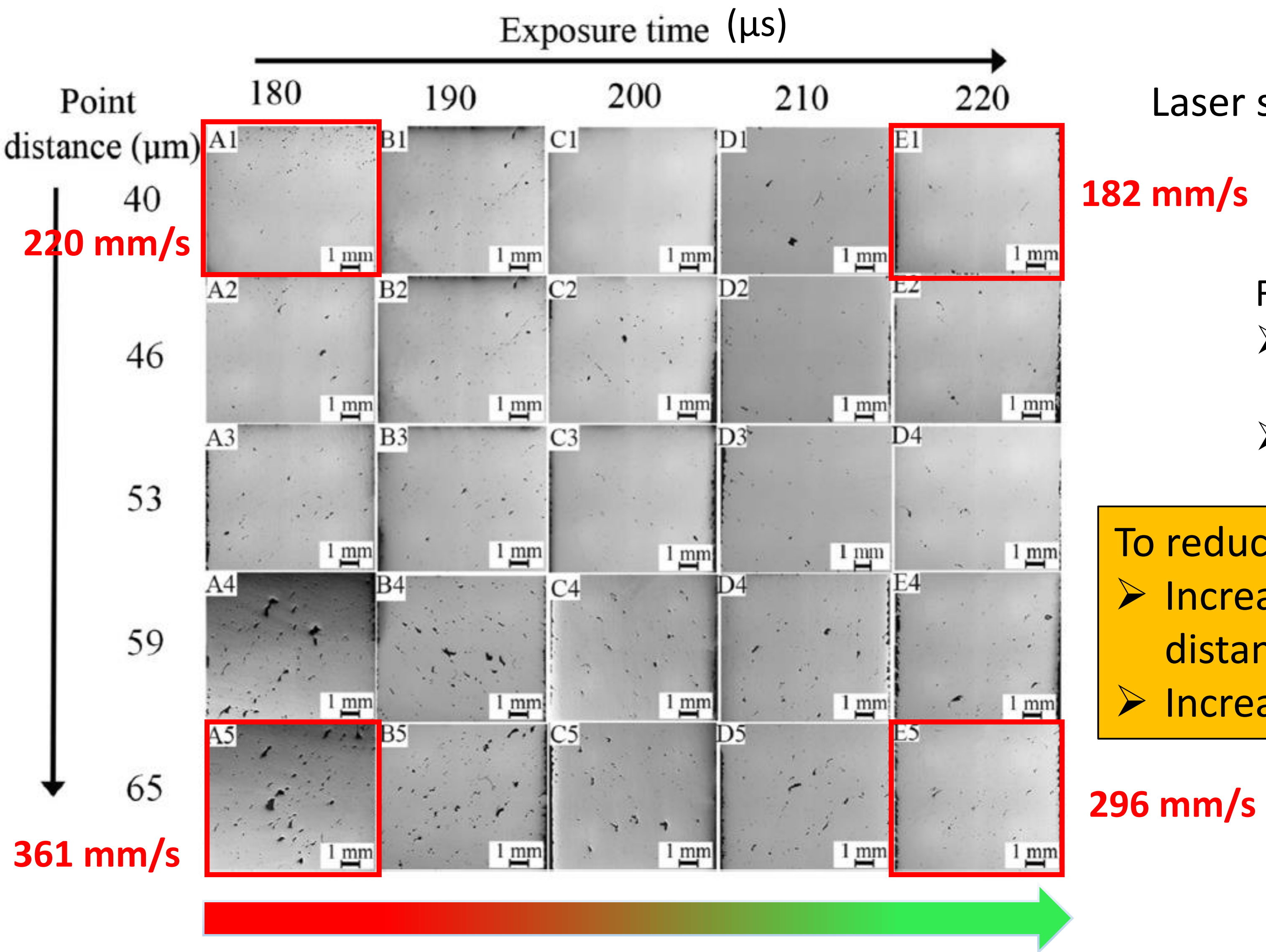
SLM IN718 : Effect of Laser Power at 1000 mm/s Scanning Speed





Kang JW, Yi JH, Wang TJ, et al. Effect of laser power and scanning speed on the microstructure and mechanical properties of SLM fabricated Inconel 718 specimens. Material Sci & Eng. 2019;3(3):72–76. DOI: 10.15406/mseij.2019.03.0009

Effects of Exposure Time and Point Distance



Laser scanning Speed = $\frac{\text{Point Distance}}{\text{Exposure Time}}$

Fixed Build Process Parameters

- Laser Power : 200W
  Layer Thickness : 0.075 mm
- Hatch Distance: 0.1 mm

To reduce porosity:

- Increase exposure time with fixed point distance to reduce laser scanning speed
- Increase laser power

Karimi, P., Raza, T., Andersson, J. et al. Int J Adv Manuf Technol (2018) 94: 2199. https://doi.org/10.1007/s00170-017-1019-1

SLM Build Process Parameters for IPPT Random Lattice Structure in IN718

Build Parameters	Set A	Set B
Scan Strategy	Meander	
Layer Thickness	30 µm	
Focal Point	0mm (beam focused on powder bed @ 70µm spot diameter)	
Beam Compensation	0.06mm	
Hatch Distance	0.09mm	
Scan Speed	400 to 1000mm/s	
Laser Power (Watts)	200	175
Exposure Time (µs)	20 to 70	164
Point Distance (µm)	50 to 70	50 to 70
Energy Density (J/mm^2)	**2.2 to 5.5**	**1.9 to 4.9 scanning speed**
	0.6 to 3.1	**4.5 to 6.4 exposure time**

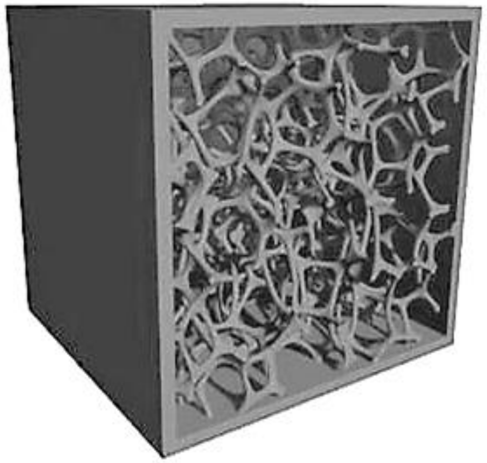
Set A = Default build parameters

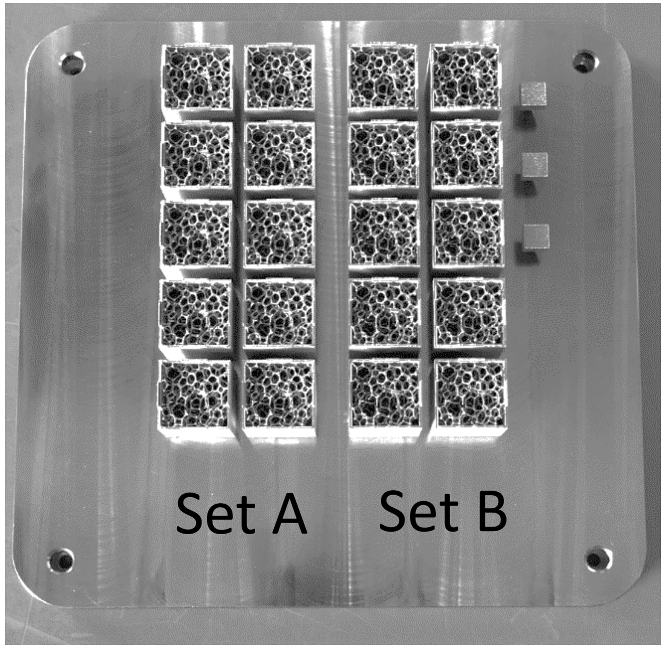
Set B = Modified build parameters to reduce micro porosity in ligaments of IN718 auxetic structures

- *Increased exposure time (reduced laser scanning speed)*
- *Higher energy density based on increased exposure time*

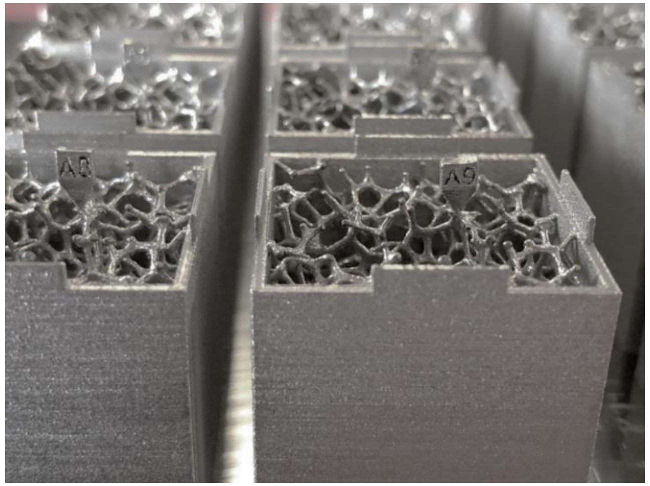
SLM Random Lattice Structure in IN718

Printed, stress relieved on build plate and wire cut

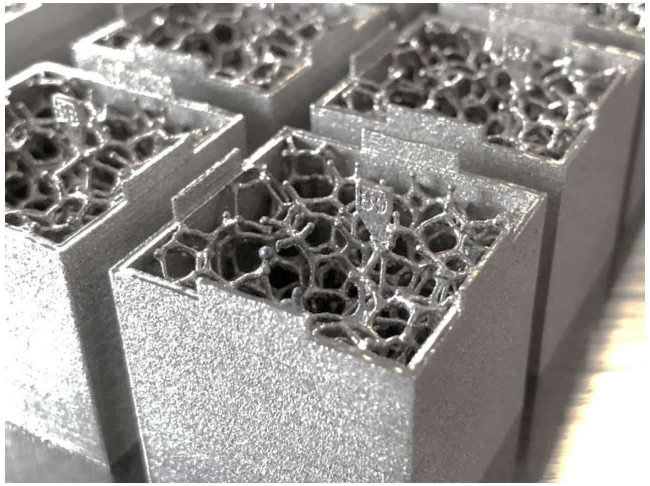




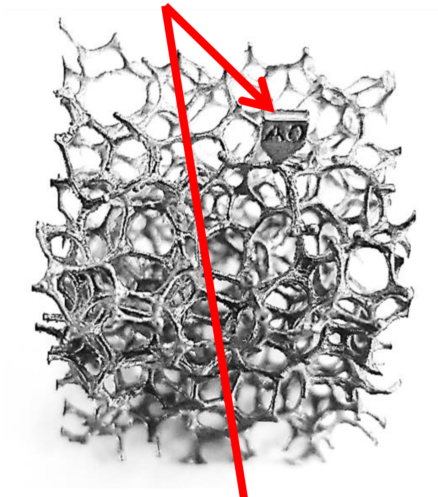
Set A

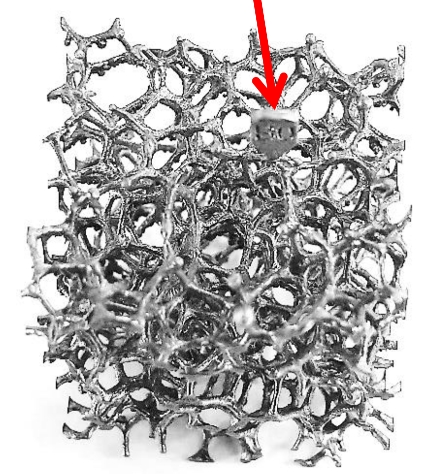


Set B

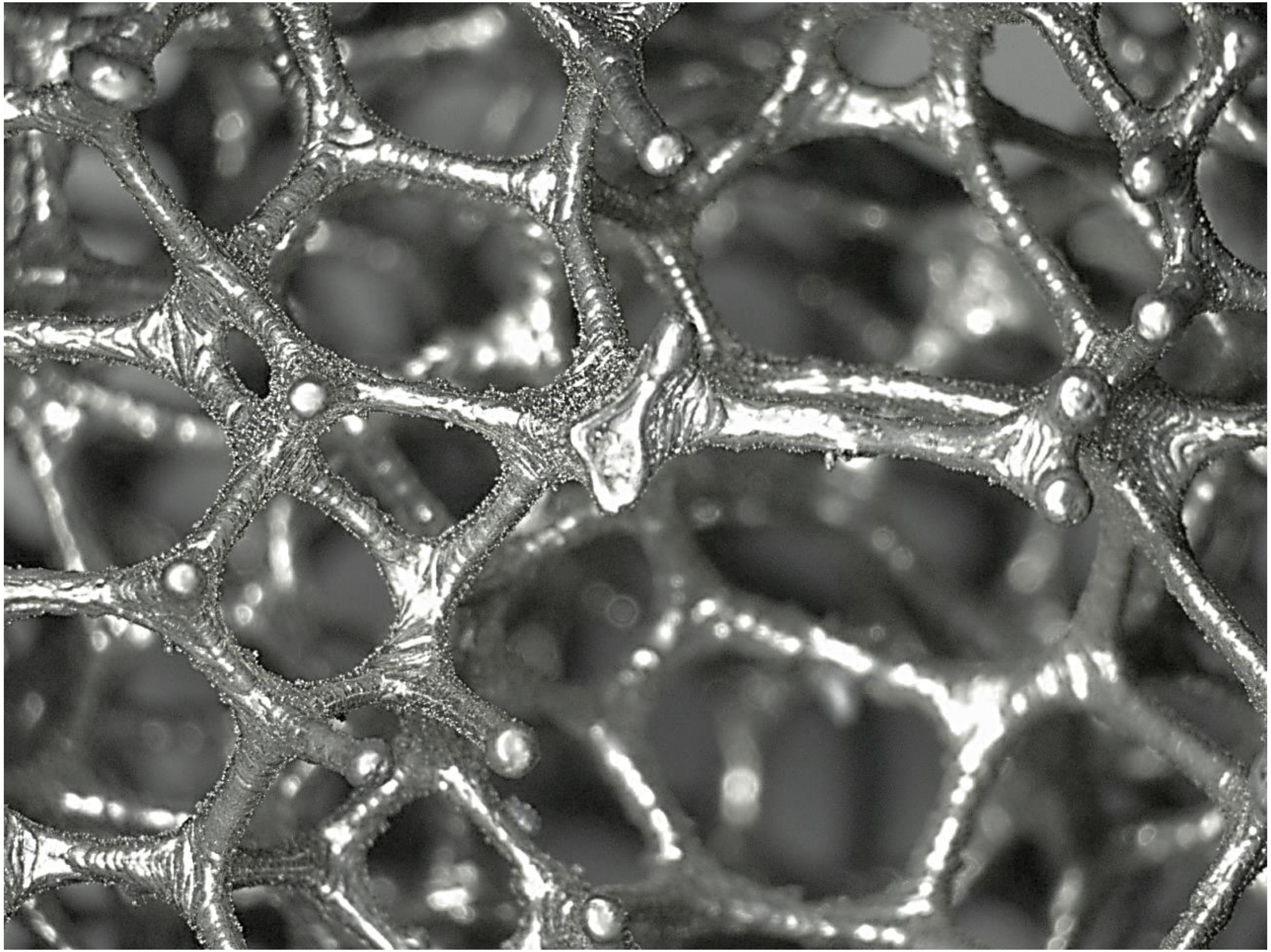


Unique print identifier



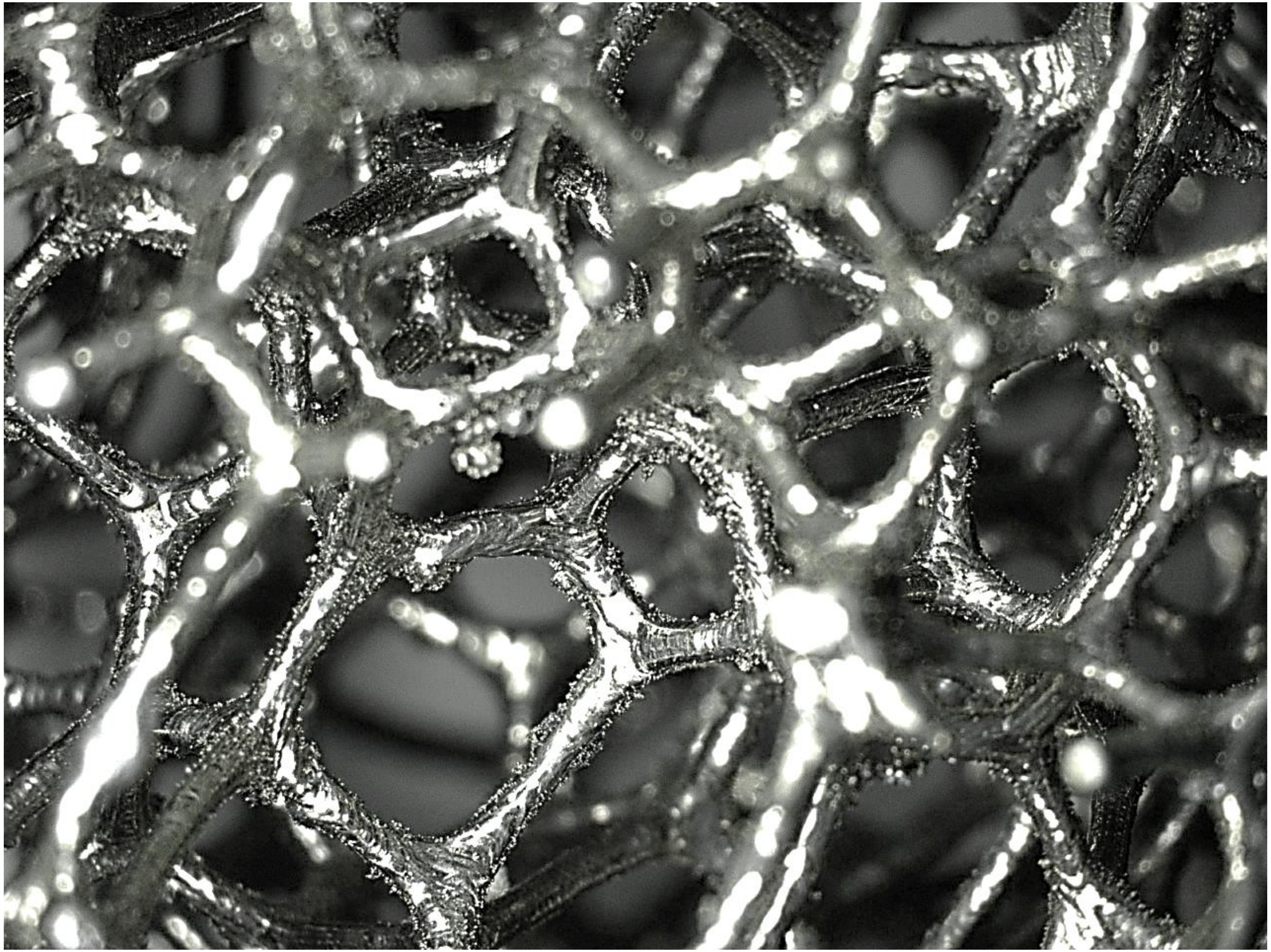


SLM Random Lattice Structure in IN718 – SET A



Laser Power (Watts)	200
Exposure Time (µs)	20 to 70

SLM Random Lattice Structure in IN718 – SET B

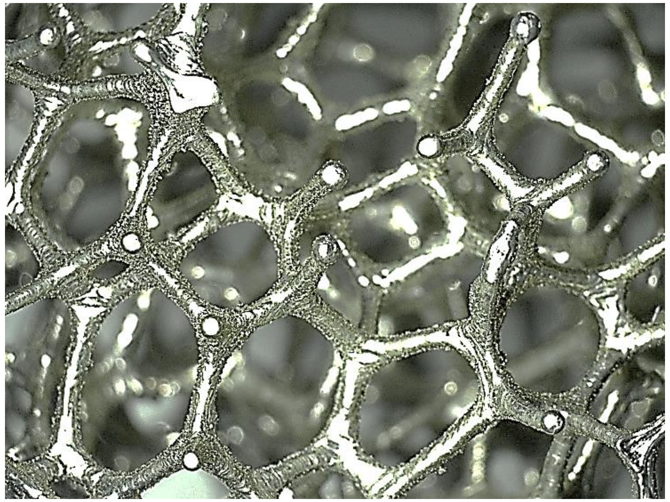


Laser Power (Watts)	175
Exposure Time (µs)	164

SLM Random Lattice Structure in IN718

Set A

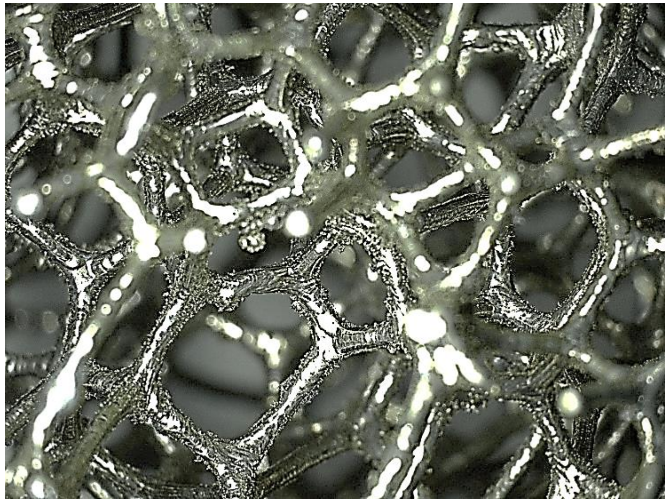
Laser Power (Watts)	200
Exposure Time (µs)	20 to 70



- Thinner struts
- Smoother surface
- Lighter

Set B

Laser Power (Watts)	175
Exposure Time (µs)	164

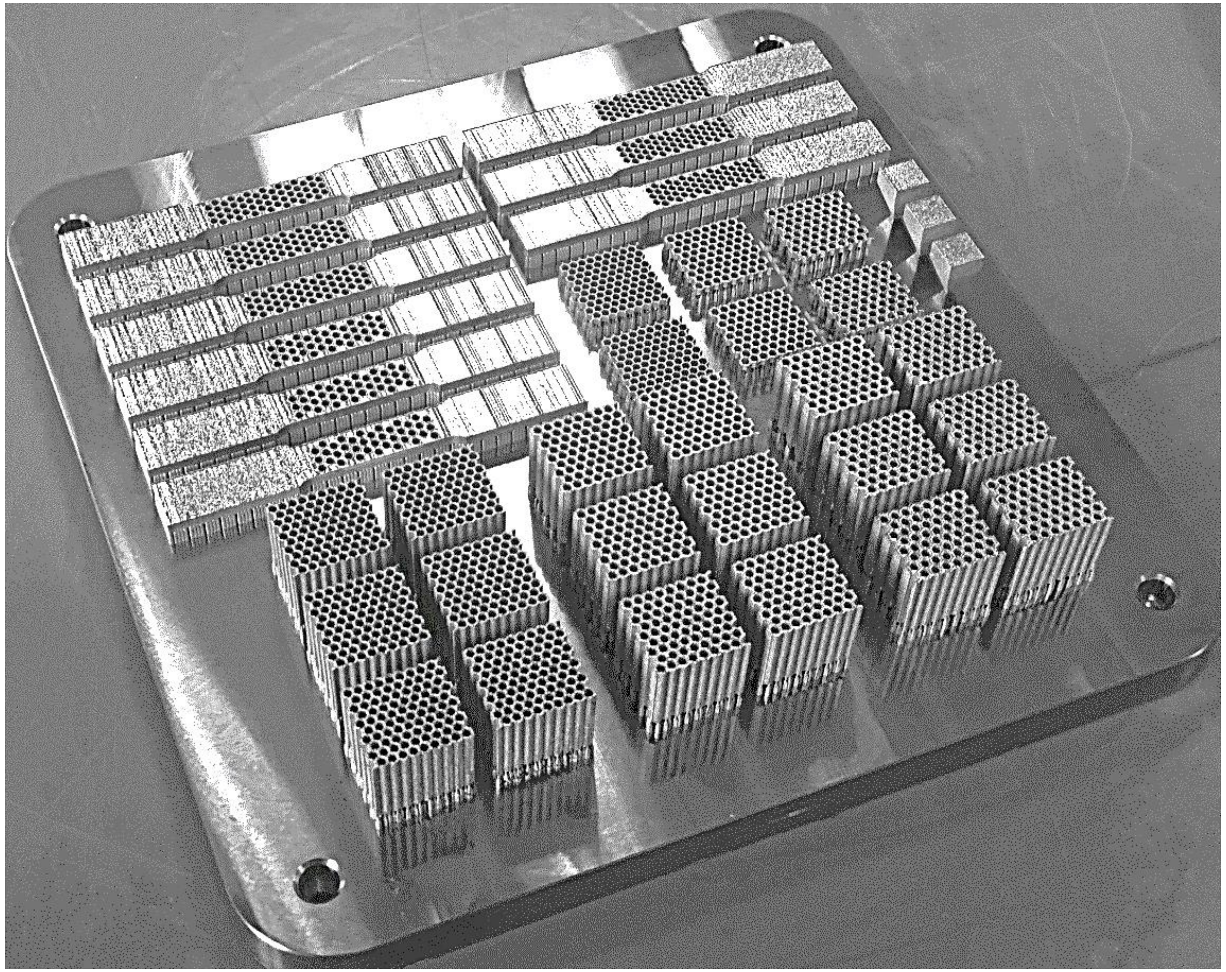


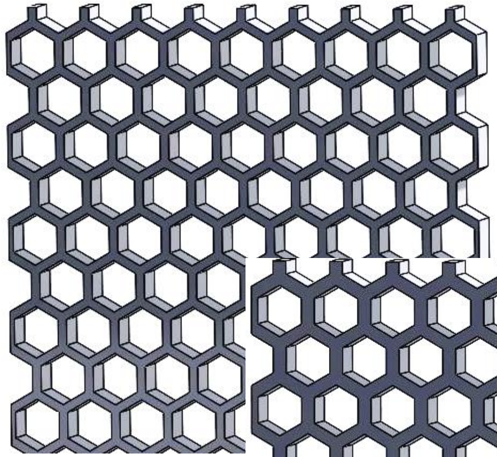
- Thicker struts
- Rougher surface
- Heavier

SLM graded lattice structures in IN718 with hexagonal cell topology for LSU

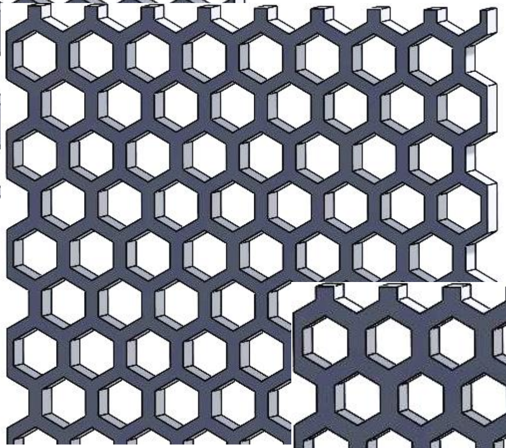
Printed, stress relieved on build plate and wire cut

SLM - Default Build Parameters

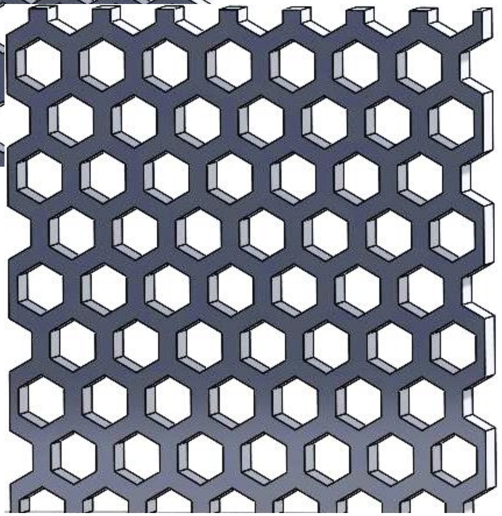




Ligament Thickness : 0.4 mm



Ligament Thickness : 0.6 mm

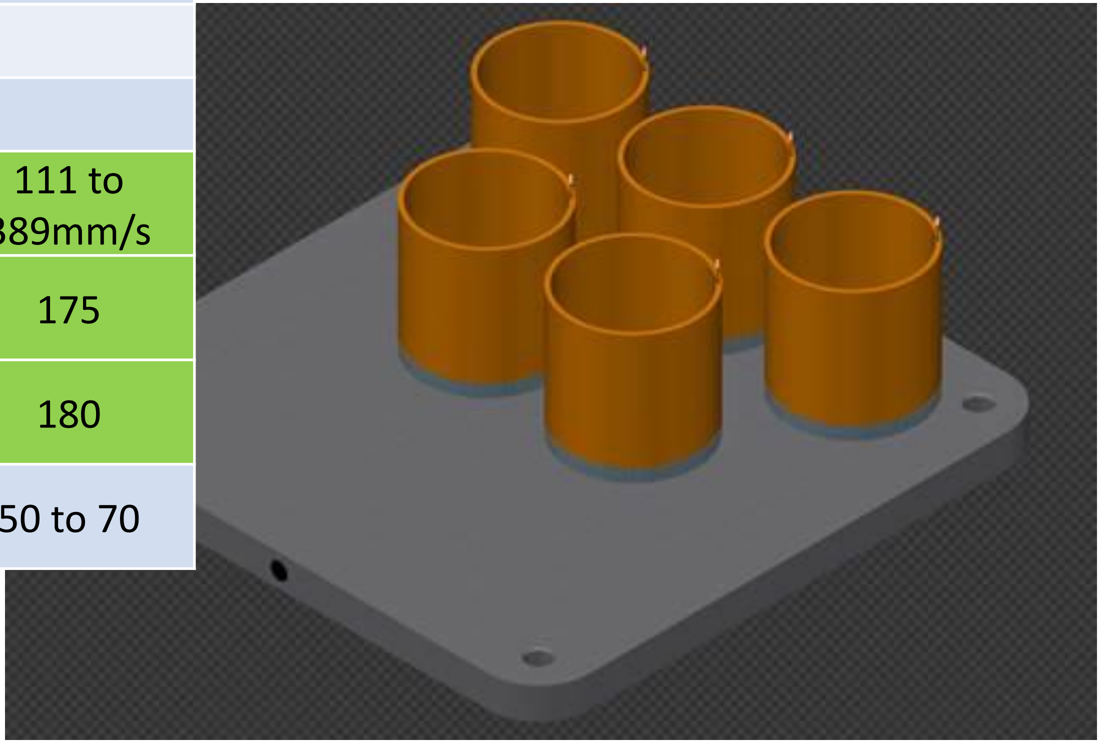


Ligament Thickness : 0.8 mm

SLM Tubes in IN718 for UC3M with graded micro porosity

Printed, stress relieved on build plate and wire cut

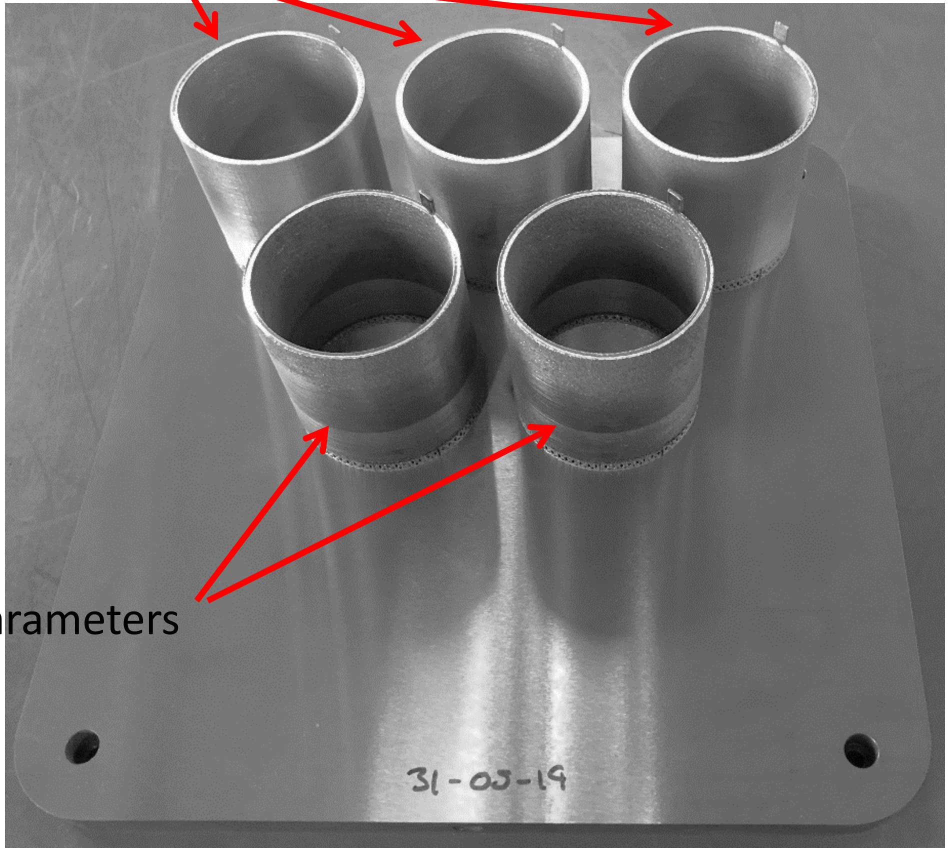
Build Parameters	Tube A	Tube B	Tube C	Tube D	Tube E
Scan Strategy	Meander				
Layer Thickness	30µm				
Focal Point	0mm (beam focused on powder bed @ 70µm spot diameter)				
Beam Compensation	0.06mm				
Hatch Distance	0.09mm				
Scan Speed	400 to 1000m/s	400 to 1000m/s	400 to 1000m/s	133 to 467mm/s	111 to 389mm/s
Laser Power (W)	200 (Default)	200 (Default)	200 (Default)	175	175
Exposure Time (µs)	20 to 70 (Default)	20 to 70 (Default)	20 to 70 (Default)	150	180
Point Distance (µm)	50 to 70 (Default)	50 to 70 (Default)	50 to 70 (Default)	50 to 70	50 to 70



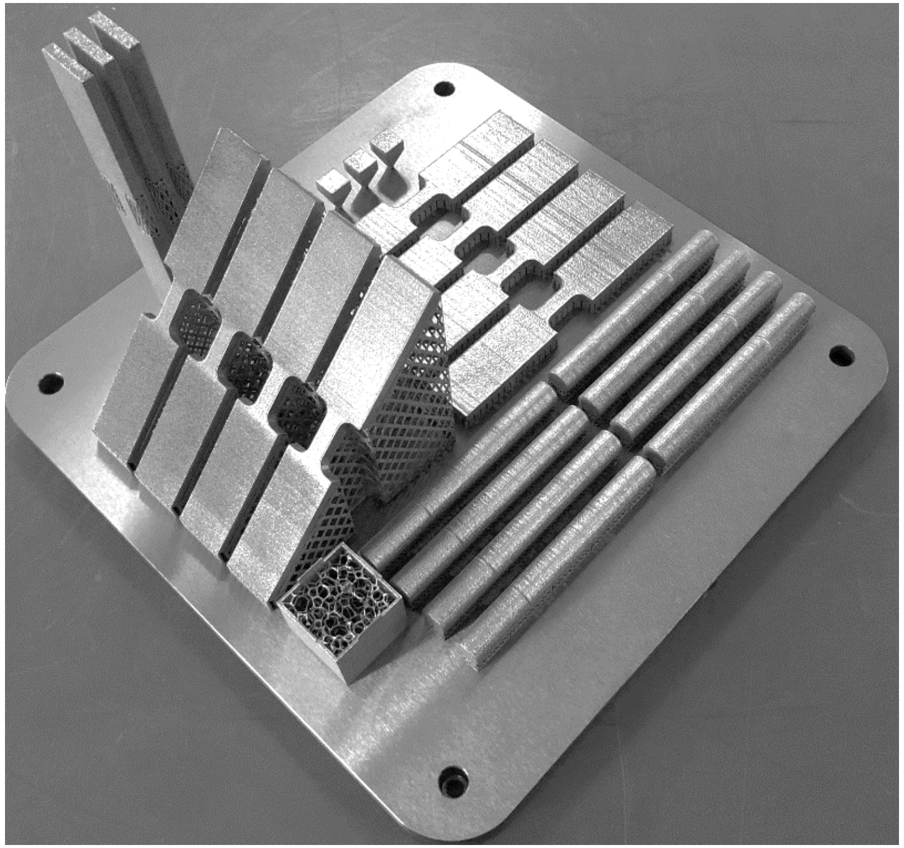
SLM Tubes in IN718 for UC3M with graded micro porosity

Printed, stress relieved on build plate and wire cut

Default Parameters



Modified Parameters

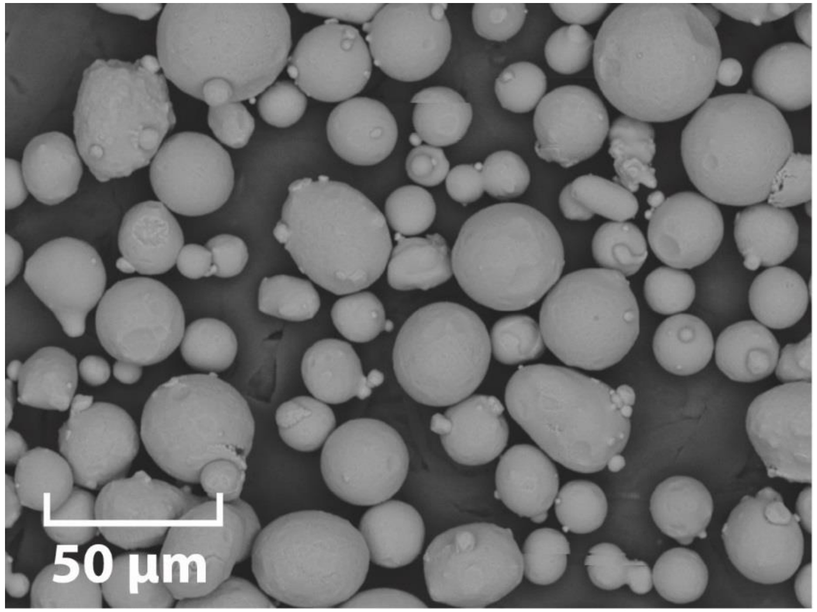


3 variations in SLM build Parameters x 2 build plates (total 10 tubes)

All Default Parameters

IN718 Powder Specifications for SLM

- IN718 powder supplied is in the range 15um to 45um particle size
- Powder bed fusion process combines new and recycled powder



- Composition of IN718 new powder stock

Fe	Al	B	C	Ca	Co	Cr	Mo	N	Nb+Ta	NI	O	P	S	Mn	Si	Ti	Cu	Mg	Se
Bal	0.30 to 0.70	0.01	0.02 to 0.08	0.01 max	1.00 Max	17.00 to 21.00	2.80 to 3.30	0.03 Max	4.75 to 5.50	50.00 to 55.00	0.03 Max	0.015 Max	0.015 Max	0.35 Max	0.35 Max	0.75 to 1.15	0.30 Max	0.01 Max	0.005 Max

Elements needed to precipitate the secondary strength hardening phases following heat treatment

Microstructure of SLM IN718

Main matrix phase is Nickel (γ) which is stable austenite with a FCC crystal structure

Strength hardening phases;

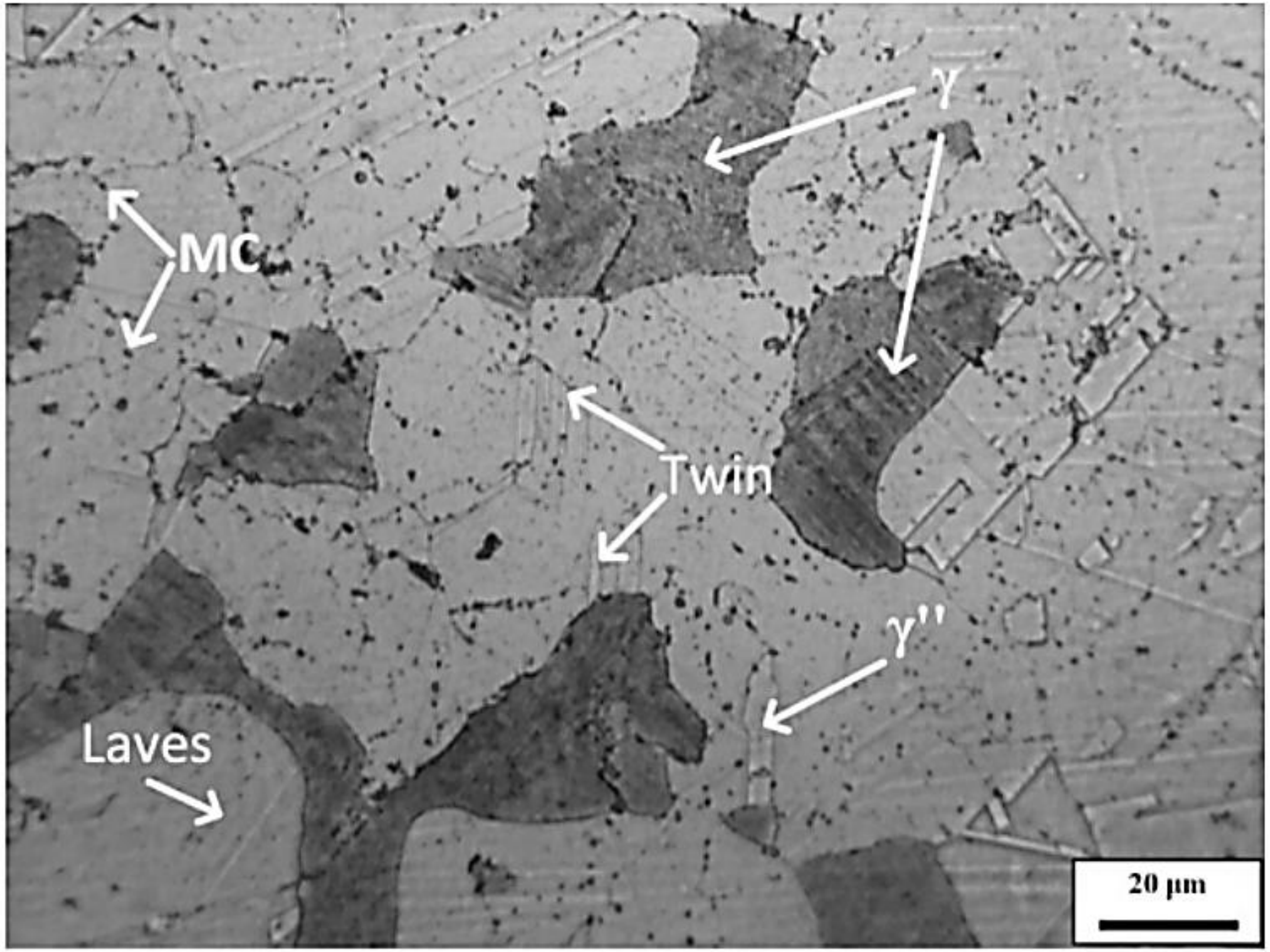
γ “ (requires addition of Al + Ti + Nb + heat treatment)

γ ‘ (requires addition of Al + Ti + heat treatment)

Brittle phases;

- Laves phase - high Nb content intermetallic
- δ phase - orthorhombic crystals incoherent with austenite matrix
- Higher laser power increases brittle phases in matrix

➢ Post fabrication heat treatment needed to optimise microstructure and phases in IN718



- Peeyush Nandwana, Amy M. Elliott, Derek Siddel, Abbey Merriman, William H. Peter, Sudarsanam S. Babu, Powder bed binder jet 3D printing of Inconel 718: Densification, microstructural evolution and challenges☆, Current Opinion in Solid State and Materials Science, Volume 21, Issue 4, 2017, Pages 207-218
- V.A. Popovich, E.V. Borisov, A.A. Popovich, V.Sh. Sufiiarov, D.V. Masaylo, L. Alzina, Functionally graded Inconel 718 processed by additive manufacturing: Crystallographic texture, anisotropy of microstructure and mechanical properties, Materials & Design, Volume 114, 2017, Pages 441-449

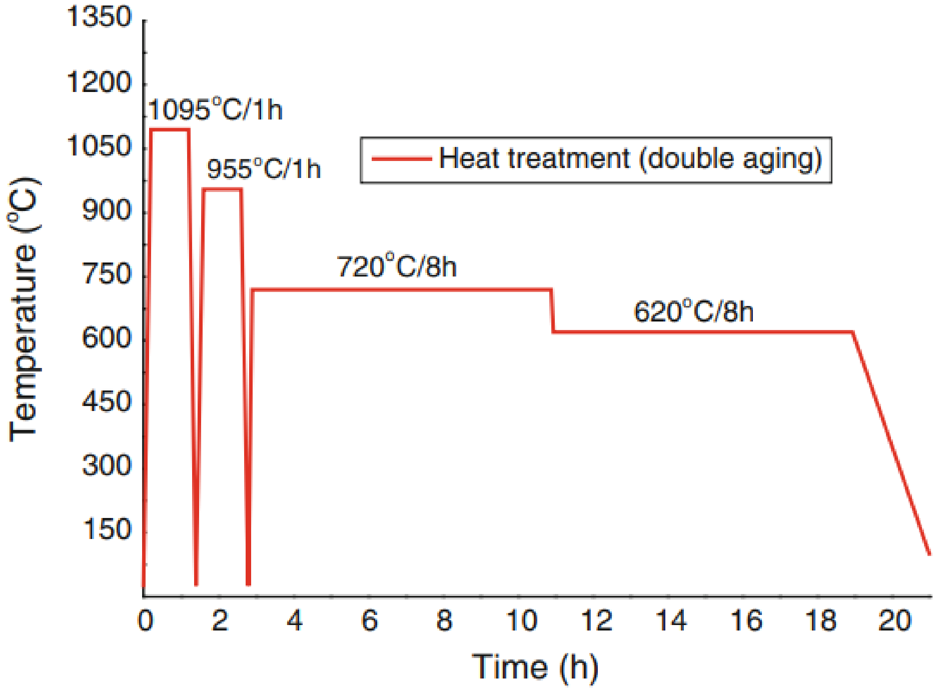
Heat Treatment of IN718

Precipitation hardening heat treatment improves microstructure of alloy which increases high temperature strength and toughness

Two steps for a IN718 alloy: solid solution (anneal) followed by an aging treatment

Heat treatment process for SLM IN718

- *Solution treatment to dissolve* γ'', γ' and brittle phases
- *Age hardening to g*enerate a more uniform and fine dispersion of strengthening phases γ'', γ' in the γ matrix
- *HIP to d*issolve laves, δ-phase and reduce pores



Double Aging following Solution Anneal (2015) in IN718 wrought alloy has shown to enhance the formation of both γ' and γ'' secondary phases and reduce content of brittle phases

K.N. Amato, S.M. Gaytan, L.E. Murr, E. Martinez, P.W. Shindo, J. Hernandez, S. Collins, F. Medina, Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting, Acta Materialia, Volume 60, Issue 5,

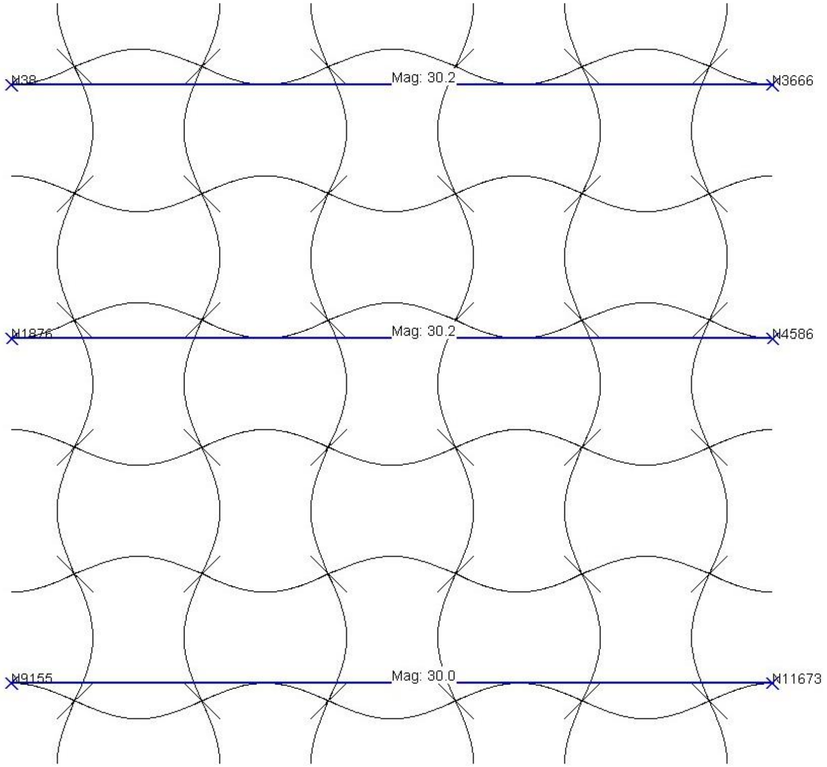
Lakshmi L. Parimi, Ravi G. A., Daniel Clark, Moataz M. Attallah, Microstructural and texture development in direct laser fabricated IN718, Materials Characterization, Volume 89, 2014, Pages 102-111

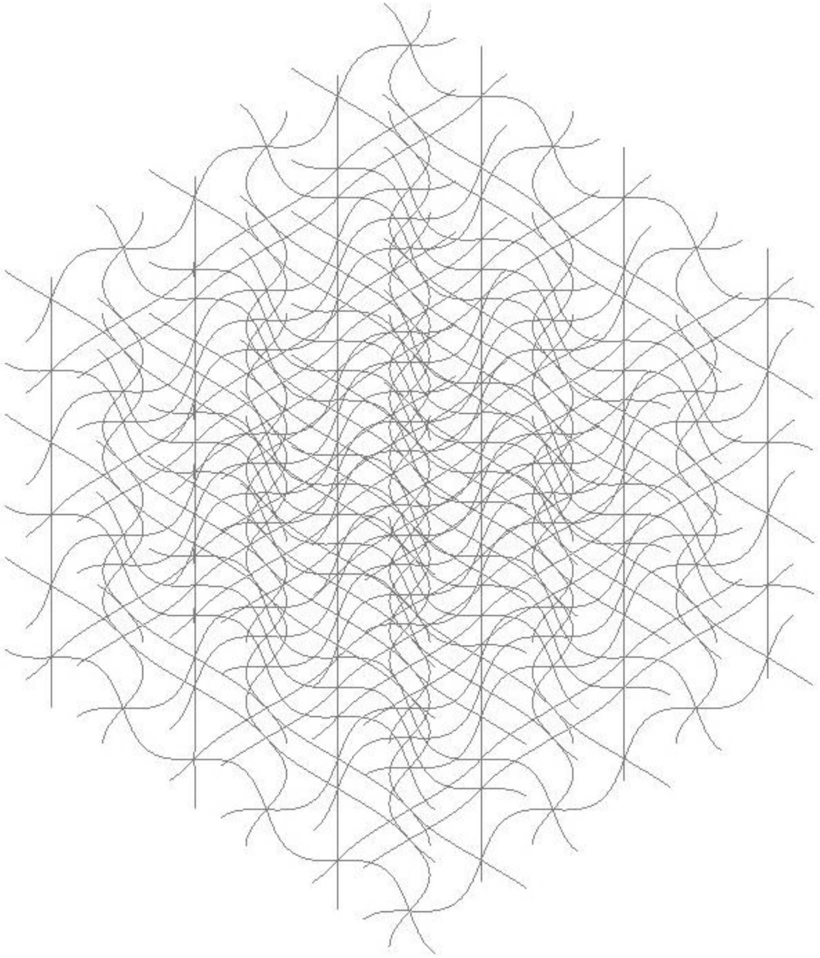
V.A. Popovich, E.V. Borisov, A.A. Popovich, V.Sh. Sufiiarov, D.V. Masaylo, L. Alzina, Impact of heat treatment on mechanical behaviour of Inconel 718 processed with tailored microstructure by selective laser melting, Materials & Design, Volume 131, 2017, Pages 12-22

Modelling of a 3D Auxetic Structure in IN718 Alloy

Cube dimensions:

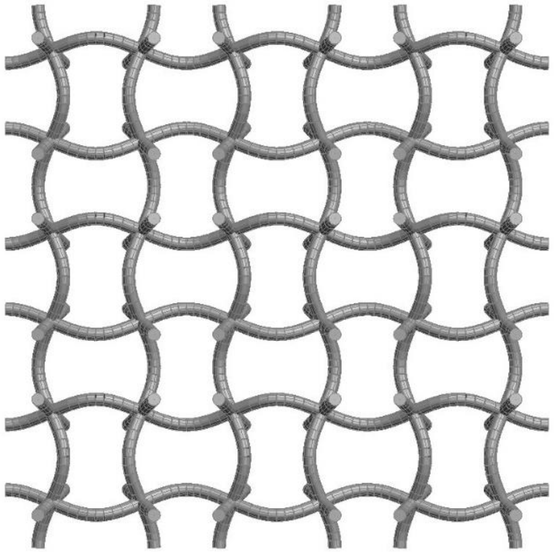
3 x 3 x 3 cm

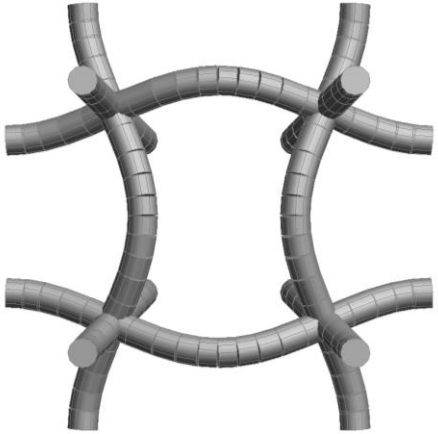


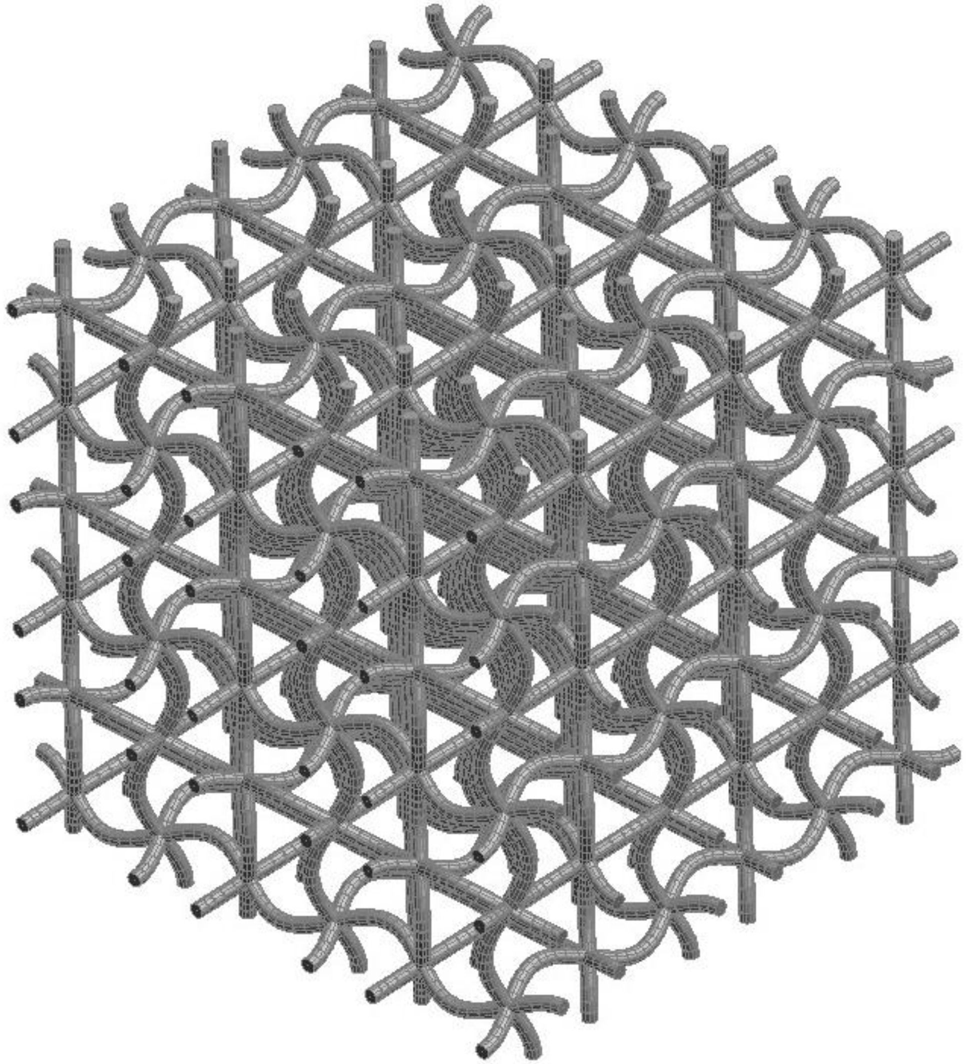


Use of Beam Elements* to Define Ligament Geometry

- Ease of manipulating the ligament thickness or diameter in keyword card and quick run time compared to solids
- Can measure non-linear properties e.g. negative Poisson ratio, under stable plastic collapse
- Can identify the energy absorbing and stabilising features in ligaments and associated strain rates under dynamic load
- Identify cell shapes that lead to premature lock up



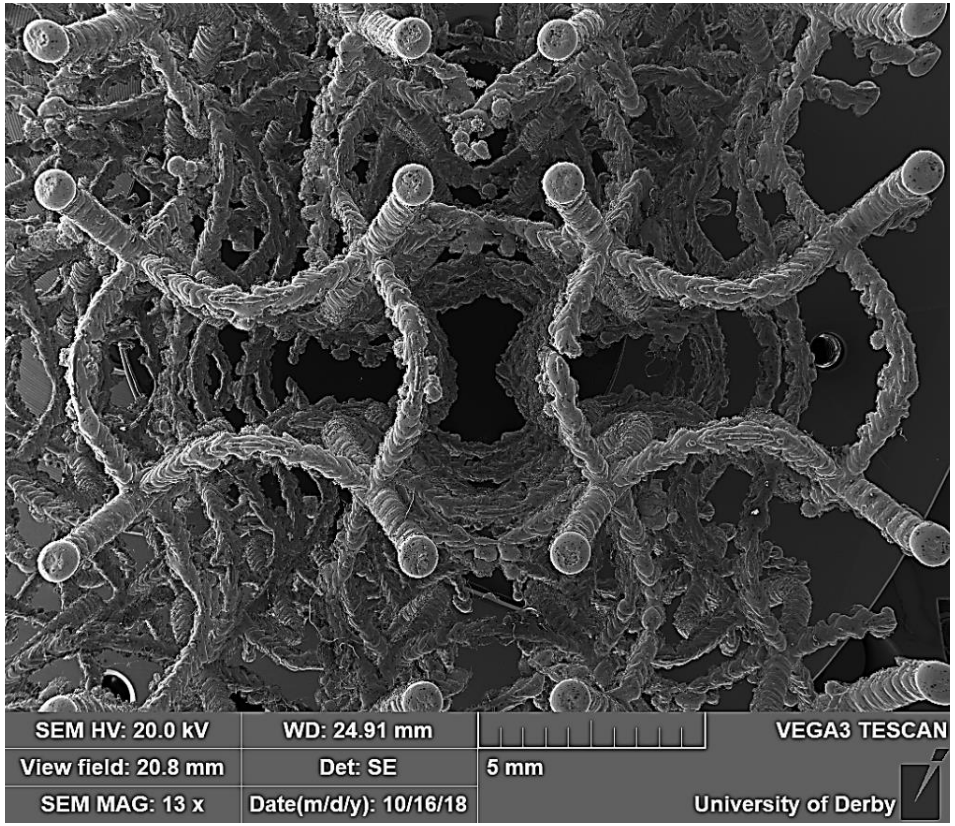


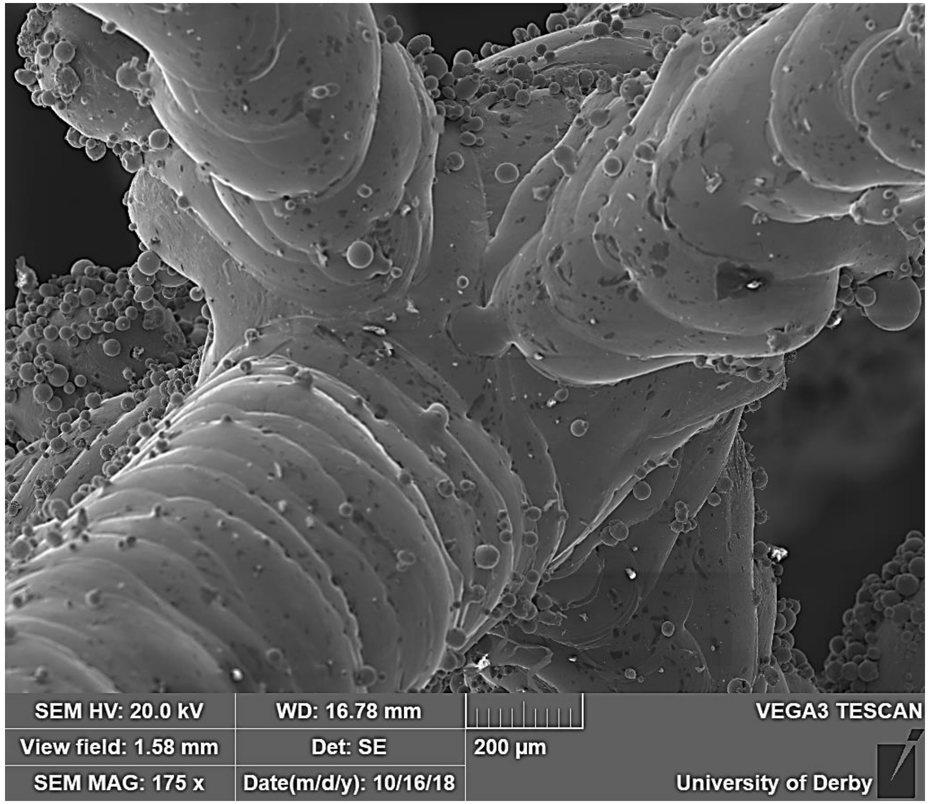


(*) integrated beam with 4 x 4 Guass quadrature

SEM Images of SLM 3D Auxetic Structures in IN718 Alloy

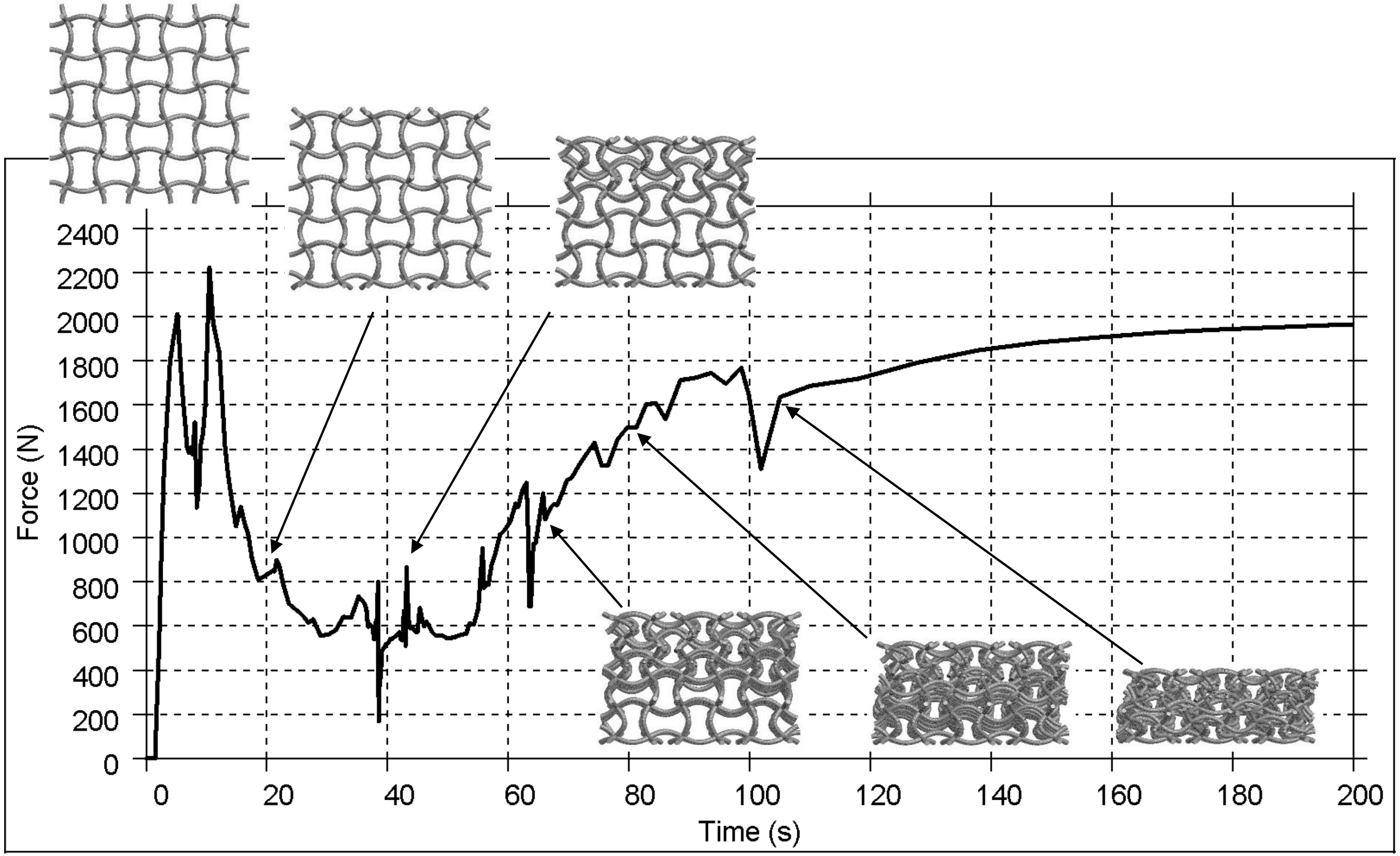
- Images suggest a need to improve build quality
- Ligament thickness is 0.4 mm, although other structures were printed with different thicknesses



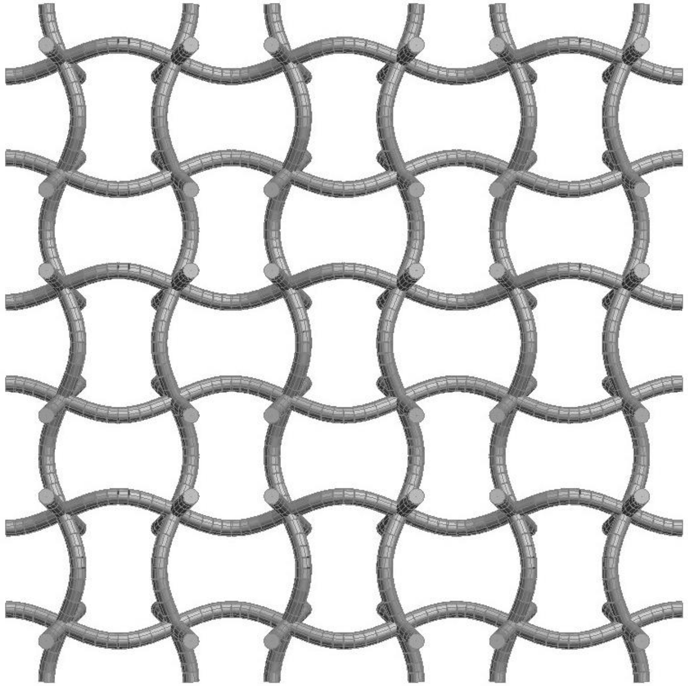


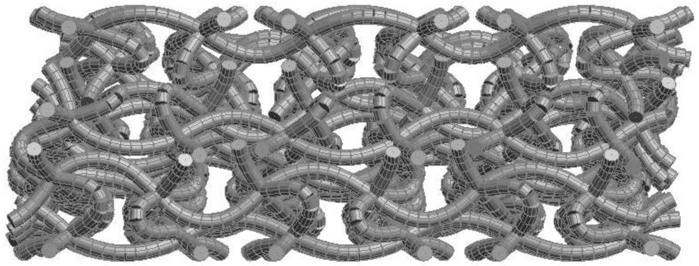
At higher magnification layered melt pools are visible in the ligaments with partially melted powder particles remaining on surface

Modelled using Implicit Solution Scheme with Static Tensile Properties



Modelled using Implicit Solution Scheme with IN718 Static Tensile Properties





Stable collapse exhibited
No change in lateral dimension

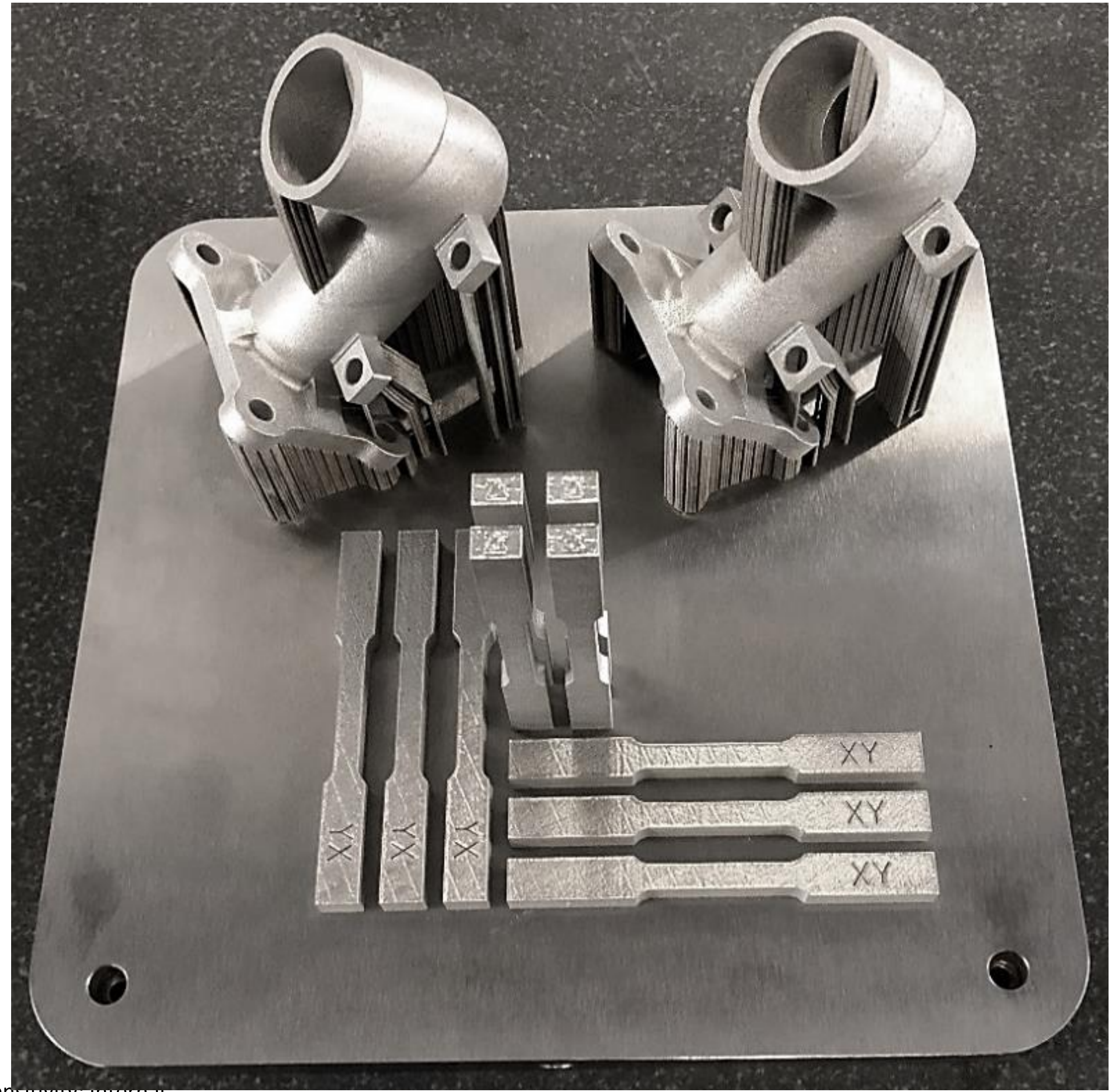
$$\nu = -\frac{\text{Strain in direction of load}}{\text{Strain at right angle to load}}$$

$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}} \longrightarrow 0$$

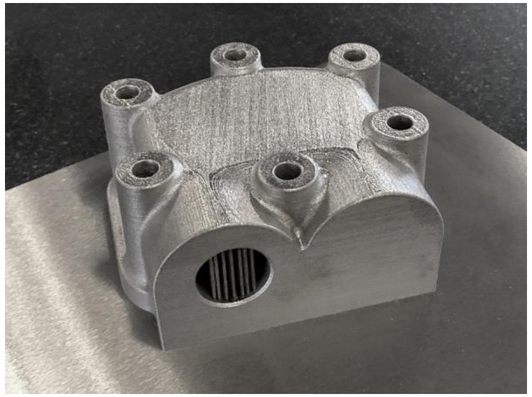
at structure scale

For this structure, stability under static load appears to be dependent on diameter of ligament and rate of work hardening of material, initial findings;
high rate hardening ~ stable collapse
Low rate hardening ~ unstable collapse

Projects with Stainless Steel 316L



Compressor cover

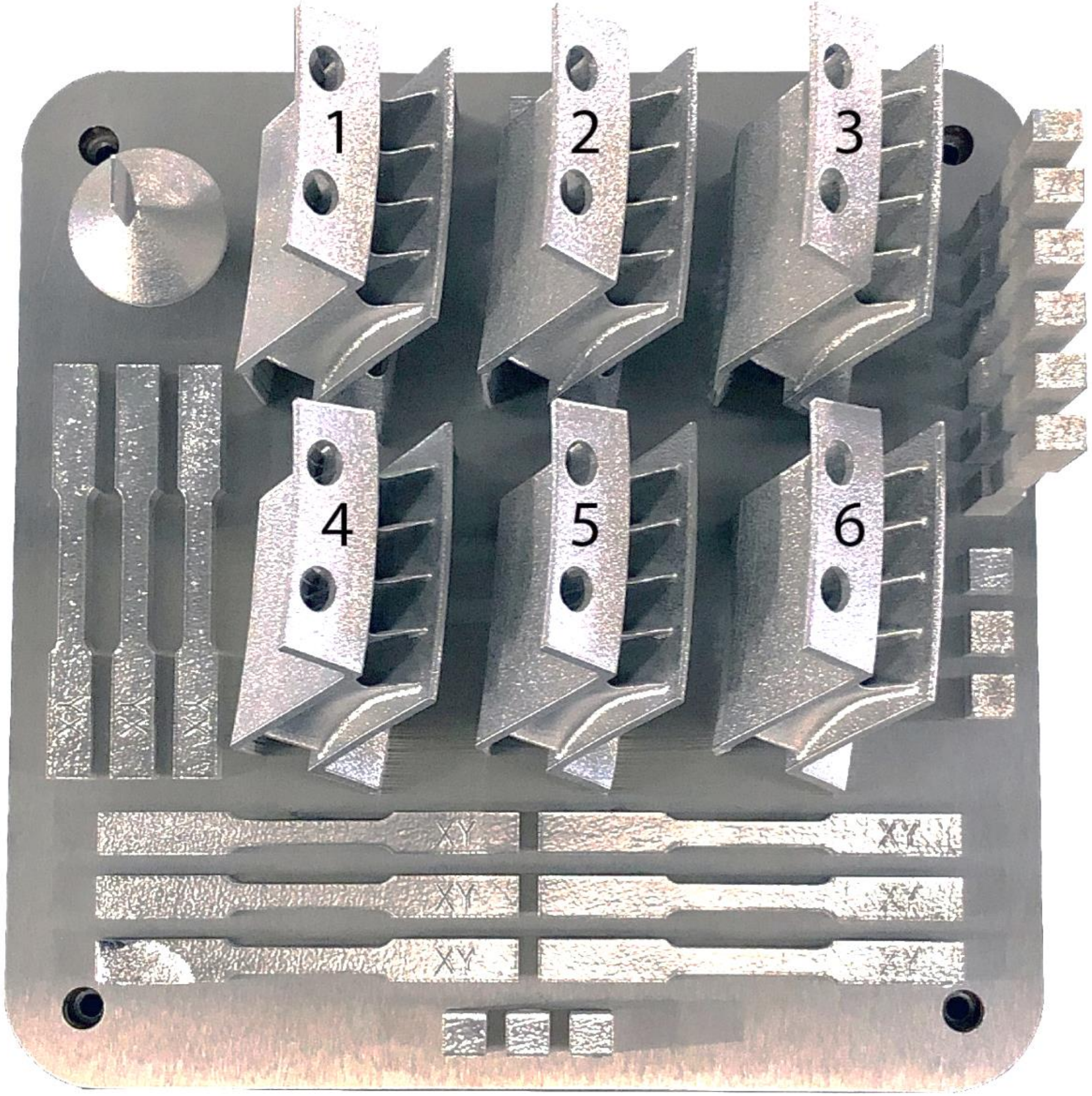


Oil Lube
Connector

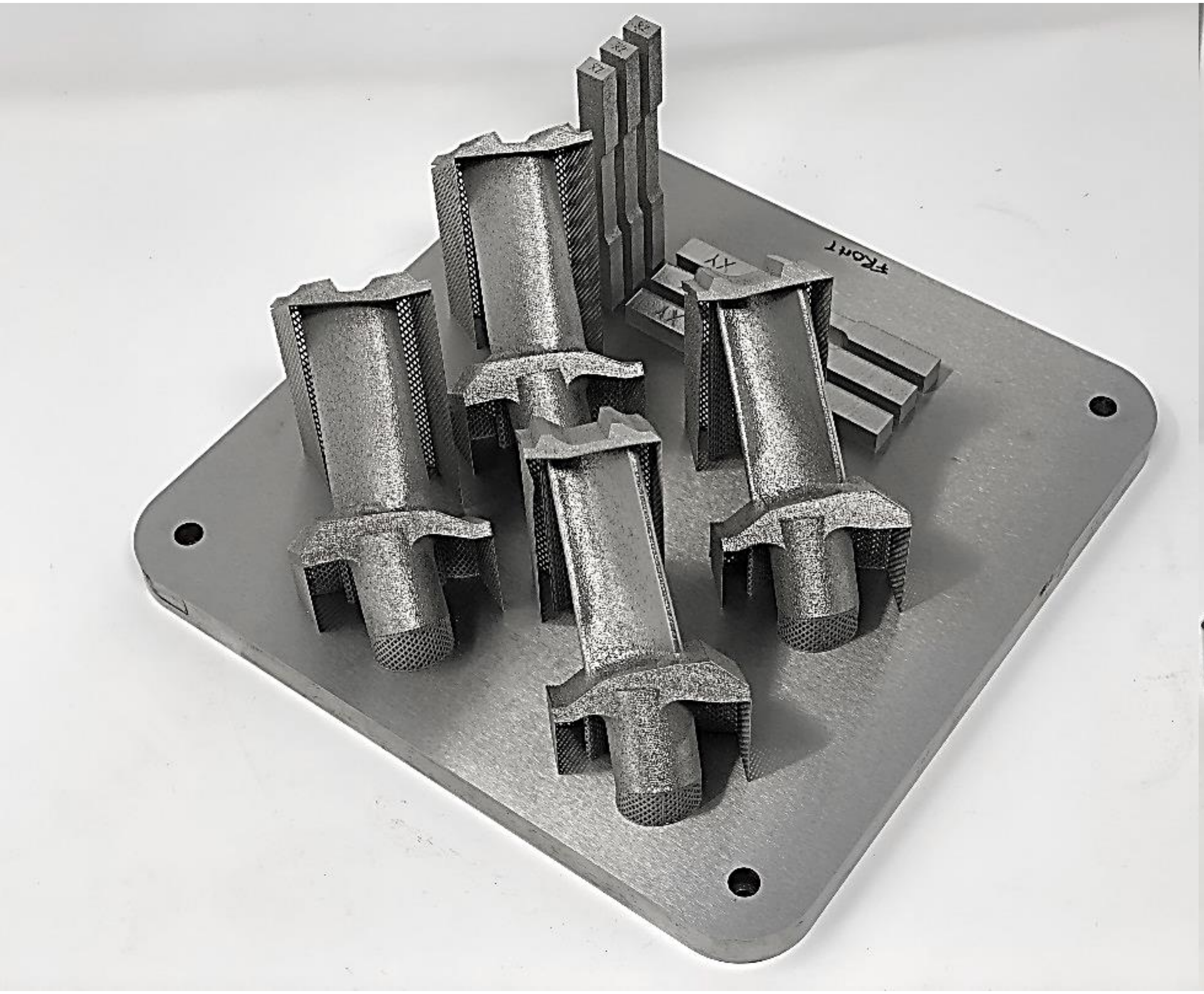
Valve Housing

Robot Wheel

Projects with INCONEL 718



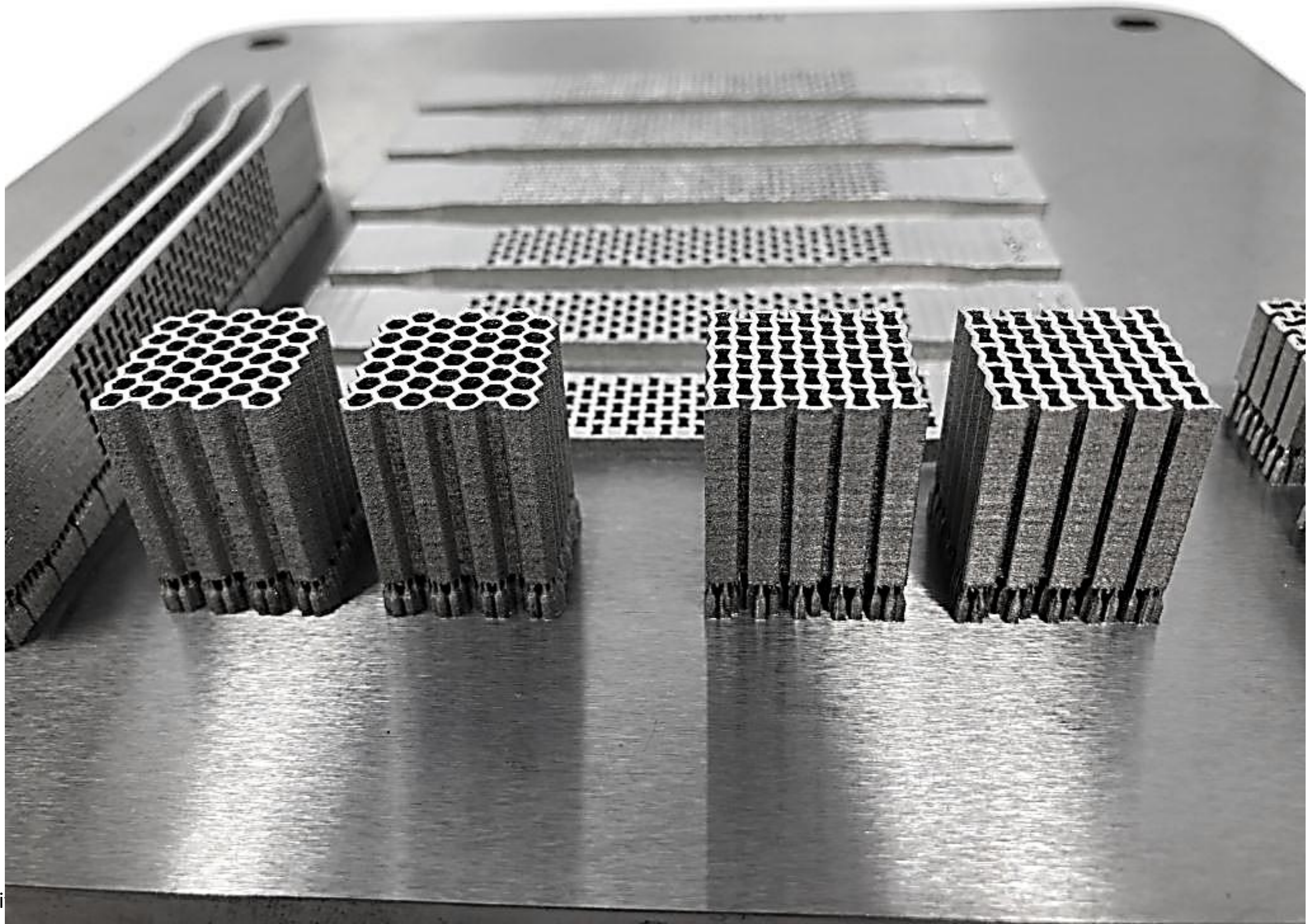
Projects with INCONEL 718



Sensitivity: Internal

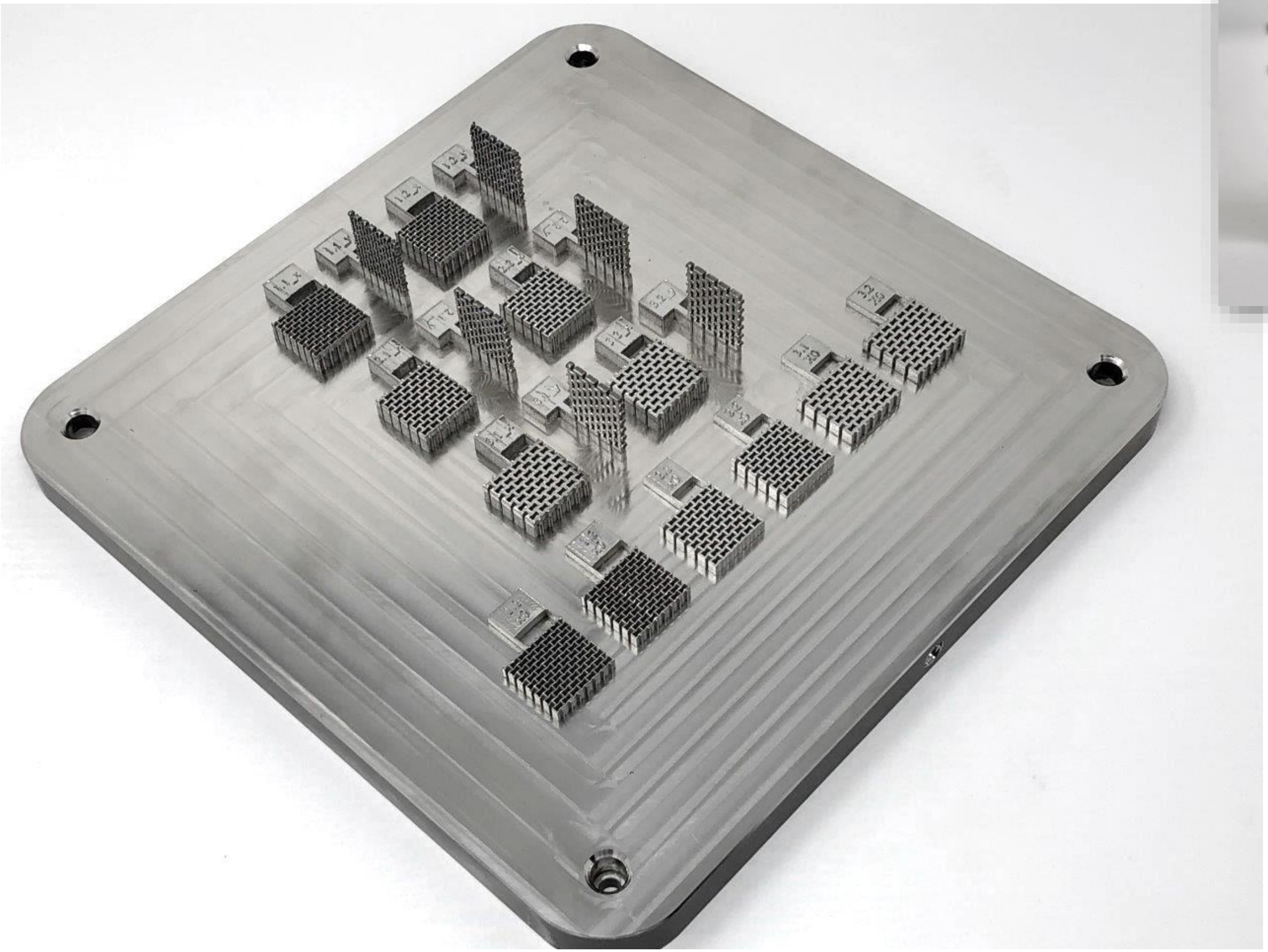
IISE and Lorraine

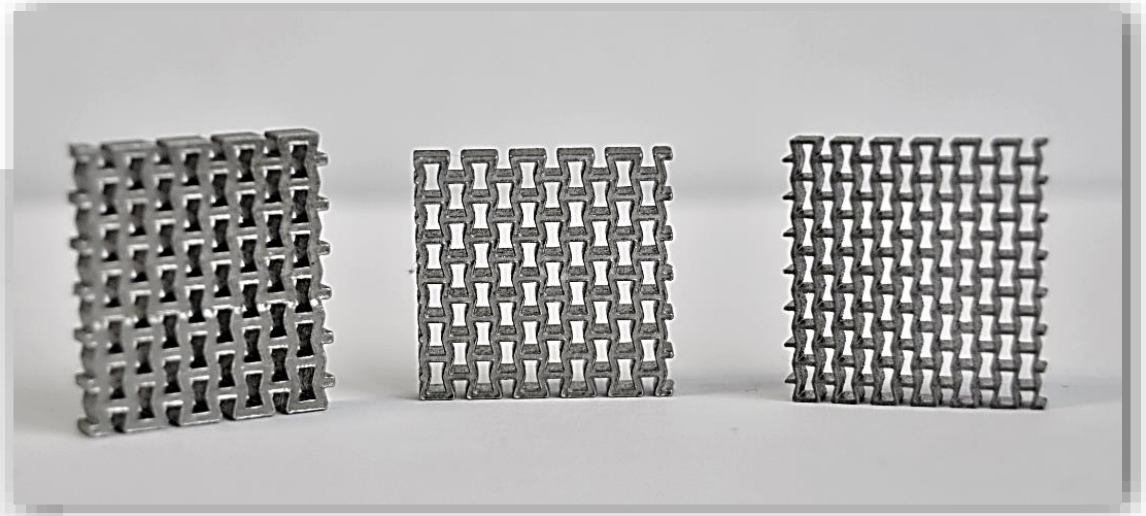
INCONEL 718

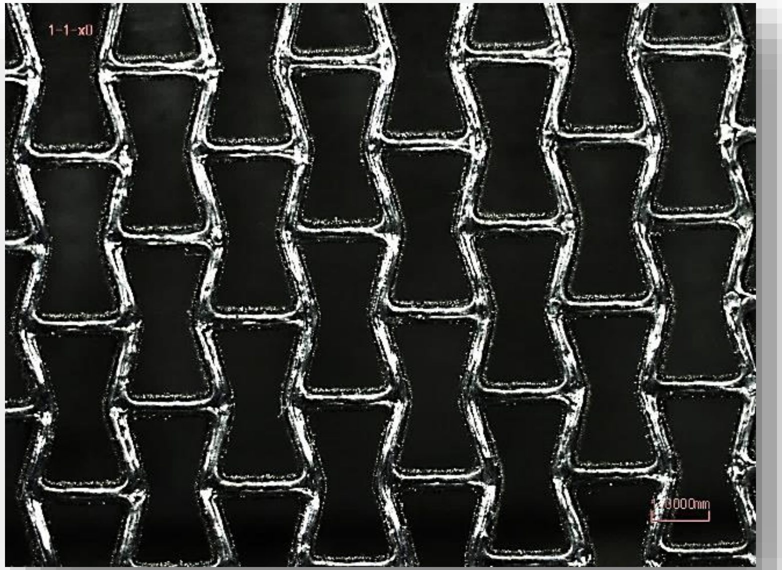


IISE and Lorraine

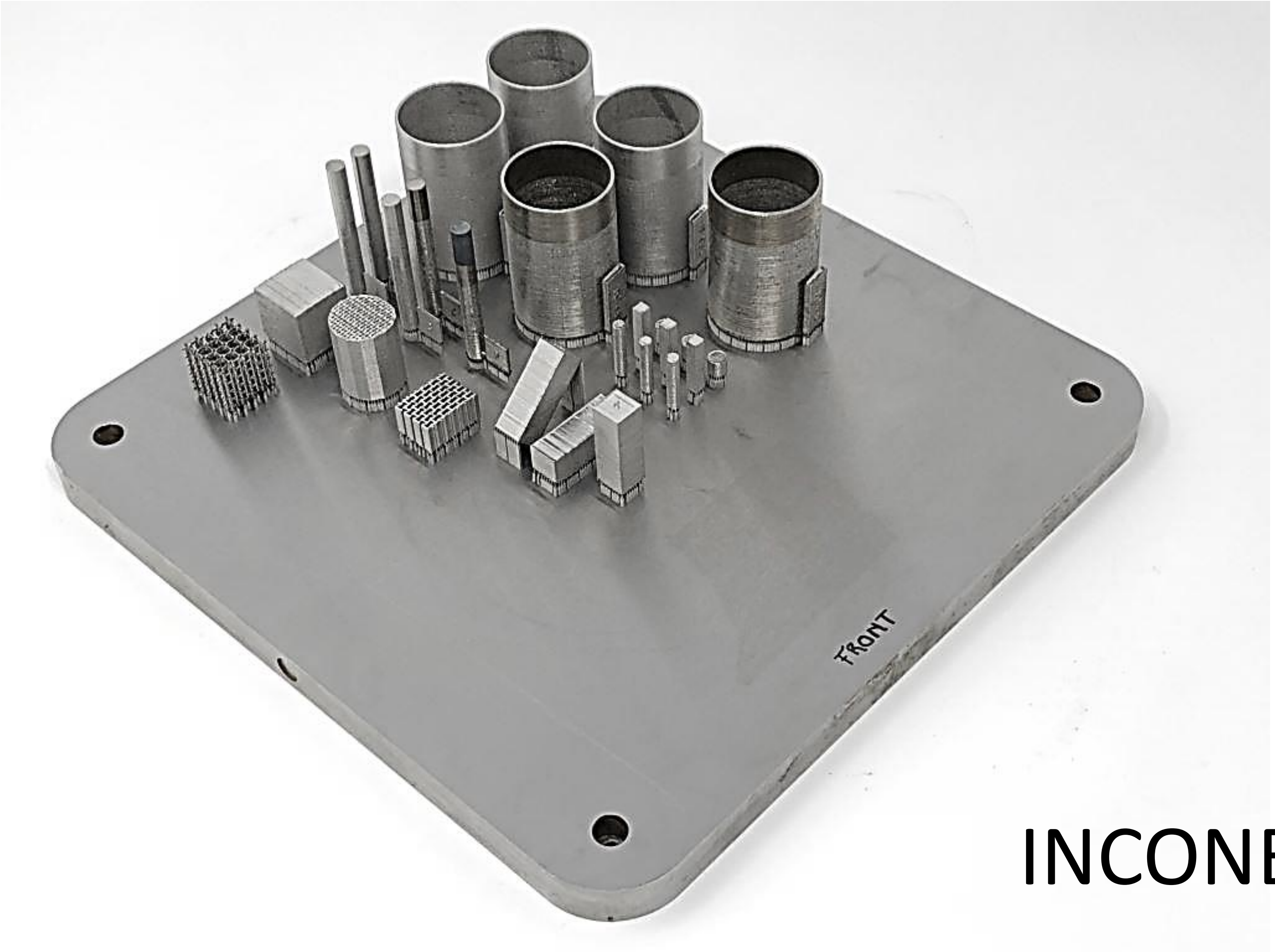
INCONEL 718







Military University of Technology in Warsaw



INCONEL 718