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Maximising the Performance of Laser-Powder AM

Prof. Moataz Attallah (on behalf of AMPLab)
Director, Advanced Materials & Processing Lab (AMPLab)
Interdisciplinary Research Centre, School of Metallurgy & Materials

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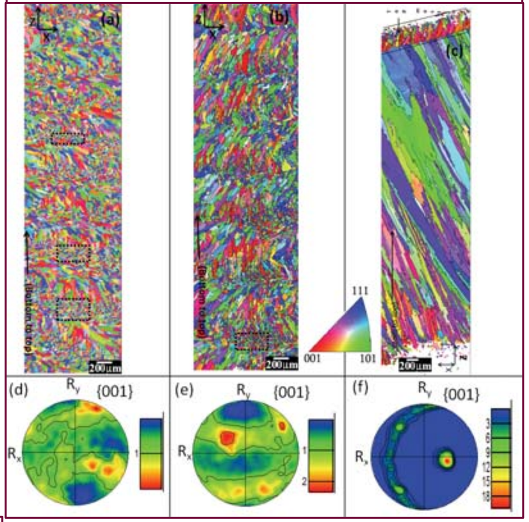
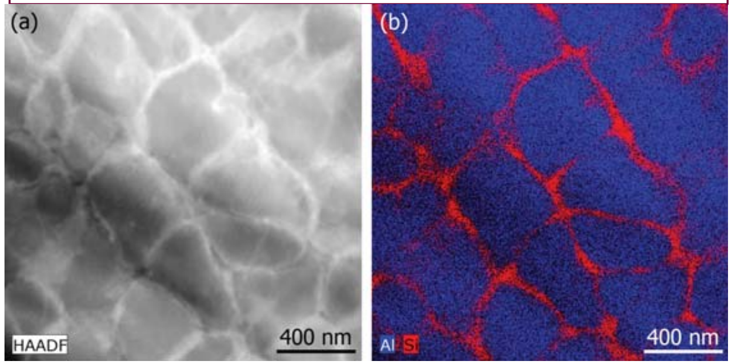
AMPLab
Trumpf DLD
Trumpf DLD
Multi-wire DLD
Concept M2 (400W)
SLM 500HL (4 lasers)
EPSI HIP

Defect formation & characterisation

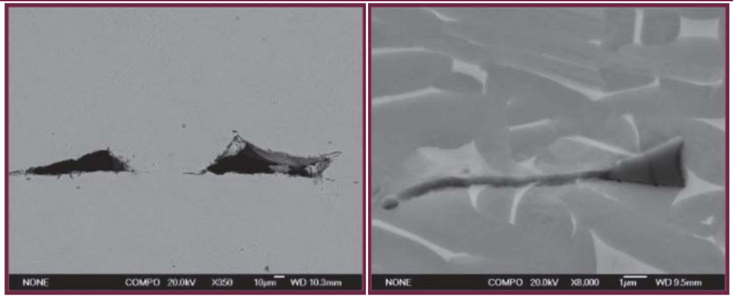
Microstructural control



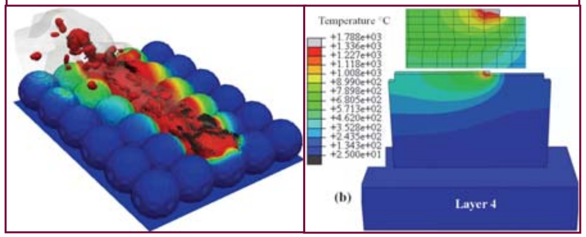
Microstructural Development



Post-processing (using HIPping)



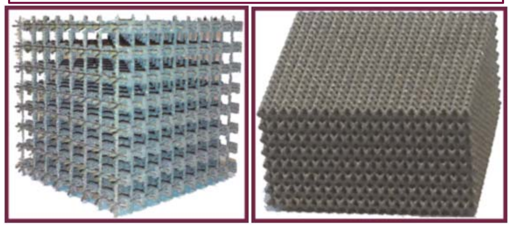
Micro & macro modelling



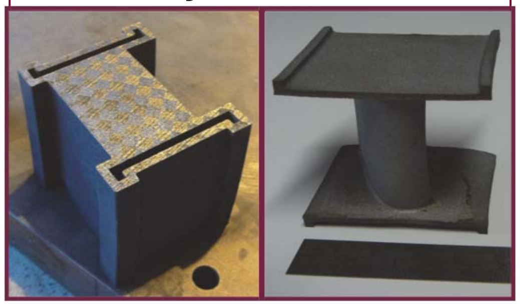
AM Research AMPLab

Large scale deposition

Multi-functional AM



Hybrid AM



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AMPLab's AM Scope

Presentation Outline

- Maximising the **material**, **component** & **process** performance through:
  - Modelling (macro & micro-scale, semi-empirical)
  - Microstructural control
  - Understanding the structure-property development
  - Functional AM structures
  - Large scale deposition
  - Post-processing
  - Hybrid processing
  - Alloy development for AM

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AM Modelling

Micro, Macro, & Empirical

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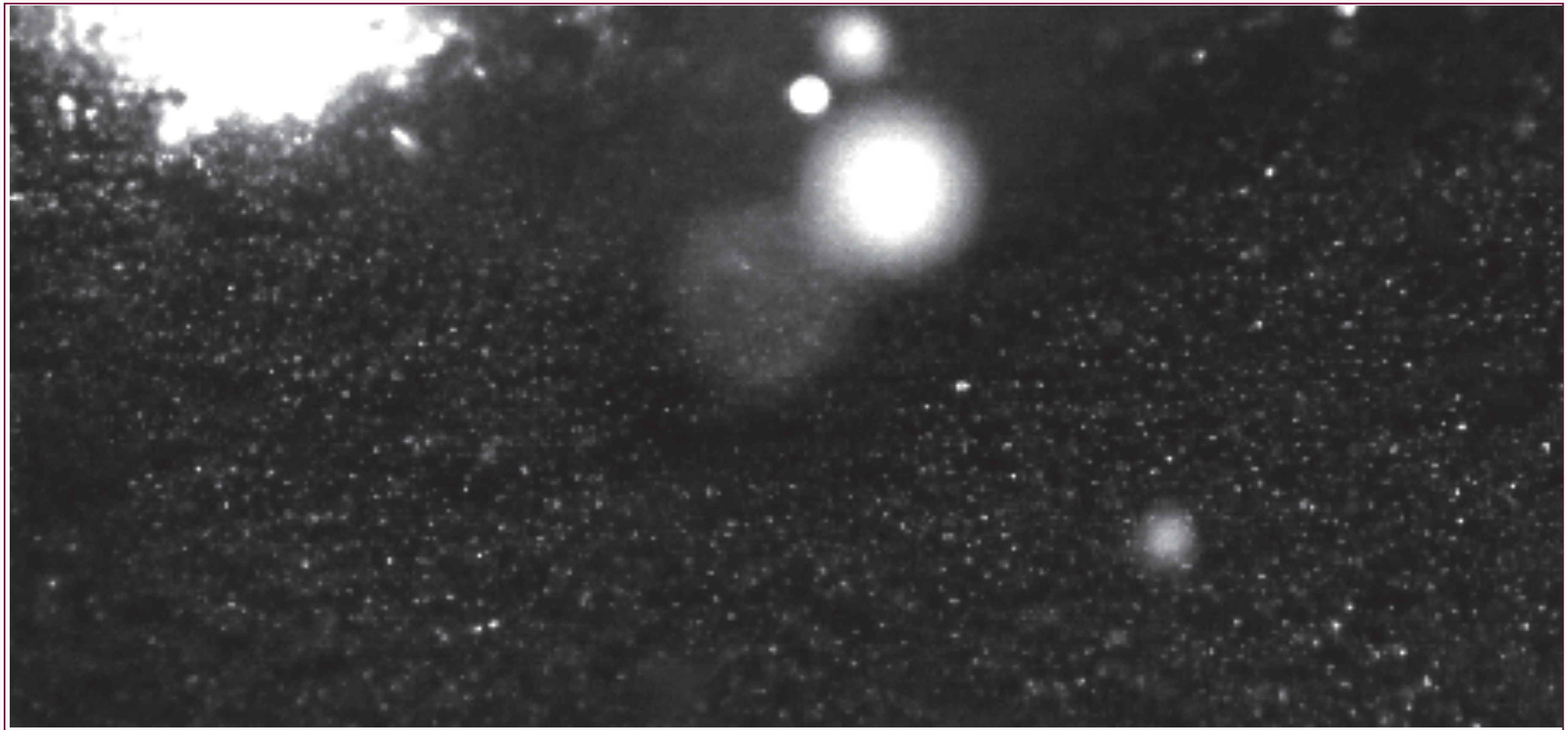
Selective Laser Melting

A.K.A. Manufacturing By Chaos



High speed imaging of SLM

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JP White, N Read, RM Ward, R Mellor, MM Attallah. Proceedings of Materials Science and Technology Conference 2014. p. 1985-92.

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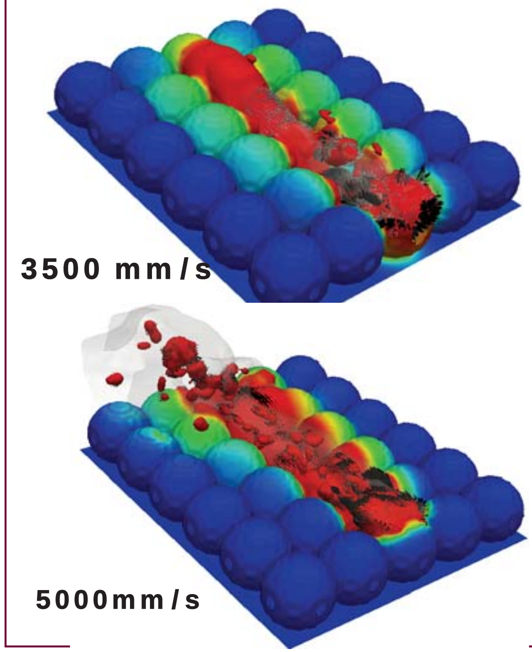
Understanding the Physics of SLM

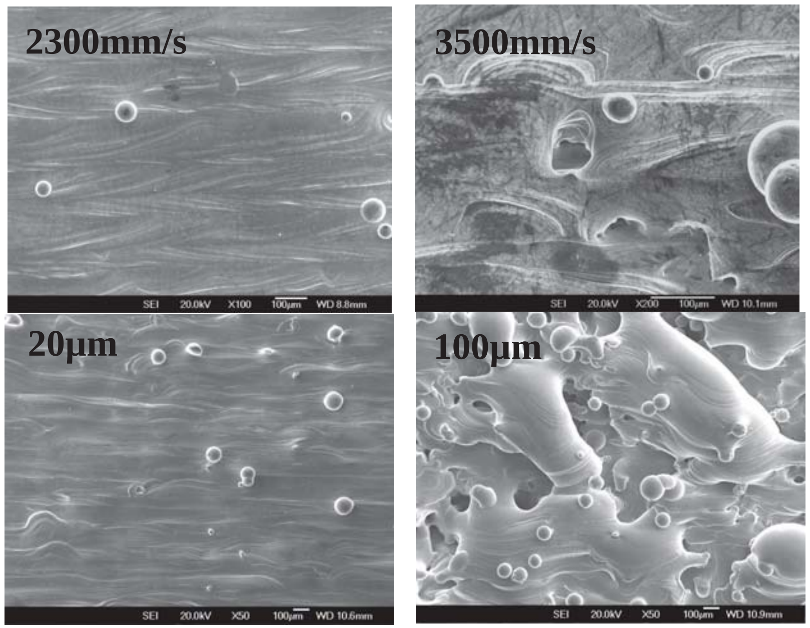
Micro-Modelling of SLM of Ti-6Al-4V

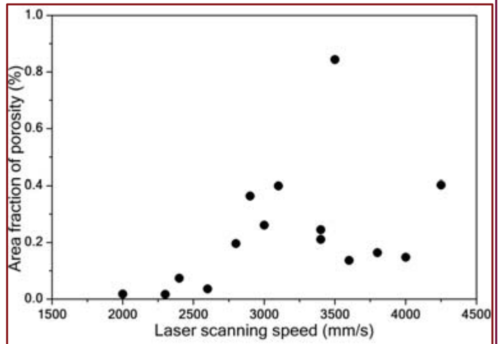
- **Aim:** Investigate the role of melt flow on the morphology of the build surface structure and porosity development during SLM.
- **Approach:** CFD Modelling the laser-powder interaction (melt splashing and pore formation), and linking the surface structure and porosity to melt flow.

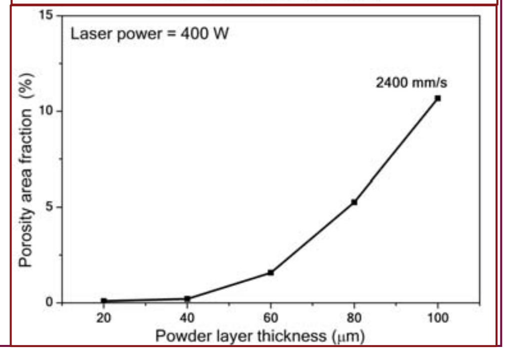
Modelling



Surface structure







C Qiu, C Panwisawas, RM Ward, HC Basoalto, JW Brooks, MM Attallah. Acta Materialia, 2015; vol. 96, pp. 72-9.

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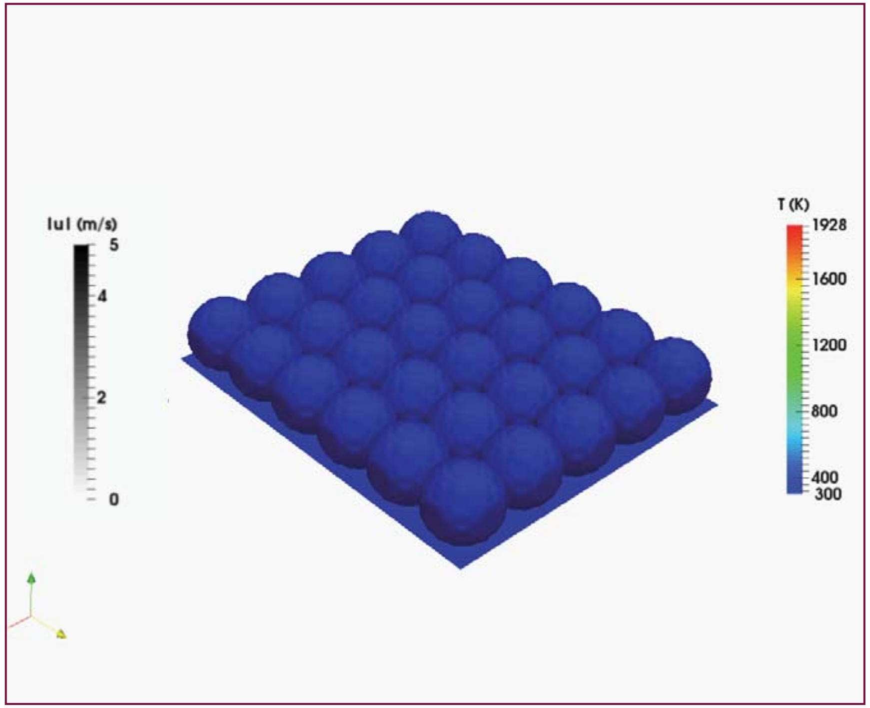
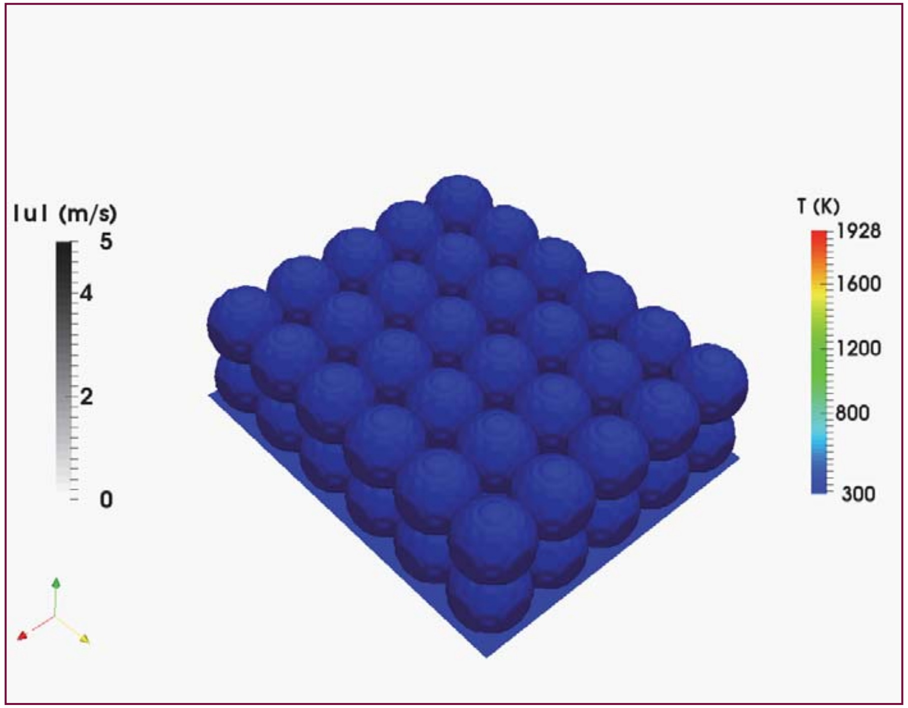
Micro-Modelling (SLM)

Influence of Layer Thickness

- Investigating the laser-powder interaction (melt splashing and pore formation) as a function of powder layer thickness and laser speed), correlating with surface structure and porosity.



50 μm



100 μm

C Qiu, C Panwisawas, RM Ward, HC Basoalto, JW Brooks, MM Attallah*. Acta Materialia, 2015; vol. 96, pp. 72-9.

Micro-Modelling (SLM)

Influence of Layer Thickness

40 µm thick powder layer

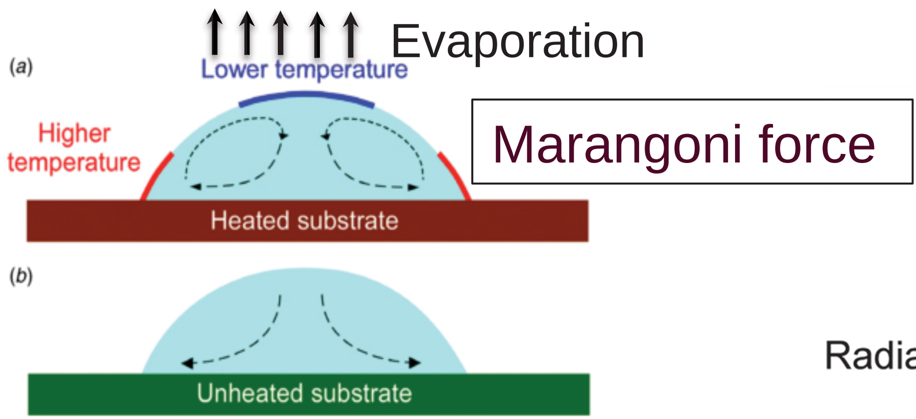
80µm thick powder layer

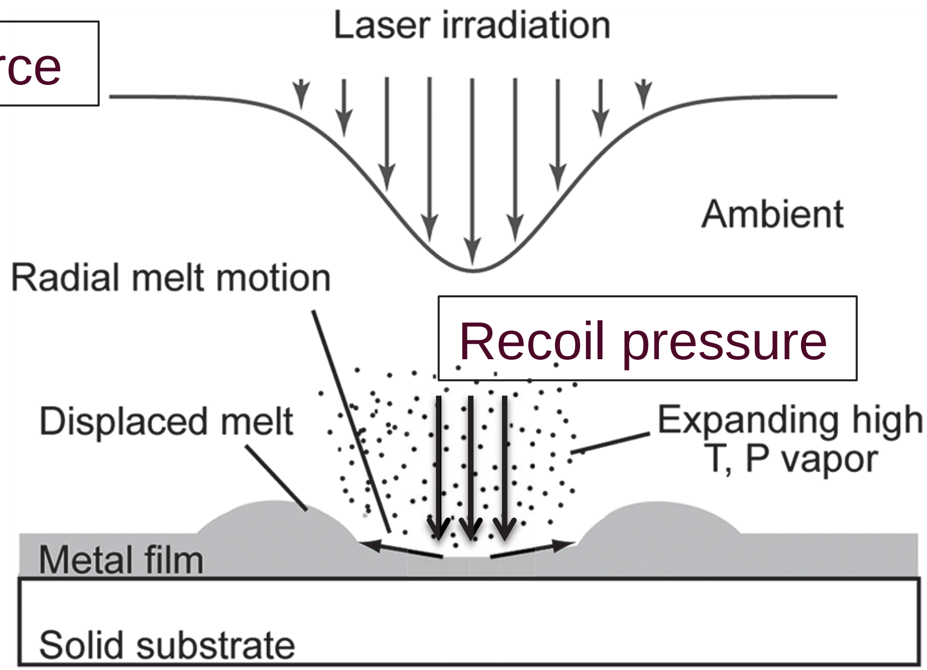
C Qiu, C Panwisawas, RM Ward, HC Basoalto, JW Brooks, MM Attallah. Acta Materialia, 2015; vol. 96, pp. 72-9.

Rationalising Melt Flow during SLM

Micro-Modelling of Laser-Powder Interaction

- Increased scanning speed and powder layer thickness may increase evaporation, and thus the Marangoni force and recoil pressure, which leads to more unstable melt flow





Micro-Modelling (SLM)

Influence of Layer Thickness on Single Tracks

- Gaussian distribution of powders.
- The laser melted track becomes increasingly irregular-shaped and intermittent with increased powder layer thickness

20µm

60µm

80µm

100µm

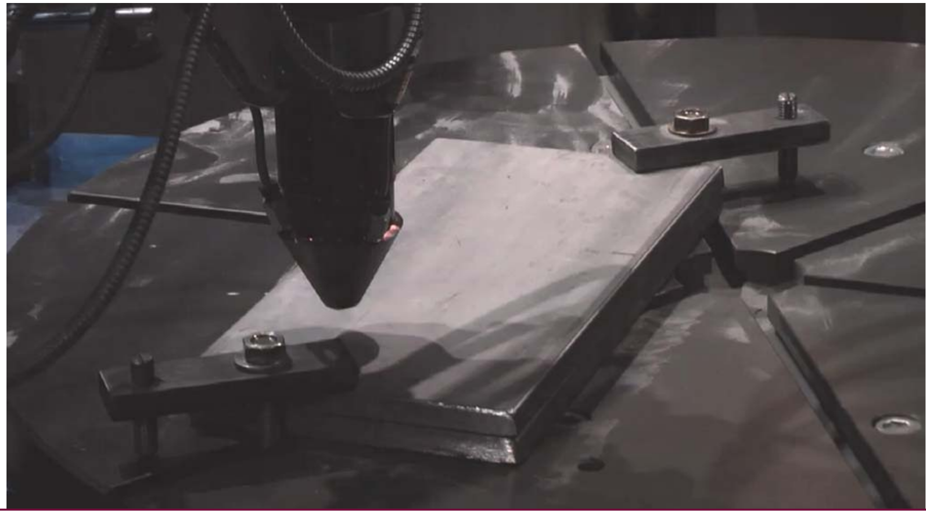
400W-2400mm/s

Panwisawas *et al.*
In preparation

Macro-Modelling

Direct Laser Deposition (DLD)

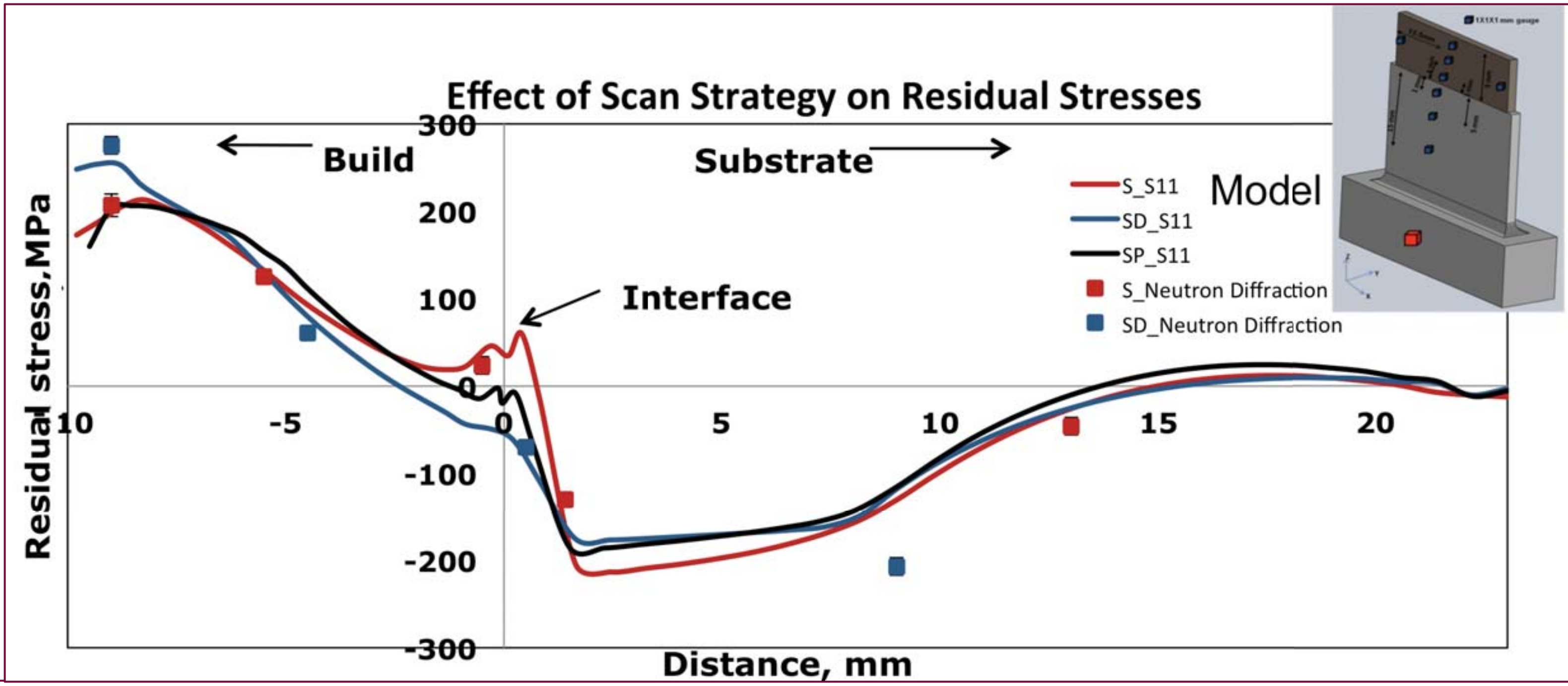
- **Thicker-layers (~0.5-1 mm):** appropriate for Finite-Element
- **Approaches:**
  - Element birth technique: each element is activated at a time to depict laser deposition strategy, with re-meshing occurring.
  - Chewing gum model: stiffness matrix is modified from 'chewing gum' properties to actual material properties after deposition.
- Can be used to predict the microstructural development, temperatures and residual stresses



Macro-Modelling (DLD)

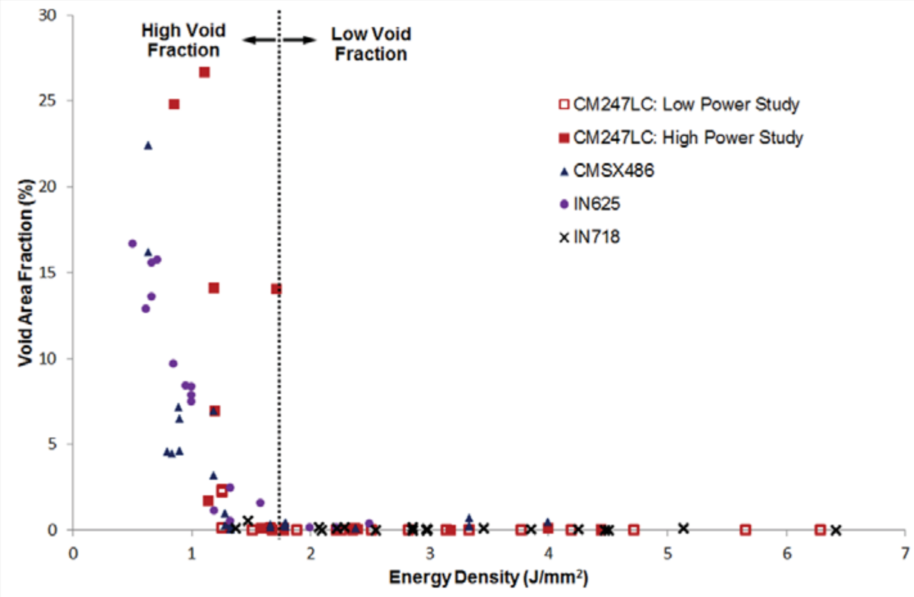
DLD of IN718: Residual Stress Modelling & Measurement

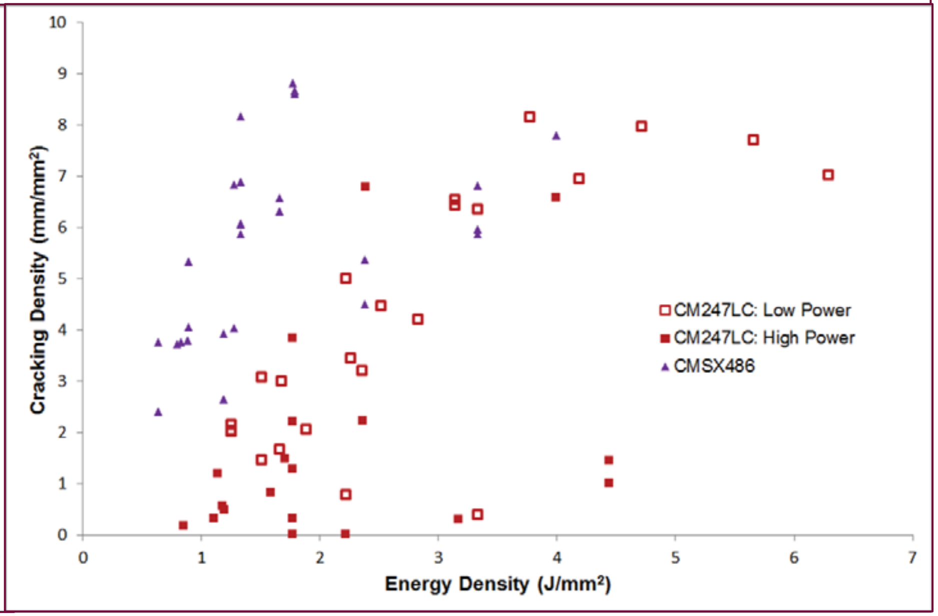
- Element birth (multi-element activation) can predict the temperature and residual stress development at a low computational cost.
- Reducing the **'fudge factors'** into a single efficiency factor.
- Neutron diffraction measurements were used to validate the model predictions, showing a good agreement.



(Semi)-Empirical Modelling
Energy Density Model (Ni-Superalloys)

- **Energy density** E (J/mm^2) = $P/(v*h)$
  P is laser Power (W), *v* is scan speed (mm/s), h is hatch spacing (mm)
- Similar alloys require an energy density threshold to achieve full consolidation, but cracking density does not correlate well.
- The energy density can be used to improve the parametric studies and reduce the number of trials.

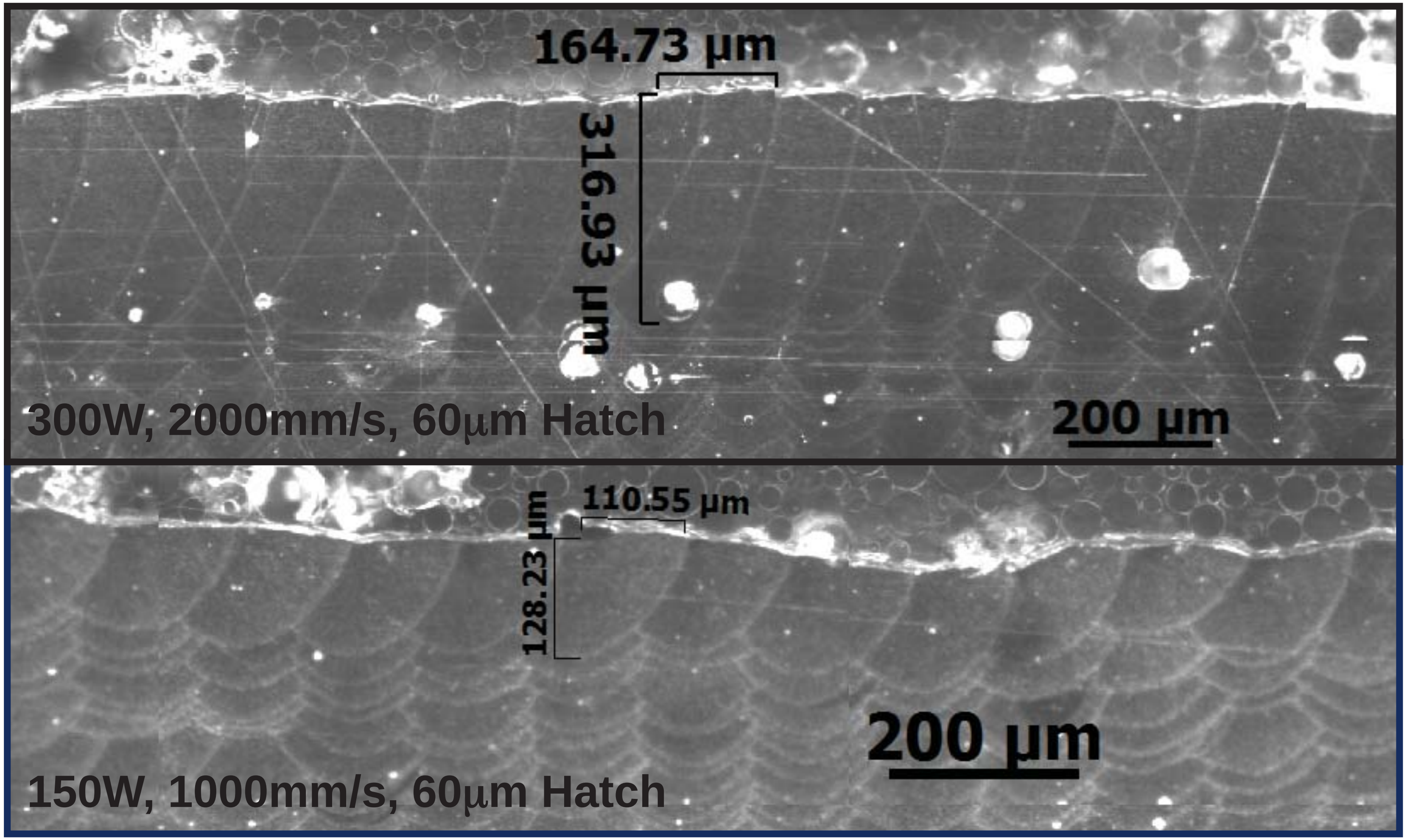




LN Carter, X Wang, N Read, M Aristizabal, K Essa, RH Khan, **MM Attallah*** Materials Science and Technology, in press, 2016.

(Semi)-Empirical Modelling

How Good is the Energy Density Model?



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Design & Control of Microstructure

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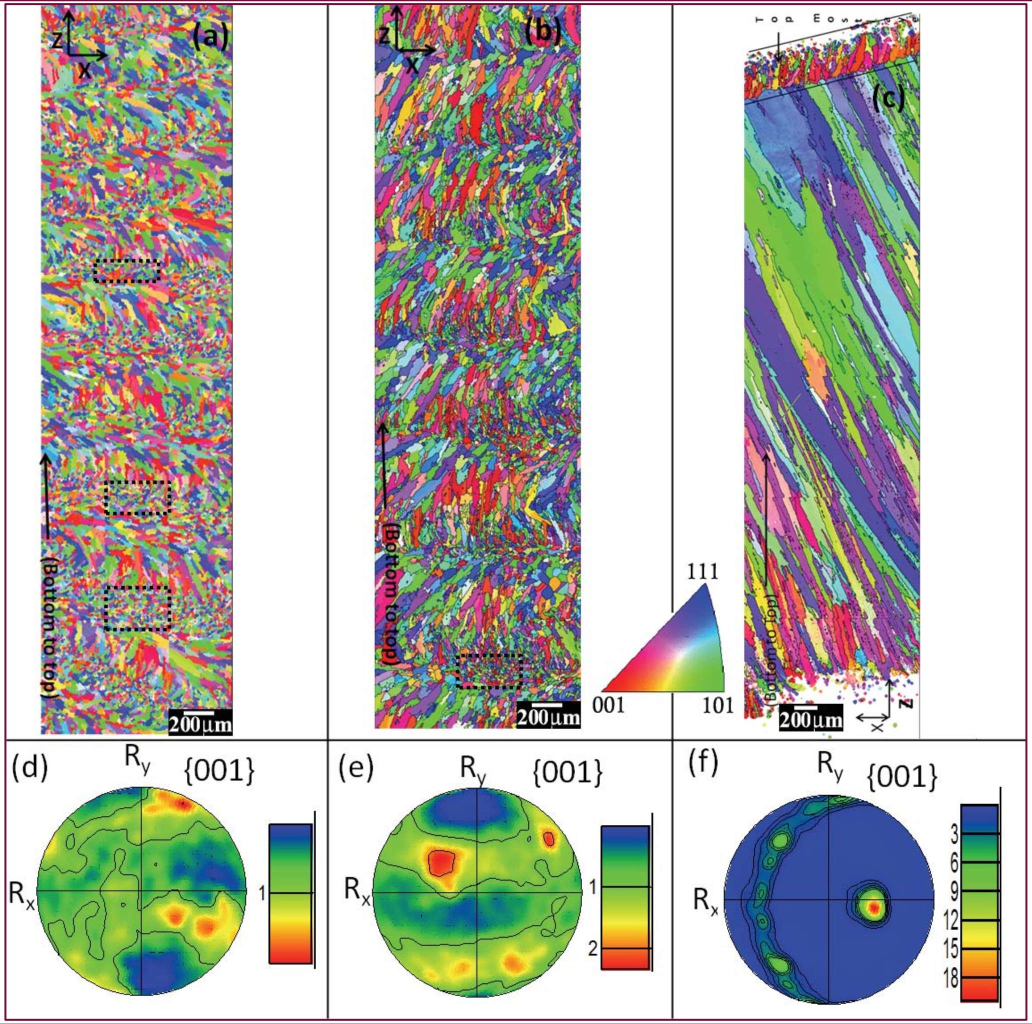
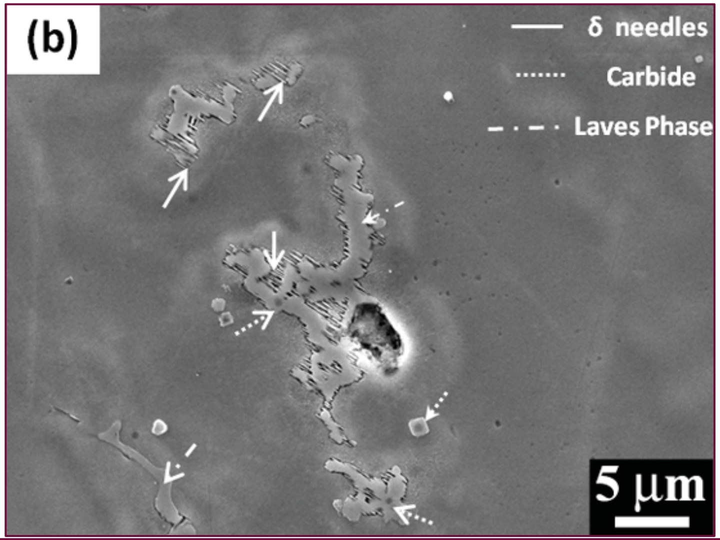
Microstructural Control (DLD)

Direct Laser Deposition of IN718 (Different Parameters)



- Grain size & texture (crystrallographic orientation) can be controlled to achieve specific performance, even on a local level.
- Detrimental phases can be controlled.

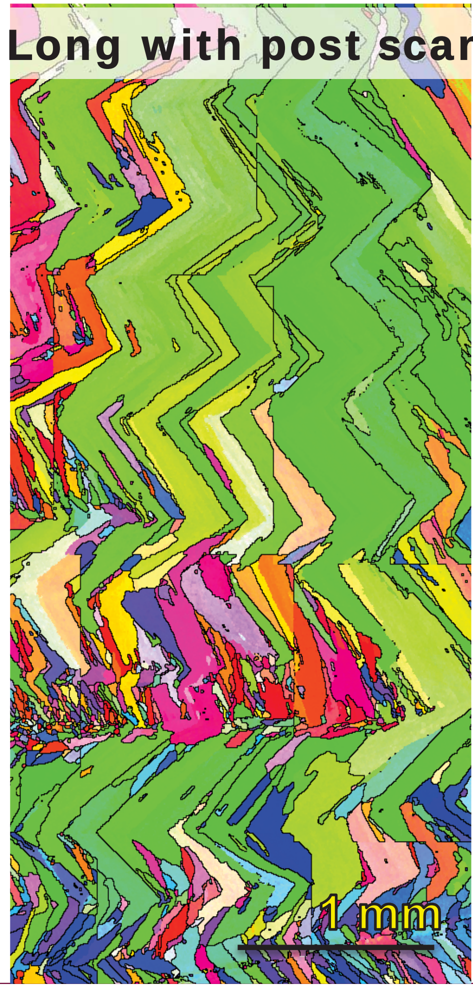


LL Parimi, Ravi GA, D Clark, MM Attallah.
Materials Characterization, 2014, vol. 89, pp. 102-11.

Microstructural Control (DLD)

Direct Laser Deposition of IN718 (Different Scan Strategies)

- The scan strategy strongly influenced the grain morphology & texture.
- Post-scanning resulted in continued epitaxial growth.

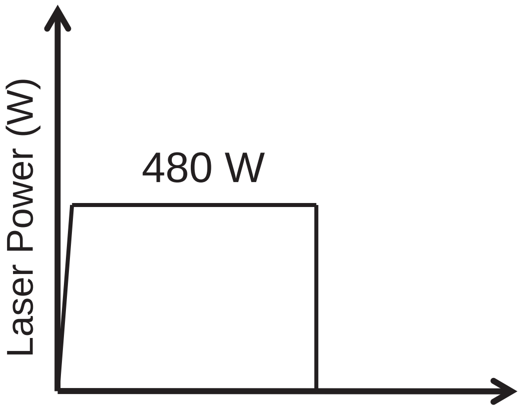


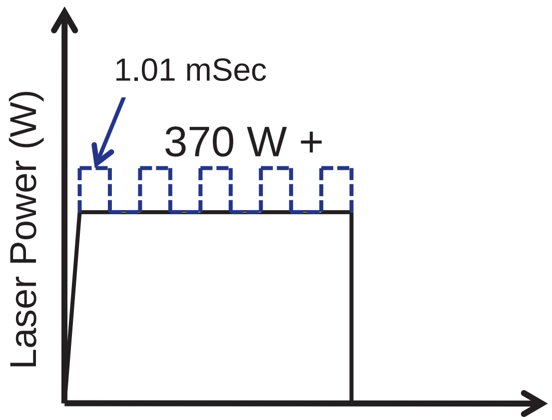
Microstructural Control (DLD)

Pulsed DLD of Ti-64

CW - 480W

X & Y Overlap
0.4 x 0.4 mm
Z step 0.4 mm





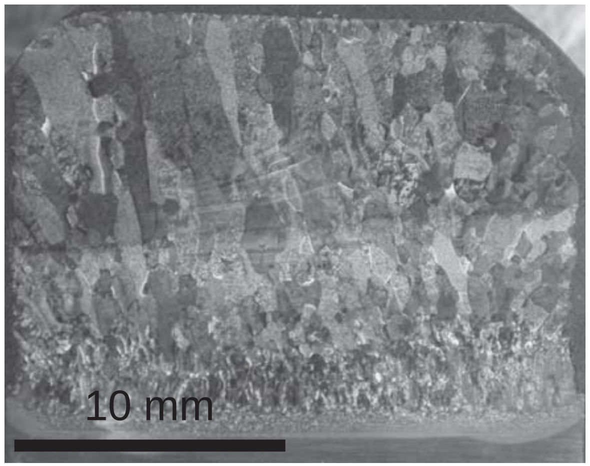
CW + PW –

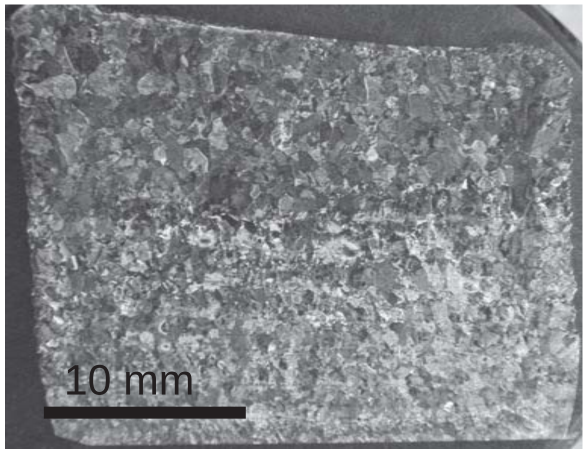
370 – 430W

X & Y Overlap
0.4 x 0.4 mm
Z step 0.4 mm

CW - 1800W

X & Y Overlap
1.5 x 1.5 mm
Z step 1.5 mm





CW + PW –

1200 – 1600W

X & Y Overlap
1.5 x 1.5 mm
Z step 1.5 mm

GA Ravi, C Qiu, **MM Attallah***. Materials Letters 179, 104-108, 2016.

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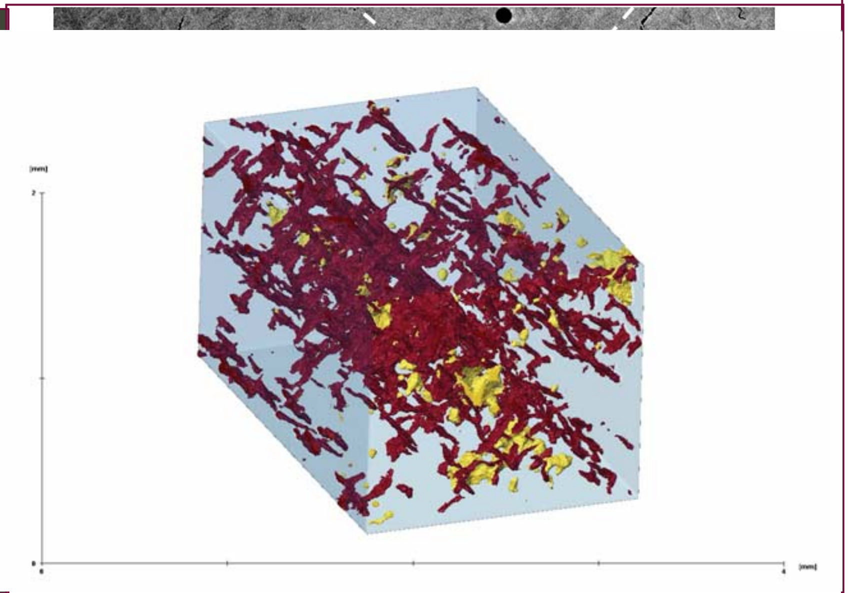
Microstructural Control (SLM)

Island Scan Vs. Simple Scan Strategies

- Laser powder bed systems use proprietary scan strategies that aim to balance/reduce the residual stress development.
- Strong correlations between the occurrence of structural defects and the laser scan strategies in Ni-superalloys.



LN Carter, C Martin, PJ Withers, MM Attallah. Journal of Alloys and Compounds, 2014, Volume 615, pp. 338-347

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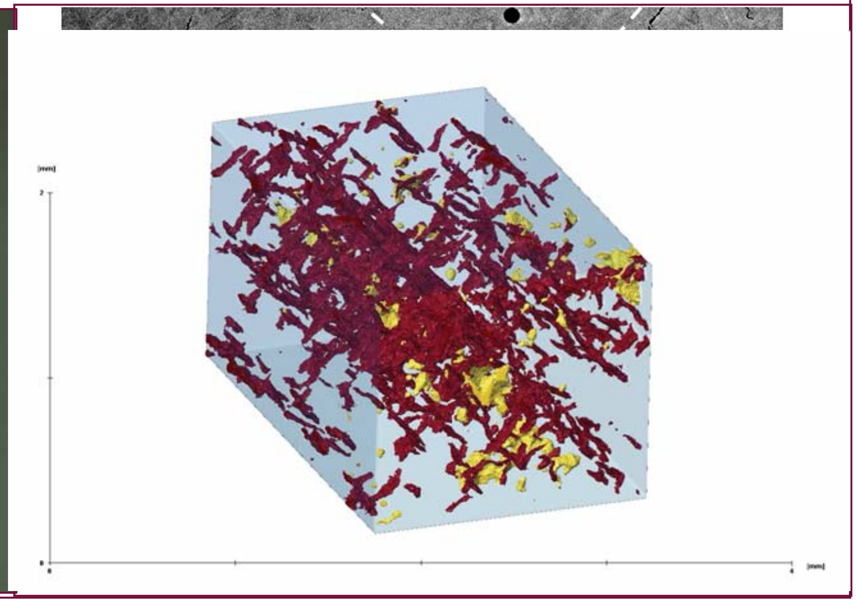
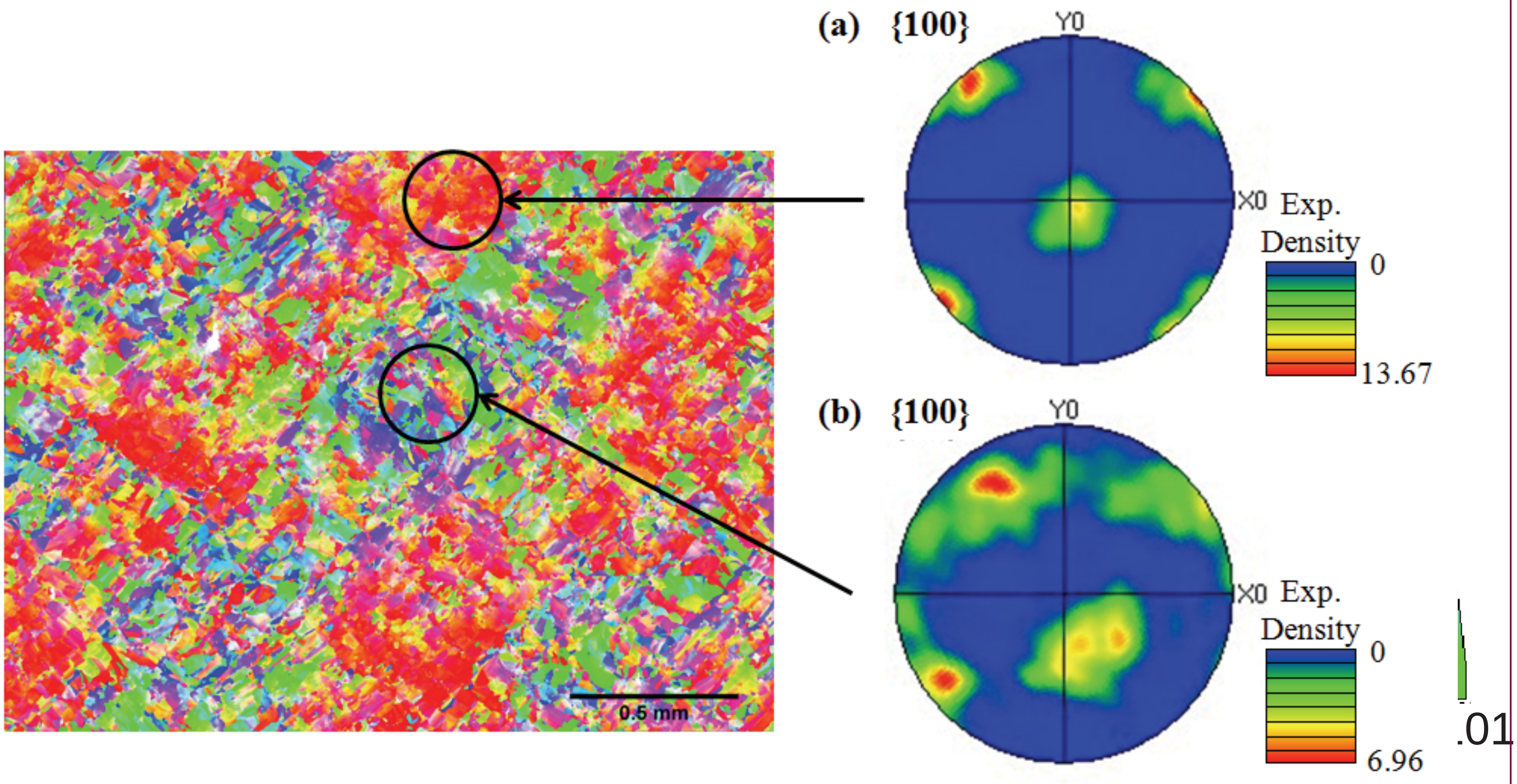


LN Carter, C Martin, PJ Withers, MM Attallah. Journal of Alloys and Compounds, 2014, Volume 615, pp. 338-347

Microstructural Control (SLM)

Island Scan Strategy: Texture Development



LN Carter, C Martin, PJ Withers, MM Attallah. Journal of Alloys and Compounds, 2014, Volume 615, pp. 338-347

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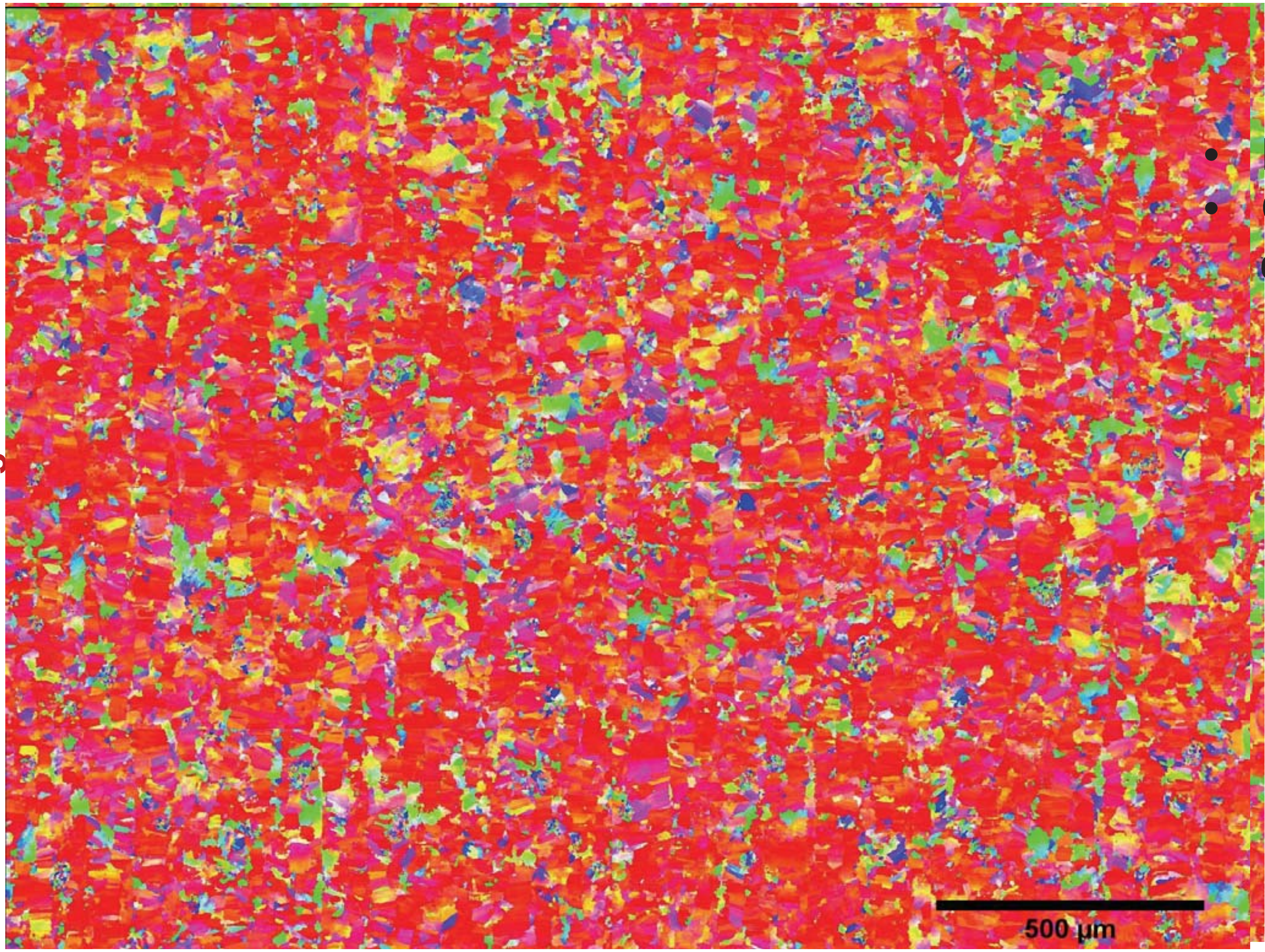
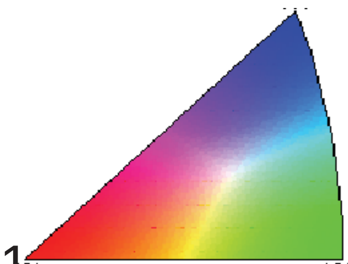
Microstructural Control (SLM)

Simple Scan Strategy: Texture Development

Laser Scanning Direction



- Low cracking
- Grain boundary character?



IPF map showing orientation with respect to the laser scanning direction (Y axis)

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LN Carter, C Martin, PJ Withers, MM Attallah. Journal of Alloys and Compounds, 2014, Volume 615, pp. 338-347

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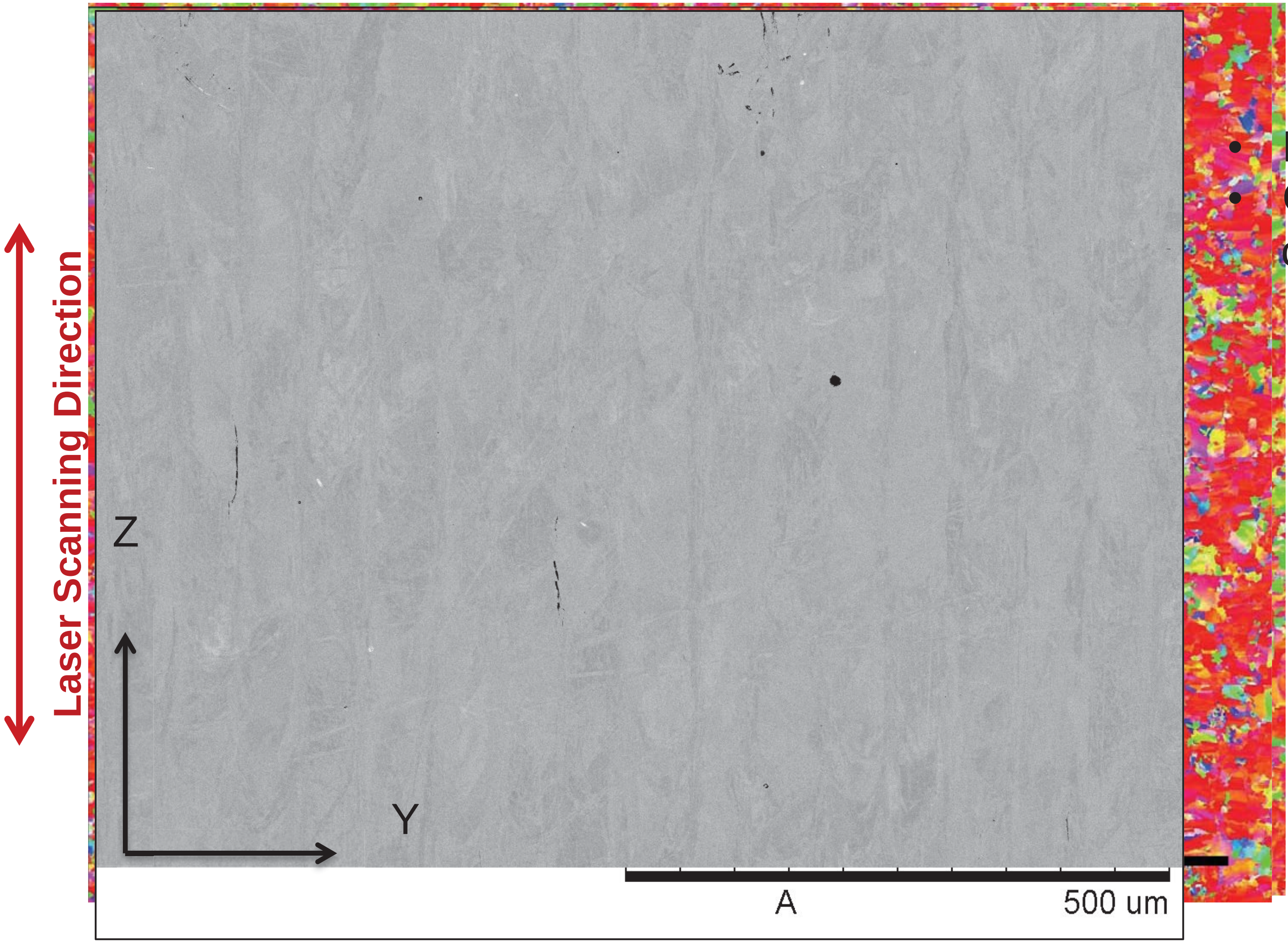
Microstructural Control (SLM)

Simple Scan Strategy: Texture Development



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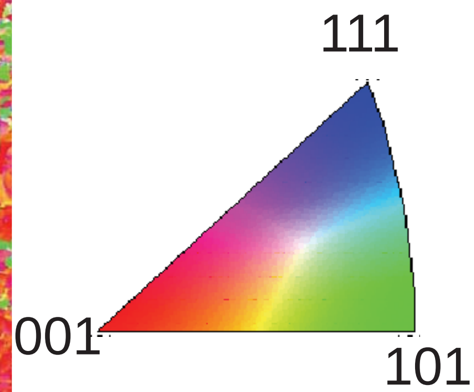

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Microstructural Development

Ni-Superalloys

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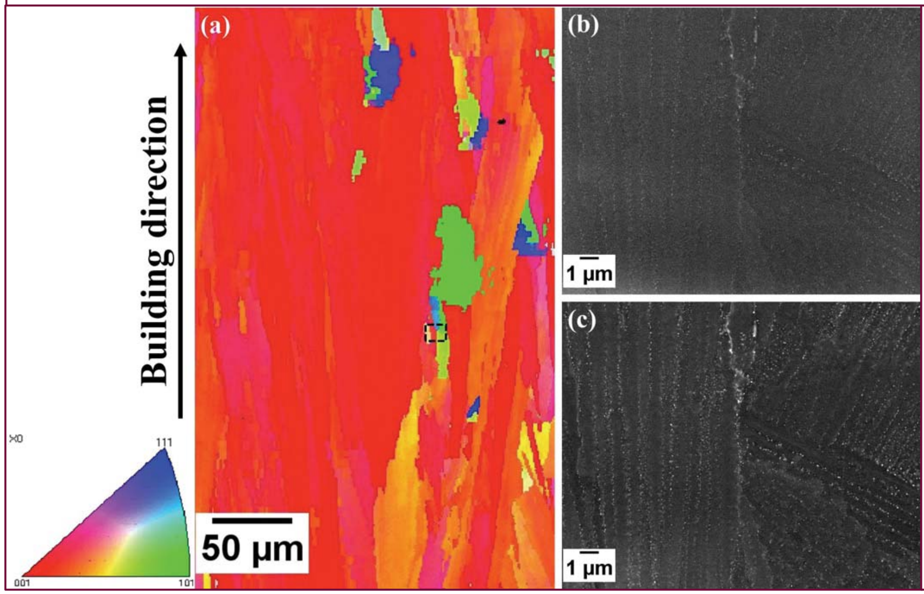
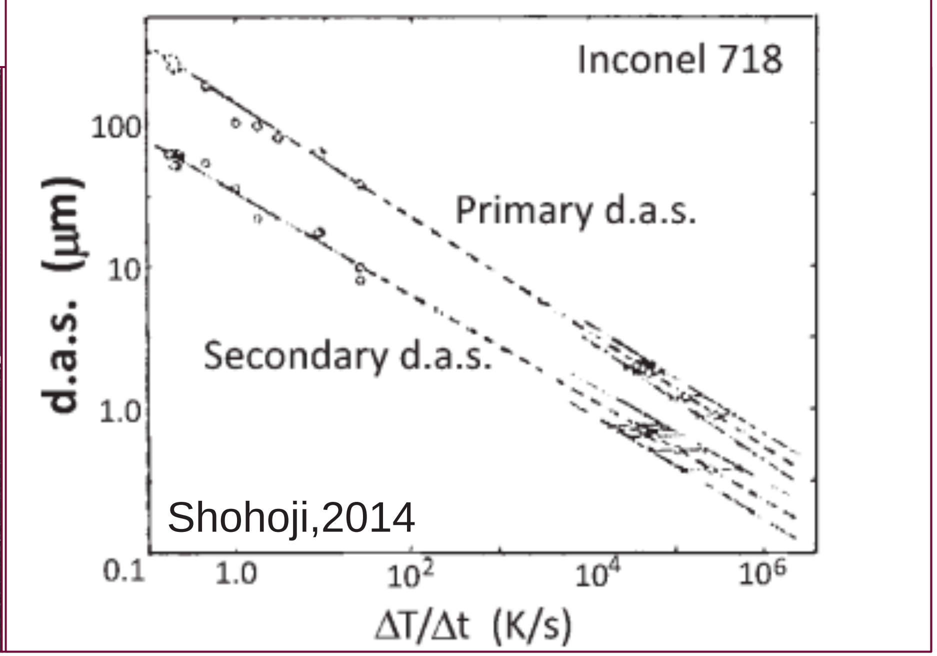
Rapid Solidification due to SLM

How Rapid (Ni-Superalloys) ?

- SLM creates a columnar γ-grain microstructure, containing virtually identically oriented γ-cells of size ~ 600 nm.
- The cells are separated by γ'/γ eutectic and a high density of Hf-rich precipitates, with a noticeable dislocation activity.
- The PDAS suggest cooling rates ~10^6 K/s.



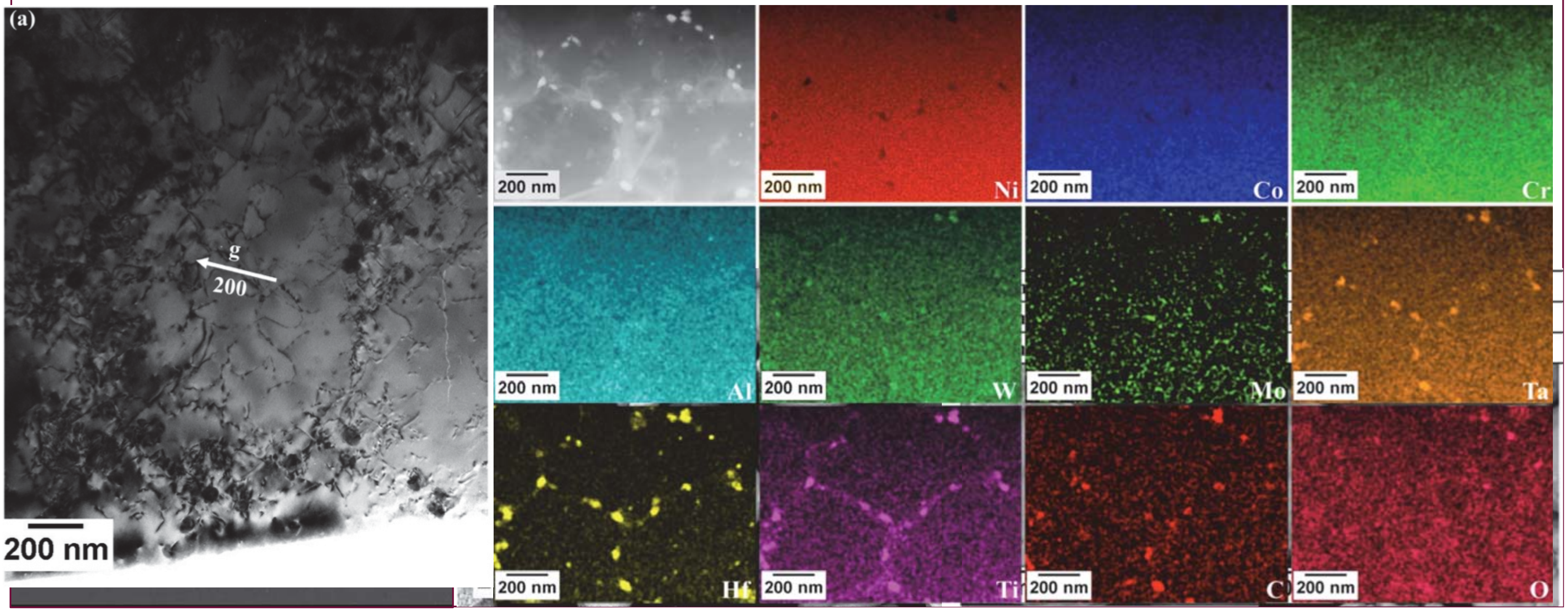


Shohoji,2014

Rapid Solidification due to SLM

Microstructural Causes of Cracking

- High dislocation activity (residual stress), particularly at the cell boundaries and at the vicinity of the (Hf,Ti,Ta)-rich particles.
- Al-evaporation, as spatter or vapour/plasma, creating condensed Al-rich particles.



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X Wang, N Read, LN Carter, RM Ward, MH Loretto, **MM Attallah**: Superalloys 2016, Seven Springs, USA, September 2016.

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Hybrid AM

Maximising the Production Rates

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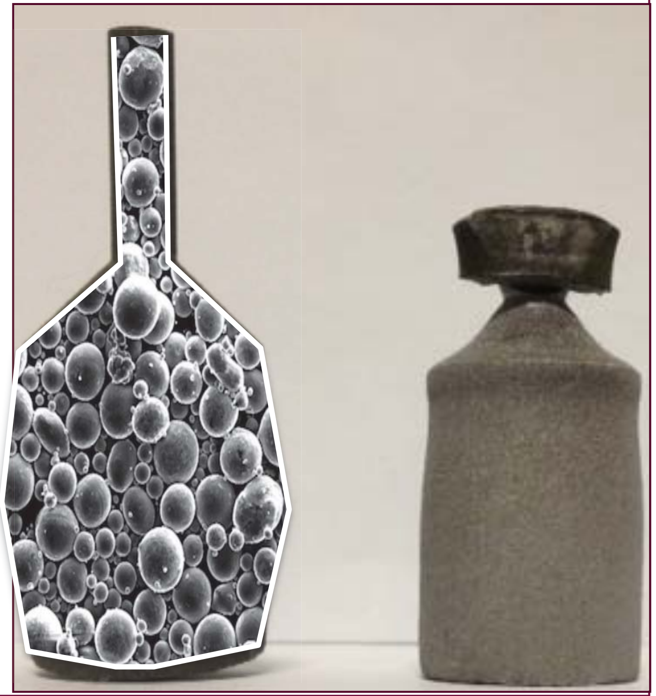
SLM / HIP
In-Situ Shelling

- **Aim:** Improve SLM productivity through creating a powder-filled shell, to be later HIPped.
- **Key challenge:**
  - FE modelling to predict the shape change due to HIPing.
  - Bond quality

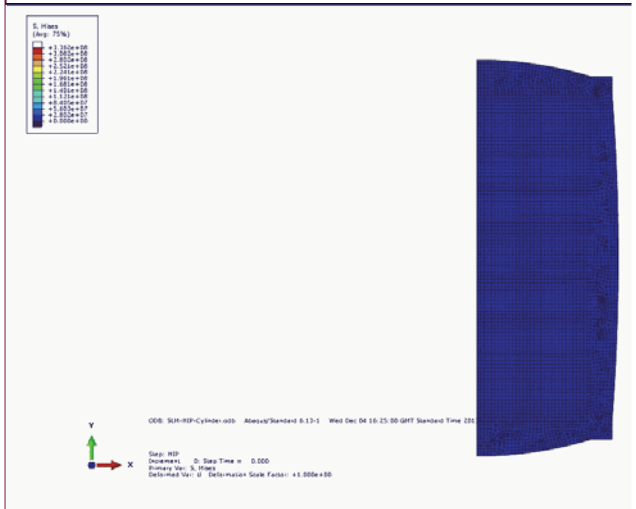


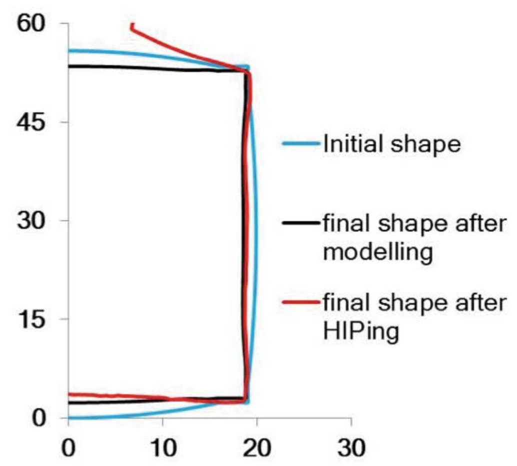
C Qiu, NJE Adkins, H Hassanin, **MM Attallah***, K Essa:, Materials & Design 87, 845-853, 2015.

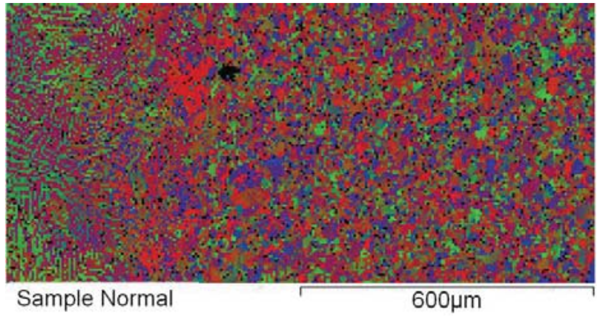
SLM / HIP

In-Situ Shelling of Ti-64

- **Aim:** Develop a novel in-situ shelling route to produce net-shape components with improved efficiency.
- **Key findings:**
  - Developed an iterative FE model to predict the shape change during HIPing, to design of SLMed tooling (pre-cursor shell).
  - Enhance the bond quality between the SLMed and HIPed parts.







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C Qiu, NJE Adkins, H Hassanin, **MM Attallah***, K Essa:, Materials & Design 87, 845-853, 2015.

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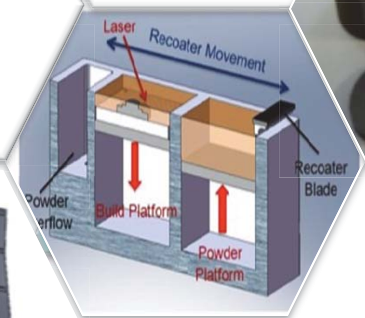
SLM-HIP of NbSi
SLM of Fe HIP Canisters

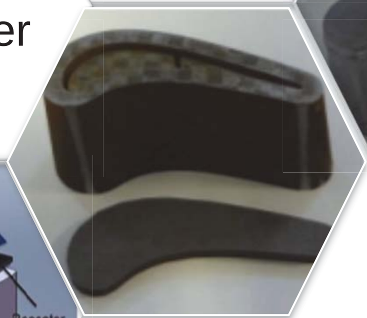
CAD design of HIP container

SLM with iron powder



Weld, fill can & HIP

Then pickle



Disclaimer

1. Fe HIP canisters are disposable.
2. Only use for un-SLM-processable alloys (e.g. crack-susceptible alloys).
3. Shrinkage need to be accounted for using FE modelling.

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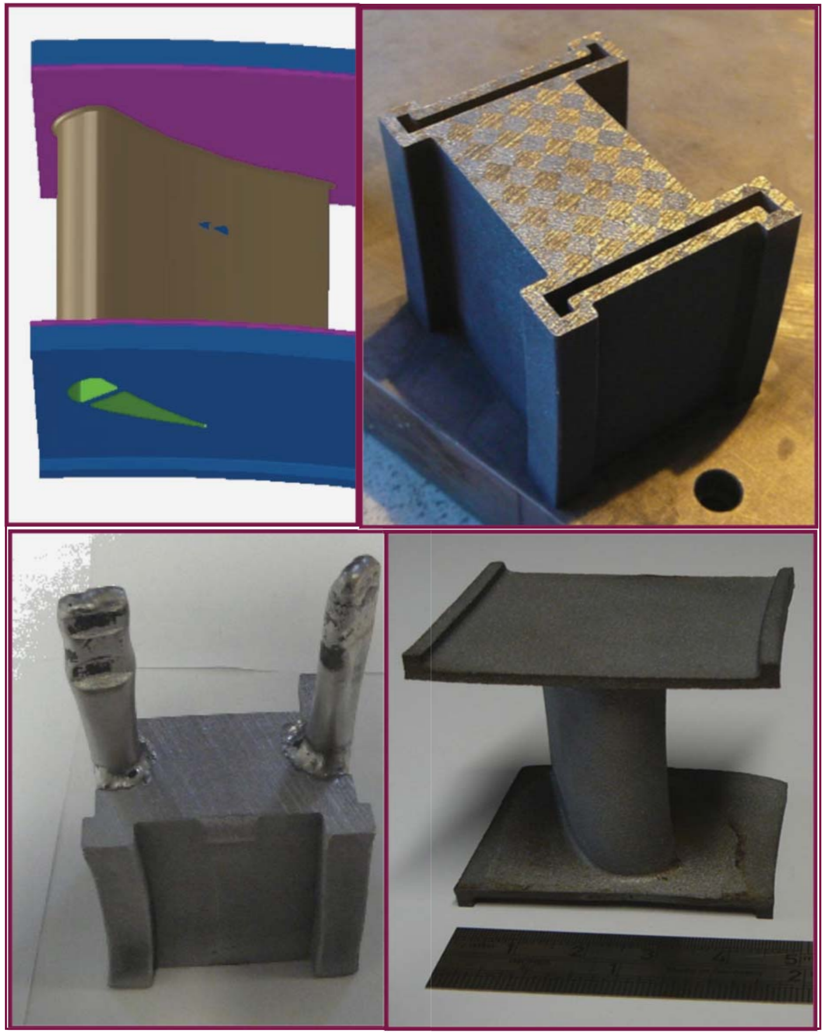
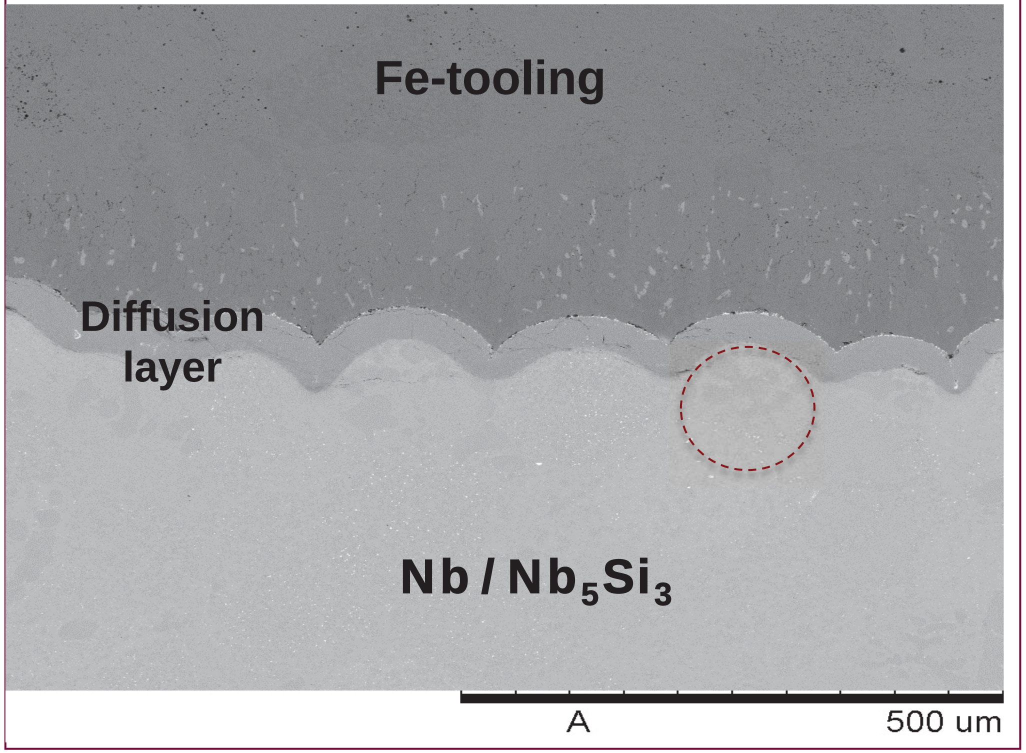
NbSi SLM-HIP Processing Route

Net Shape Tooling by SLM (Vane)



- ☐ Post-processing is required to remove the diffusion layer between the Fe-tooling and the component.



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Functional Structures

Lattices, Auxetics, & Drug Delivering Structures

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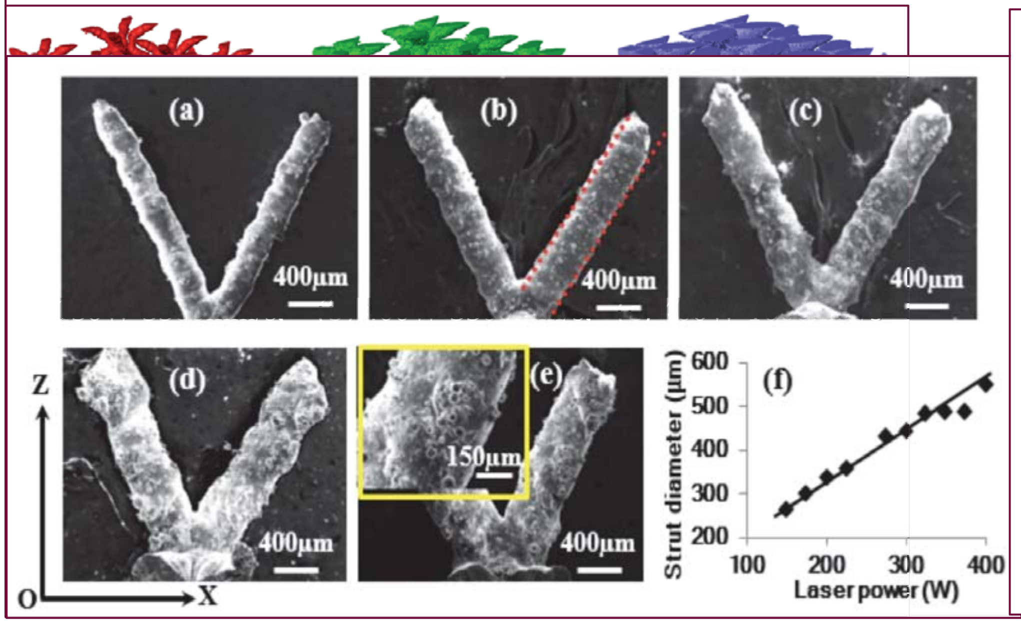
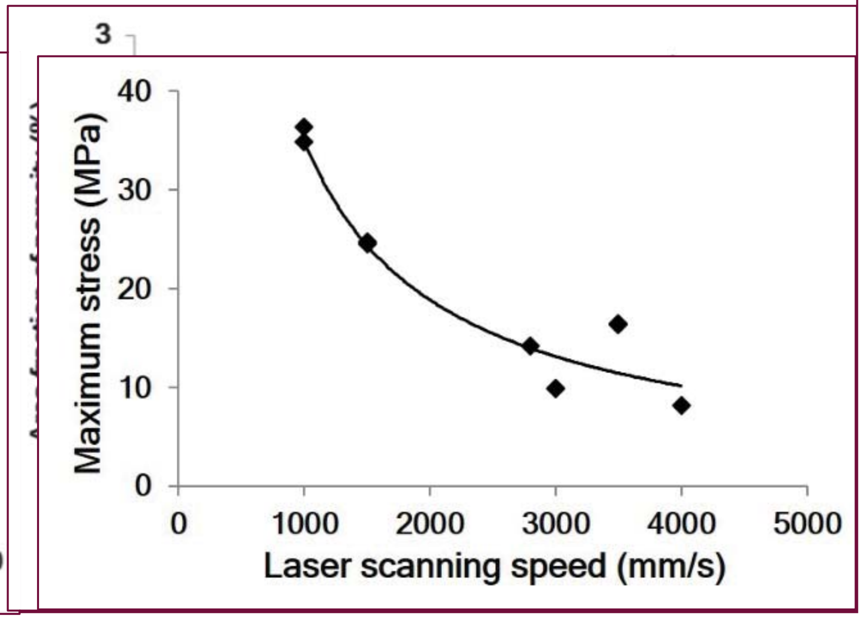
SLM of Lattice Structures

The Limit of SLM Resolution

- **Aim:** Investigate the influence of SLM parameters on the strut size, internal porosity and compressive strength of lattice structures.
- **Key findings:**
  - Characterisation of the internal porosity of lattices.
  - Microstructural and mechanical properties developments.





C Qiu, S Yue, NJE Adkins, RM Ward, H Hassanin, PD Lee, PJ Withers, MM Attallah. Materials Science and Engineering A, 2015, vol. 628, pp. 188-97.

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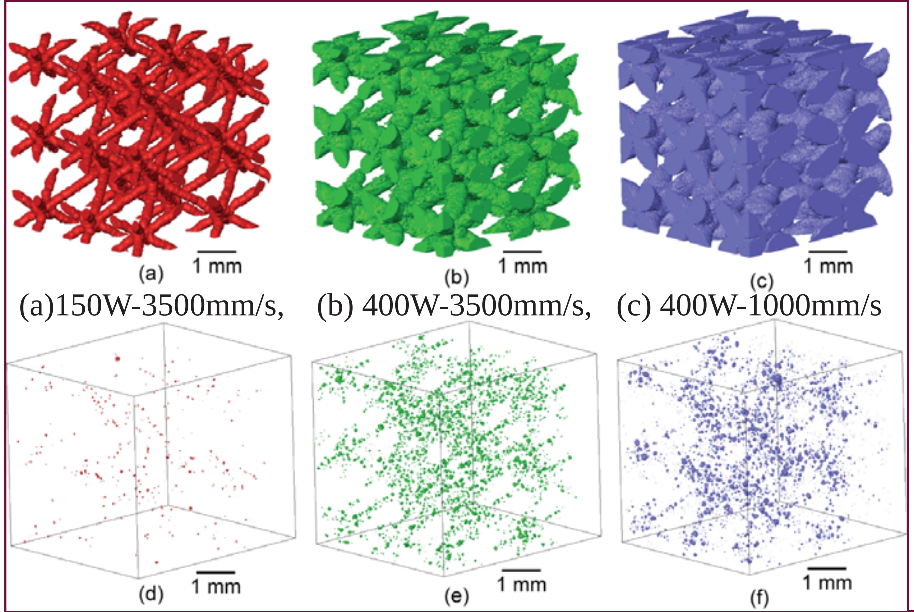
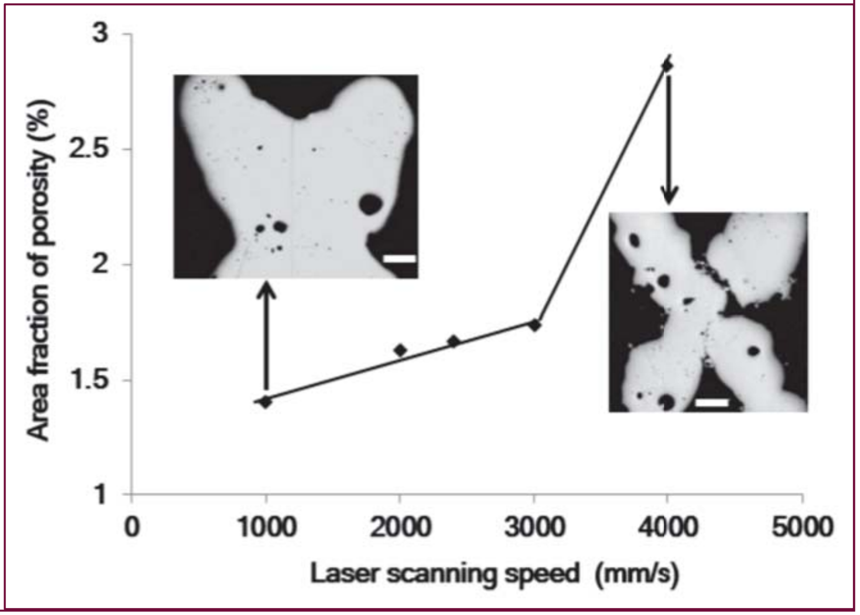
- **Key findings:**
  - Characterisation of the internal porosity of lattices.
  - Microstructural and mechanical properties developments.



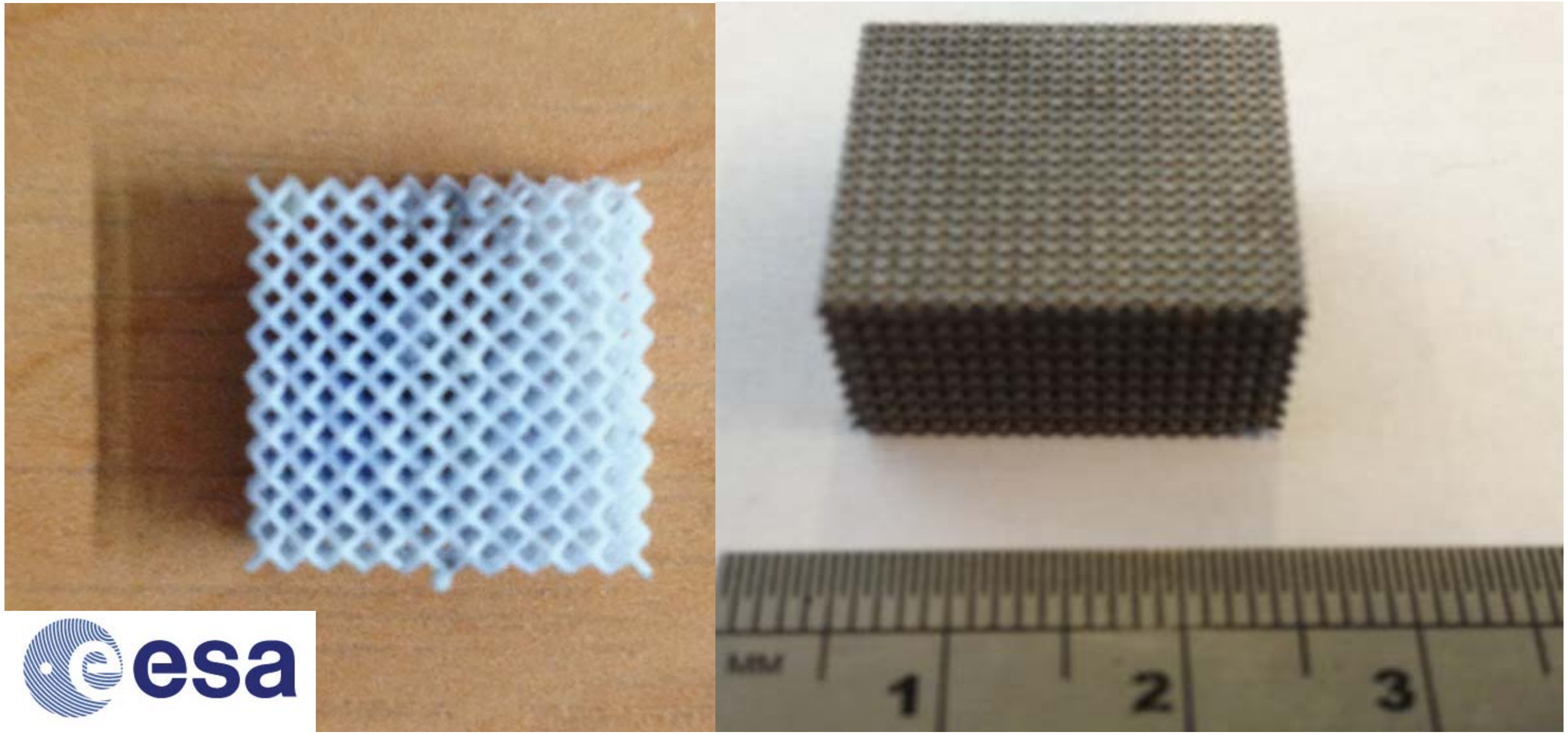


C Qiu, S Yue, NJE Adkins, RM Ward, H Hassanin, PD Lee, PJ Withers, MM Attallah. Materials Science and Engineering A, 2015, vol. 628, pp. 188-97.

Transforming Metals to Ceramics

Ceramic Catalyst Bed for Propulsion

The formation of ceramic lattices via oxidation of a metal preform.



H. Hassanin, N. Adkins, D. Jarvis and W Voice
"Manufacturing of A Ceramic Article from a metal perform provided by 3D-Printing or 3D-Weaving ", European Patent Office (EPO), PCT/EP2013/075550, **2013**.

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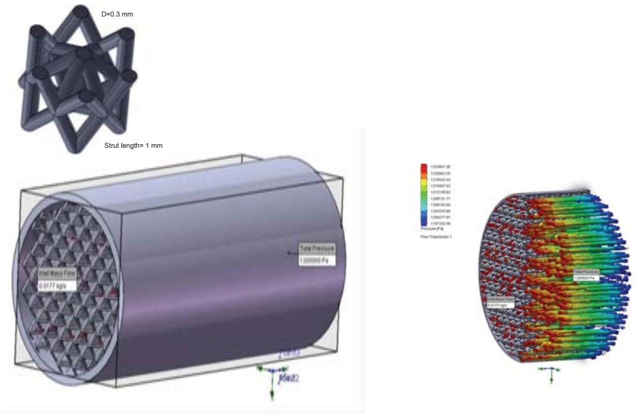
Research Highlights

Additive Manufacturing of Ceramic Catalyst Beds

- **Aim:** to use additive Manufacturing as a Key Enabler for Enhanced Monopropellant Catalyst Bed Design.
- **Approach:**
  - Design and computational fluid dynamics calculations.
  - Develop a novel additive manufacturing route suitable for catalyst bed applications and define their limitations.
  - Manufacture a breadboard catalyst bed and perform firing tests.



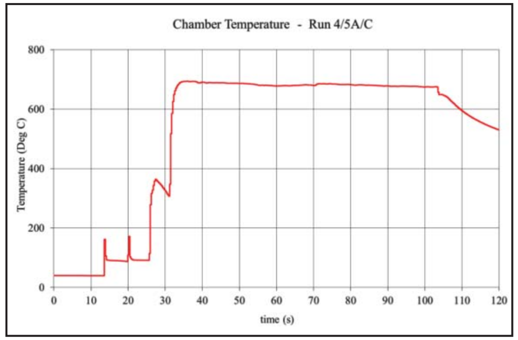
Design and CFD

AM Alumina Catalyst Bed

Thruster Assembly

Coated Catalyst Bed

Thruster After firing



Temperature Increase
(firing test)

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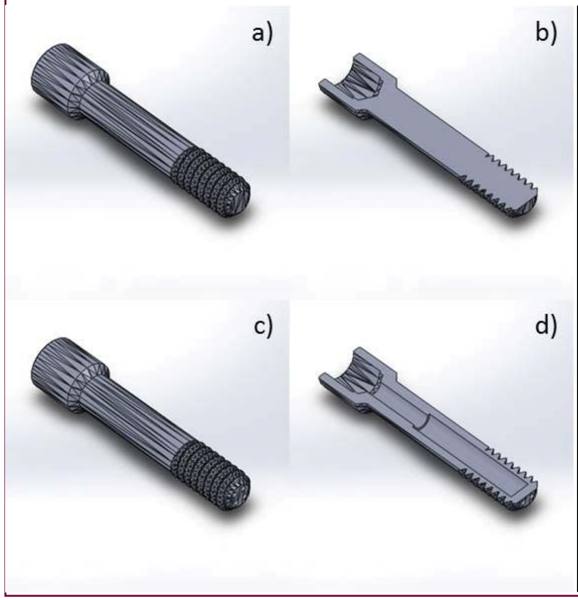
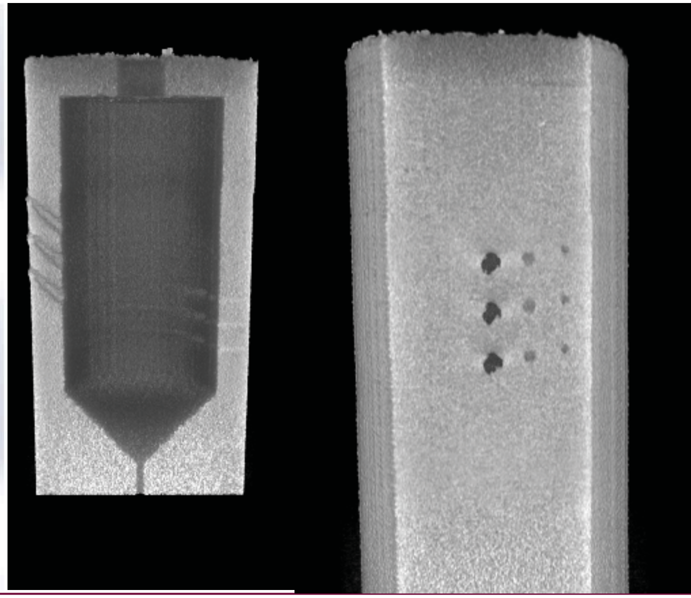
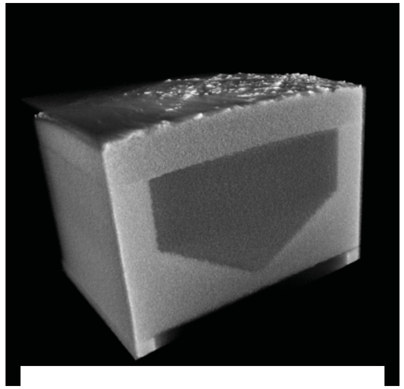
Monitoring Drug Release in SLMed Implants

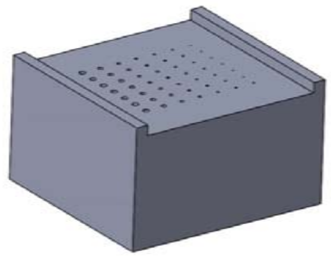
Implants with Embedded Therapeutics (NIDMET)

- The use of ALM in the manufacture of drug-delivering metallic implants.
- Drugs will be fed into the implants during fixation, and will be dispensed during their life to decrease the likelihood of infection.









SC Cox, H Hassanin, MM Attallah, DE Shepherd, O Addison, U Gbureck, LM Grover. Materials Science & Engineering C: 2016.

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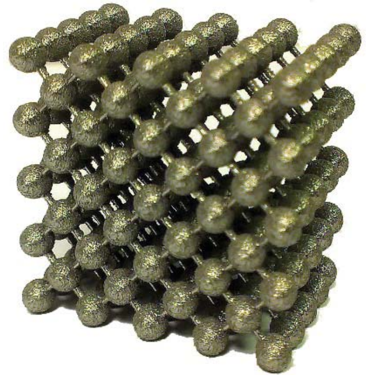
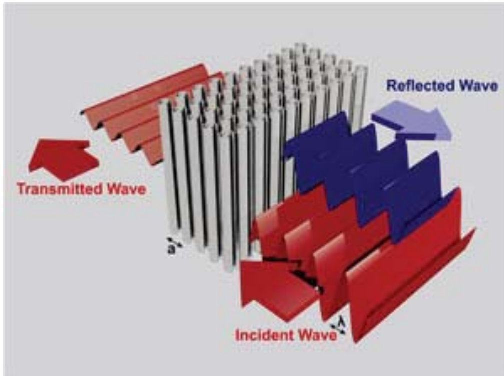
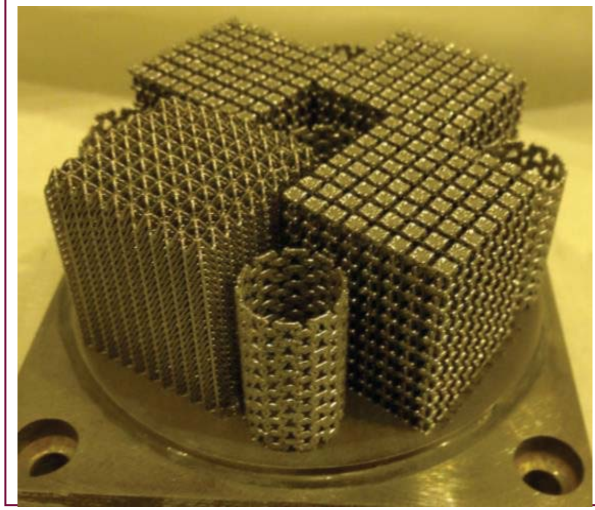
TiNi Functional Structures

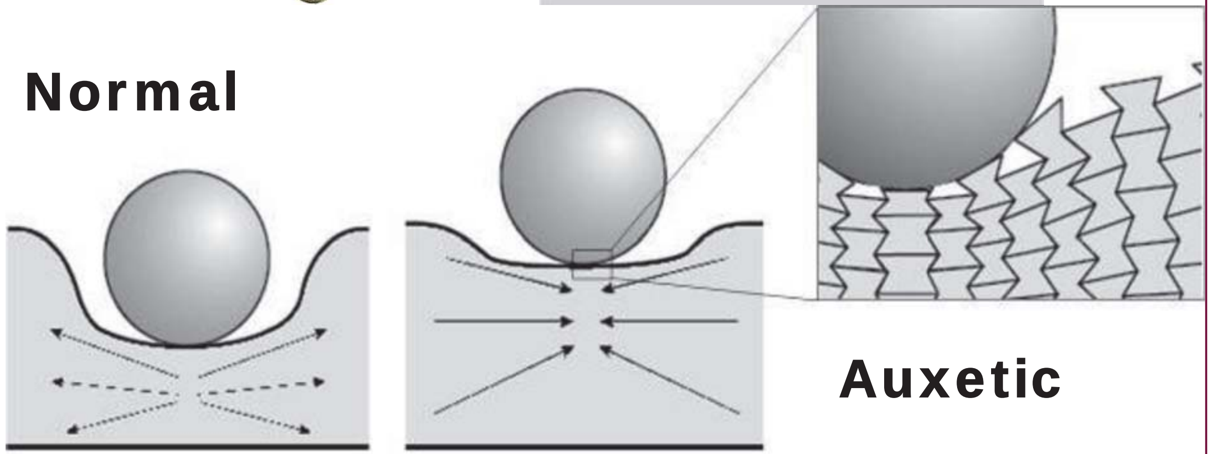
AM Functional Structures

- Sonic crystals: Structure blocks certain wavelength.
- Auxetic structure: Negative Poisson's ratio.







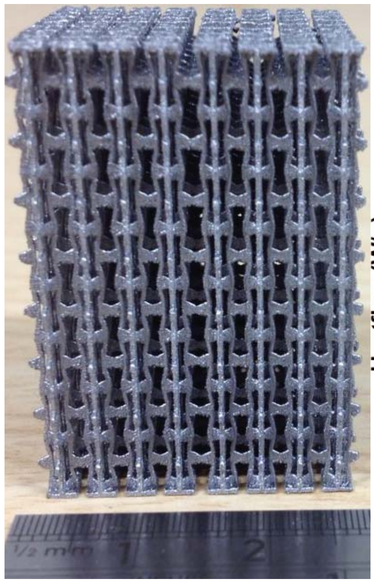


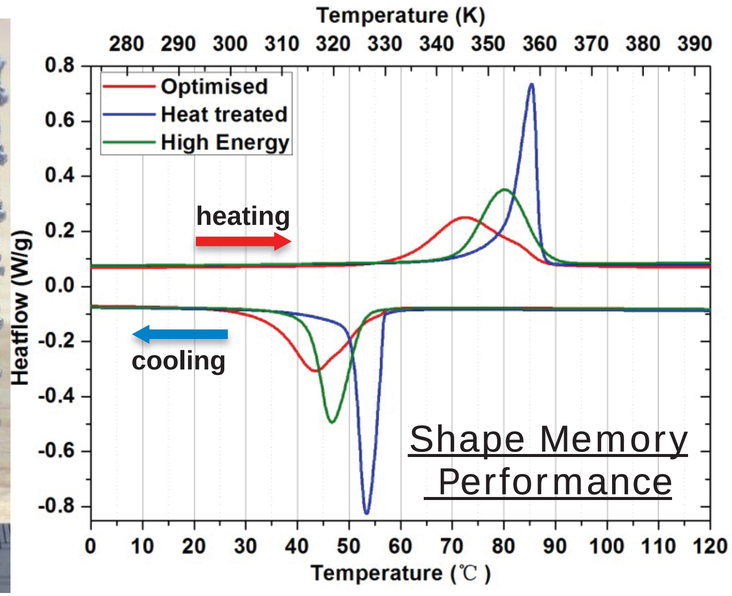
S Li, H Hassanin, **MM Attallah***, NJE Adkins, K Essa: Acta Materialia 105, 75-83, 2016.

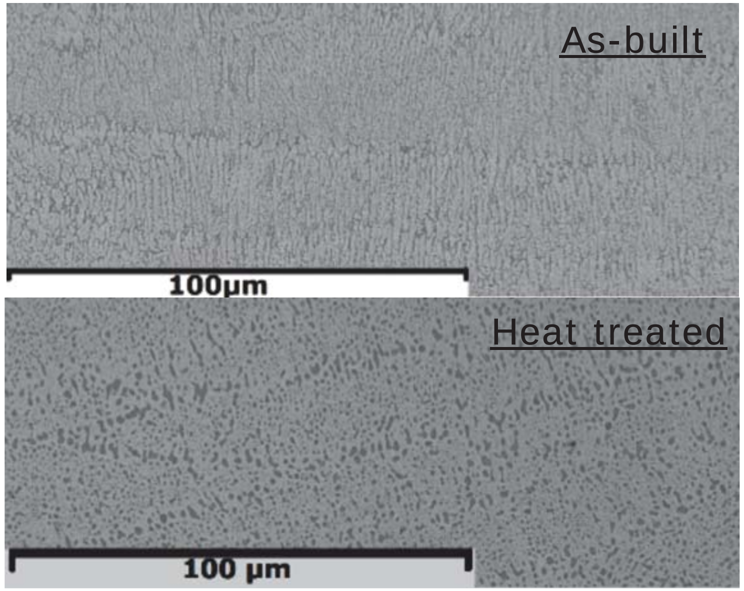
Research Highlights

SLM on TiNi Shape Memory Alloys Auxetics

- **Aim:** Using selective laser melting (SLM) to produce NiTi auxetic structure components with superelastic effect.
- **Key findings:**
  - Reduction of cracking and porosity;
  - Using heat treatment to improve shape memory performance;
  - Achieving auxetic performance during mechanical testing.







S Li, H Hassanin, **MM Attallah***, NJE Adkins, K Essa: Acta Materialia 105, 75-83, 2016.

ALM Processing of NiTi
Challenges

- **Powder quality:** Functionality sensitive to oxygen content.
- **Cracking susceptibility:** due to residual stresses and the presence of brittle intermetallics.
- **Control of defects via laser parameters:** pores or cracks
- **Ni-evaporation**
- **Formation of intermetallics**: a need for thermal post processing.

S Li, H Hassanin, **MM Attallah***, NJE Adkins, K Essa: Acta Materialia 105, 75-83, 2016.

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Large Scale AM

DLD of Large Ti Structures

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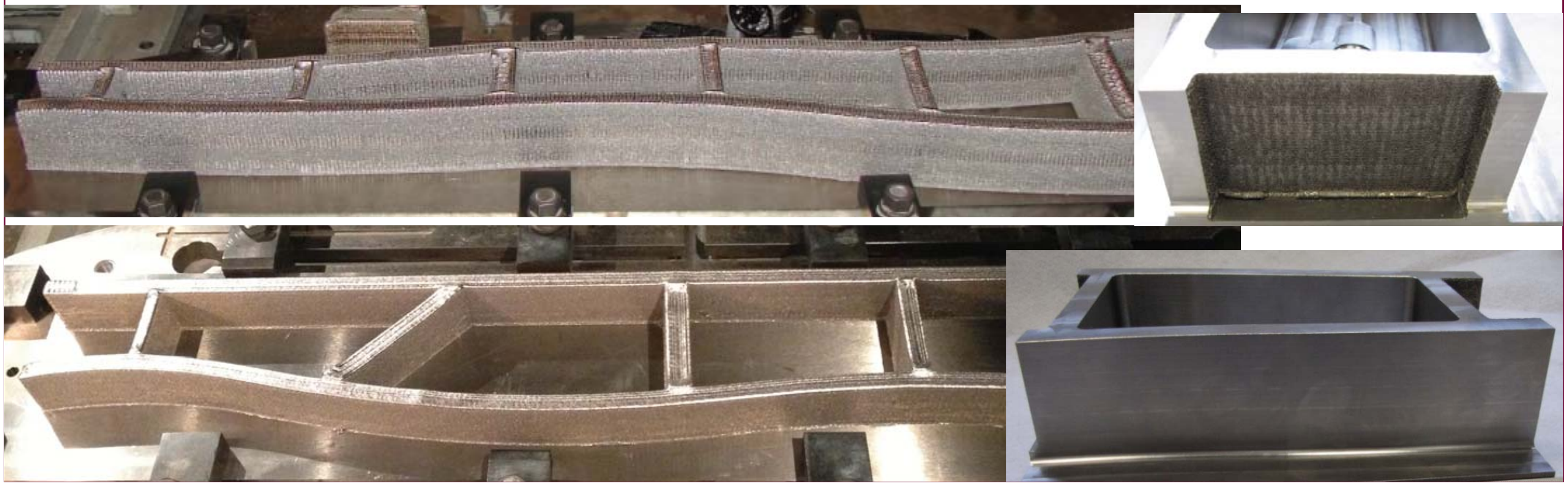
Research Highlights (DLD)

Netshaping using Direct Laser Deposition of Ti-64

- **Technology scale up** at UoB to produce large (>1m long structures) through optimisation of the process parameters and tool path to minimise porosity and microstructural heterogeneity, and maximise the geometrical consistency.
- The properties of the final component **(after HIPping)** were similar to a conventionally manufactured component, with significant reduction in material waste and processing time.



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C Qiu, GA Ravi, C Dance, A Ranson, S Dilworth, **MM Attallah***: Journal of Alloys & Compounds 629, 351-61, 2015.

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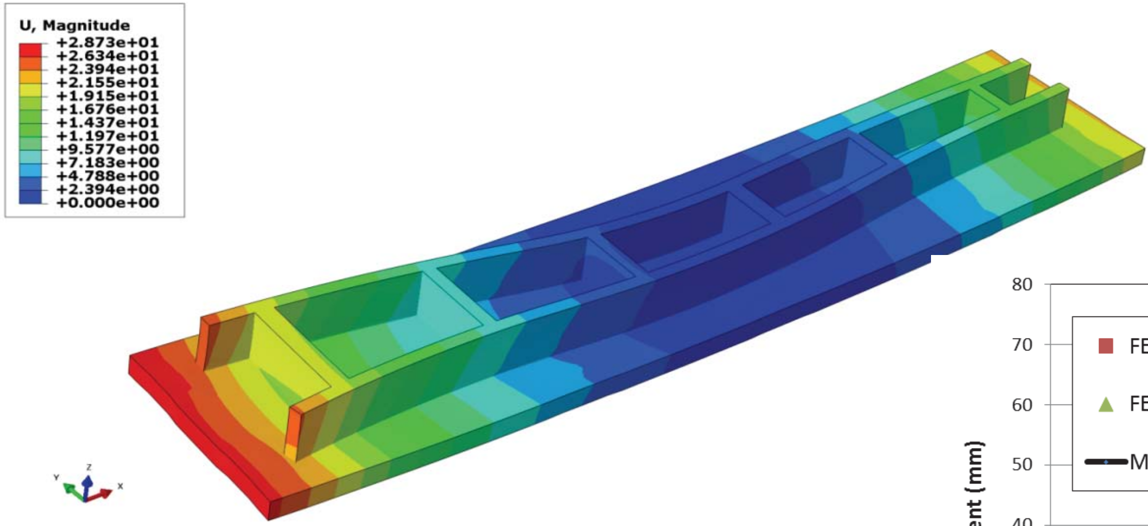
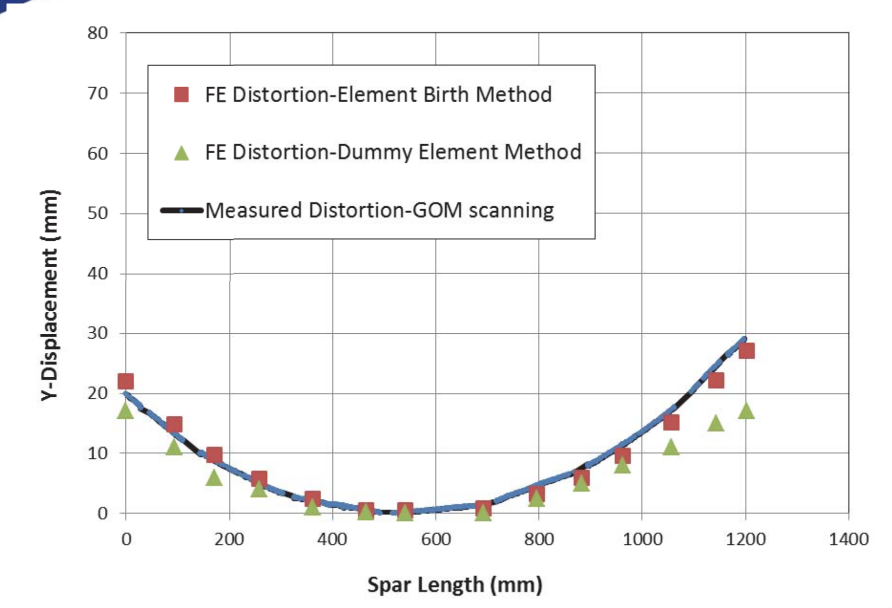
Addressing AM Research Challenges

Modelling Distortion in DLD of Large Structures

- Developing rapid simulations without undermining the computational accuracy.





C Qiu, GA Ravi, C Dance, A Ranson, S Dilworth, **MM Attallah***: Journal of Alloys & Compounds 629, 351-61, 2015.

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Maximising Performance

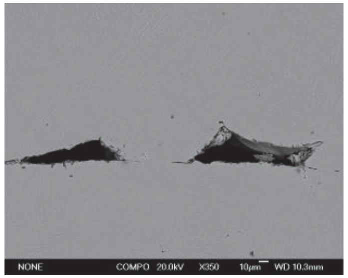
Thermal Post-Processing

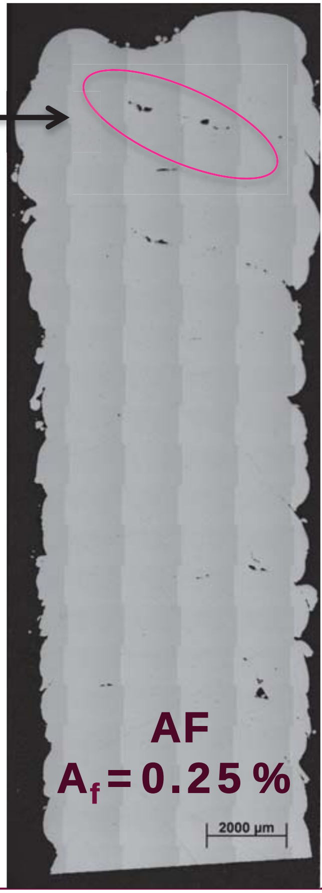
Influence of HIPping on Porosity

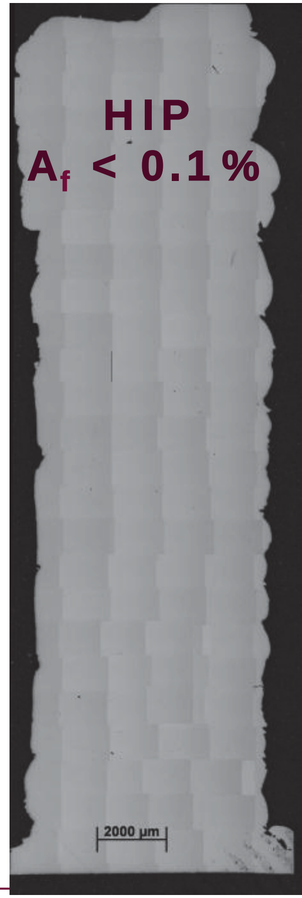
Ti-6Al-4V DLD (Blown Powder)

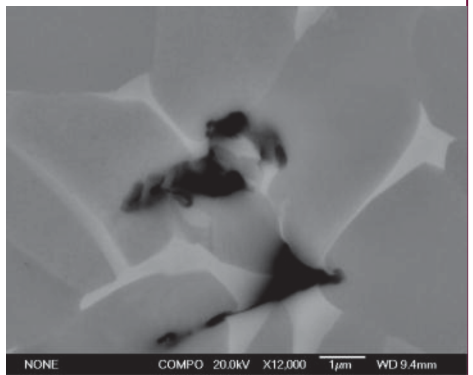
- HIPping closed most of the spherical pores within the build microstructure, but struggled with lack of fusion defects.

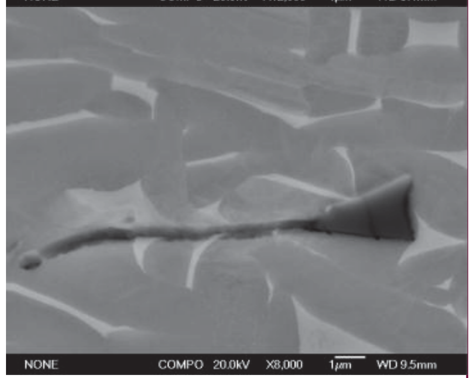
Lack of fusion defect











Pores collapsed after HIPping

Z

Y

C Qiu, GA Ravi, C Dance, A Ranson, S Dilworth, **MM Attallah***: Journal of Alloys & Compounds 629, 351-61, 2015.

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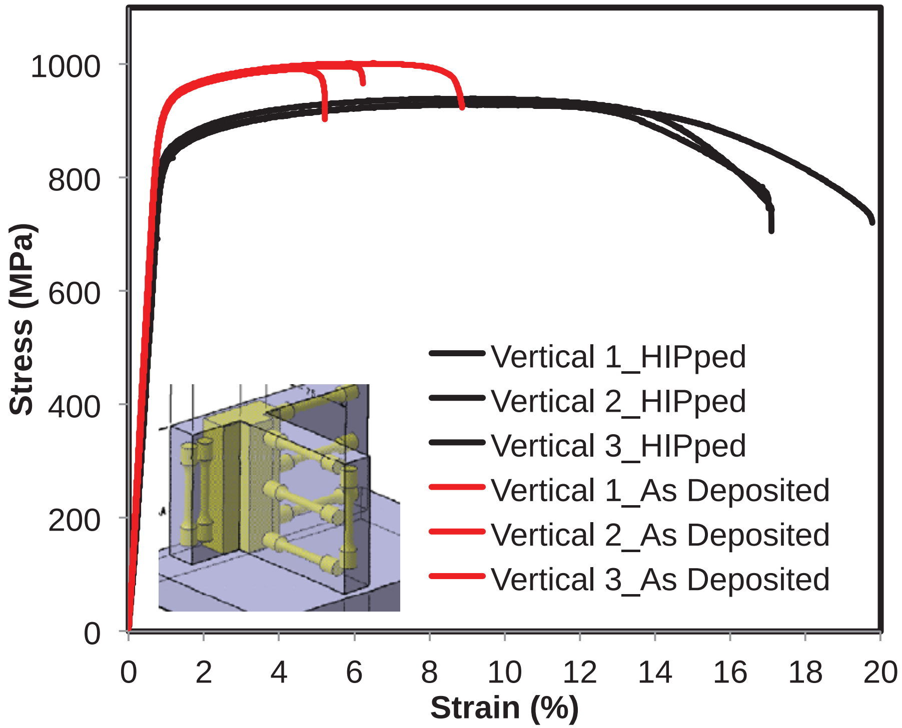
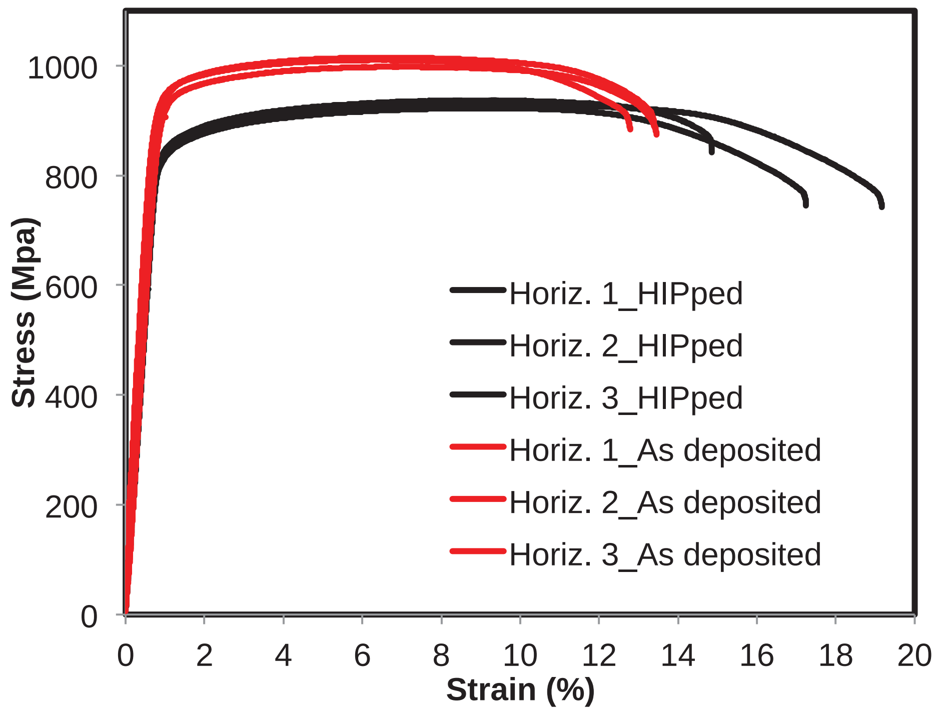
Research Highlights (DLD)

Netshaping using Direct Laser Deposition of Ti-64

- The as-fabricated samples show generally high UTS but low EL
- The horizontal samples show better EL% than vertical ones.
- HIPping considerably improved the ductility with the reduction of tensile strength.





C Qiu, GA Ravi, C Dance, A Ranson, S Dilworth, **MM Attallah***: Journal of Alloys & Compounds 629, 351-61, 2015.

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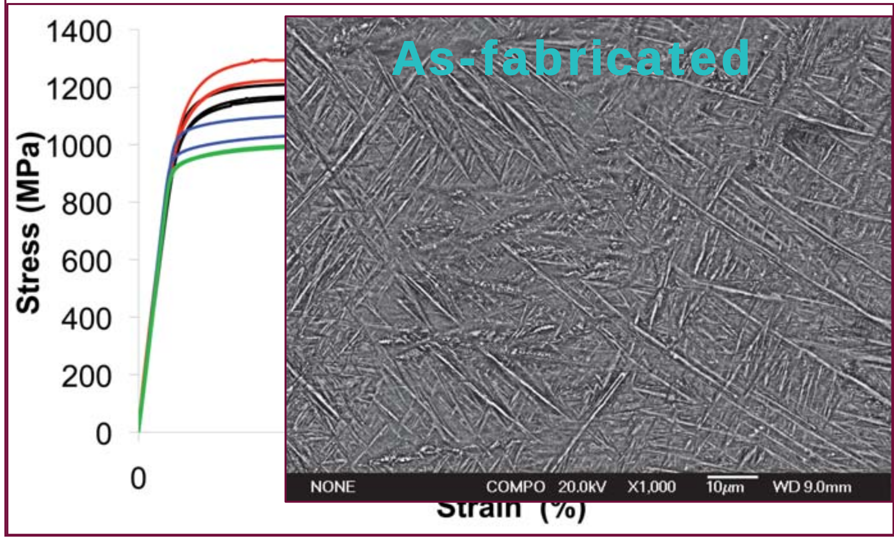
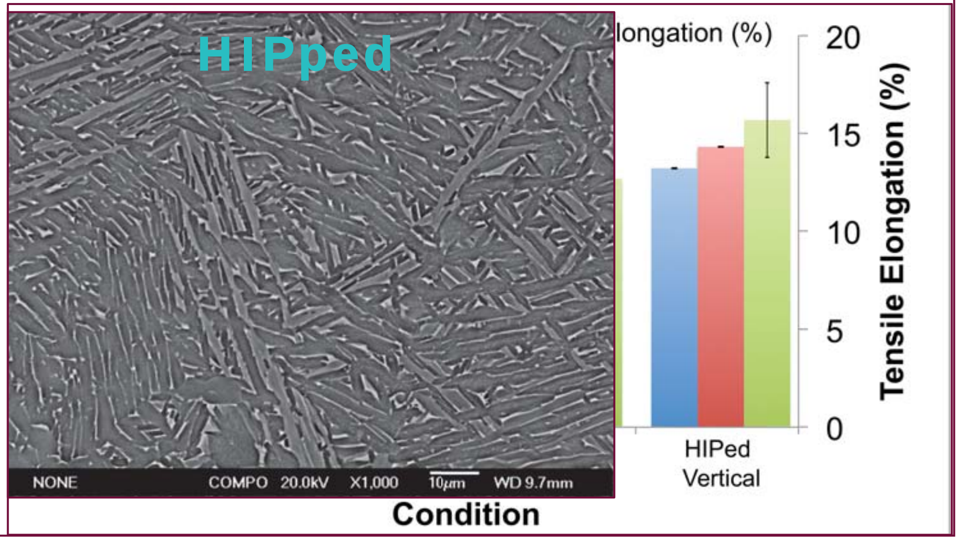
Tensile Properties Ti-6Al-4V SLM

As-Fabricated & HIPed, Build Orientation

- HIPping results in coarsening the fine α/α' structure to the $\alpha+\beta$ microstructure, slightly dropping the tensile strength.
- Considerable improvement in the tensile ductility was observed following HIPing, for both orientations (vertical & horizontal).
- The vertically-built specimens showed a generally higher tensile elongation (either as-fabricated or HIPed).

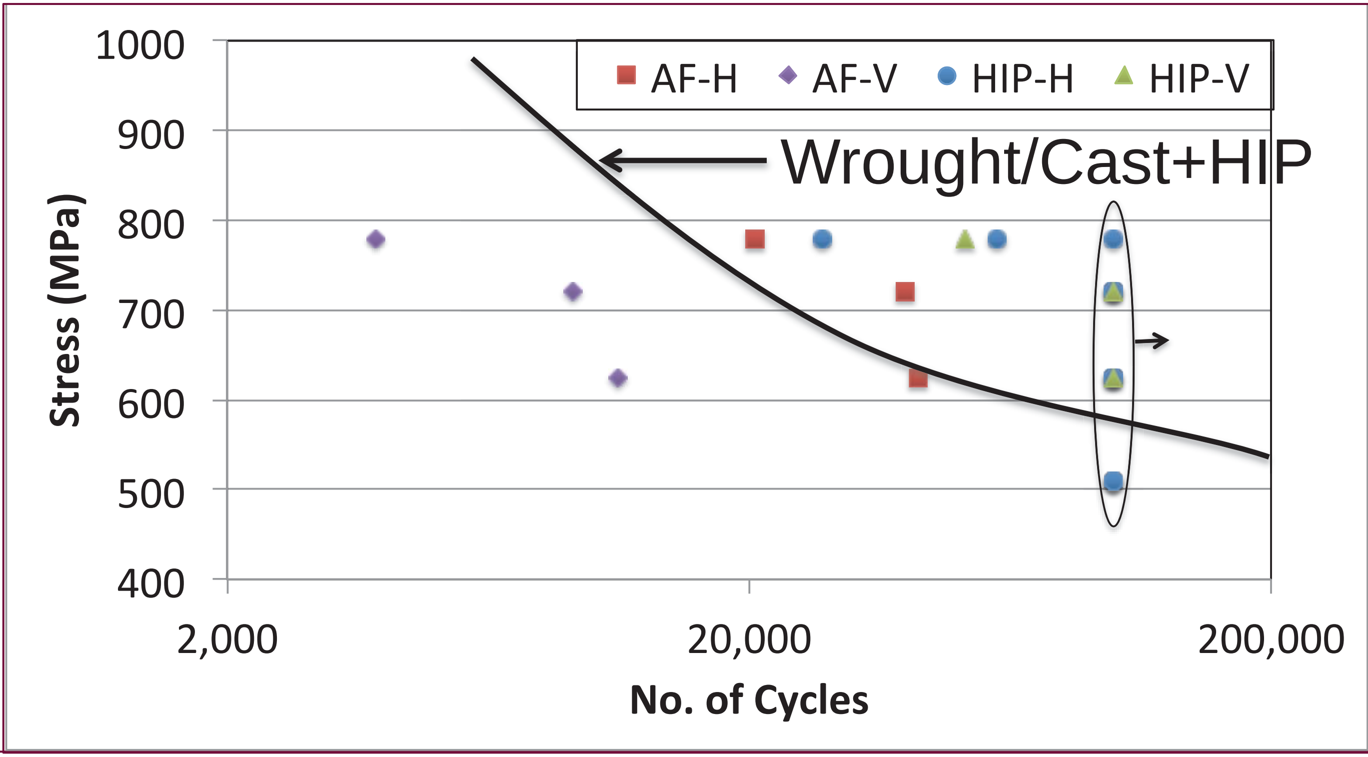




Fatigue Properties Ti-6Al-4V SLM

As-Fabricated & HIPed, Build Orientation

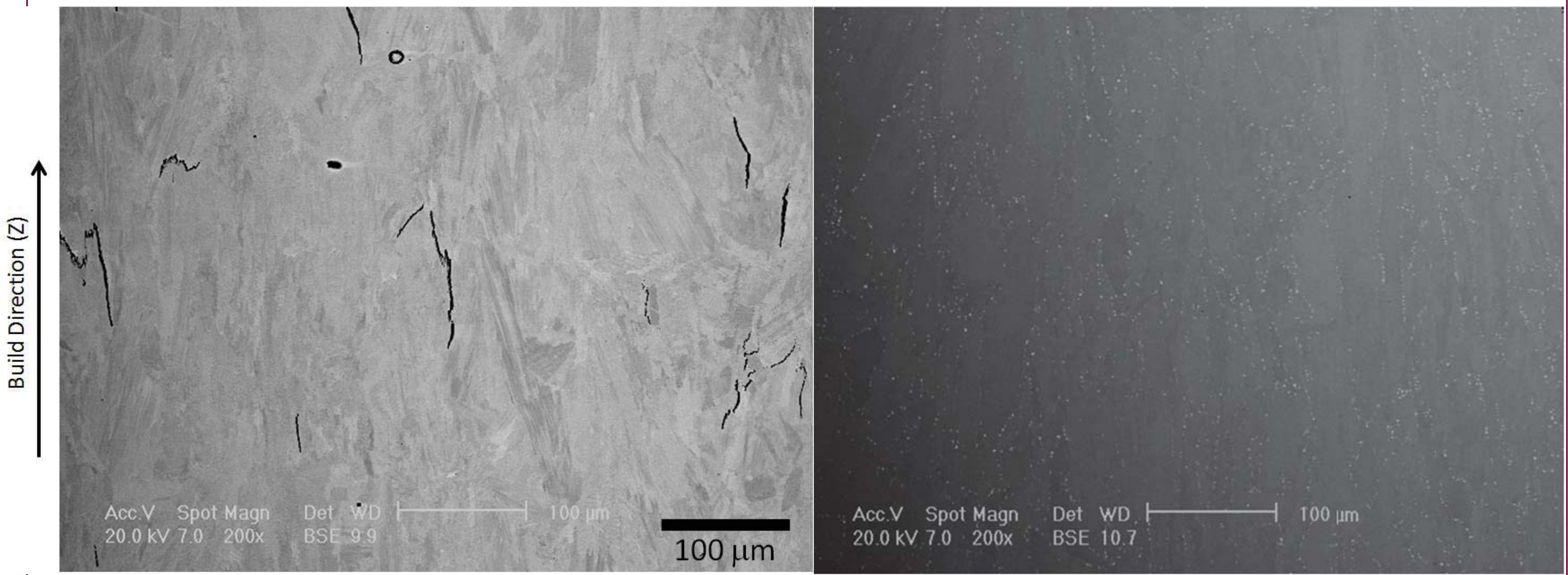
- HIPping results in an improvement in the fatigue life, yet still a scatter exists after HIPping, but generally similar to Cast+HIP or wrought Ti-6Al-4V.



HIPping for Crack Closure (Post SLM)

CM247LC Ni-Superalloy

- -HIPping has been shown to effectively close internal cracks

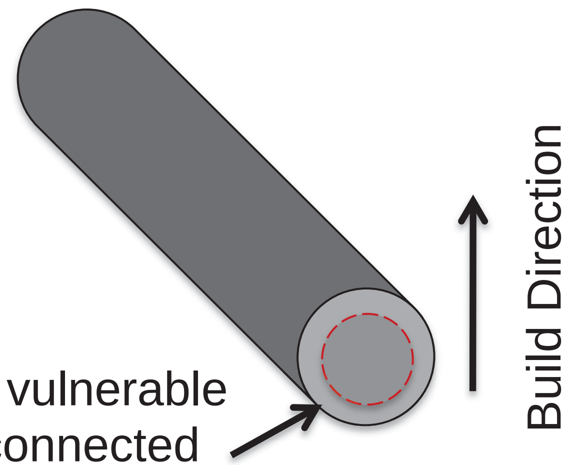


SLM Fabricated CM247LC Before and After HIPping

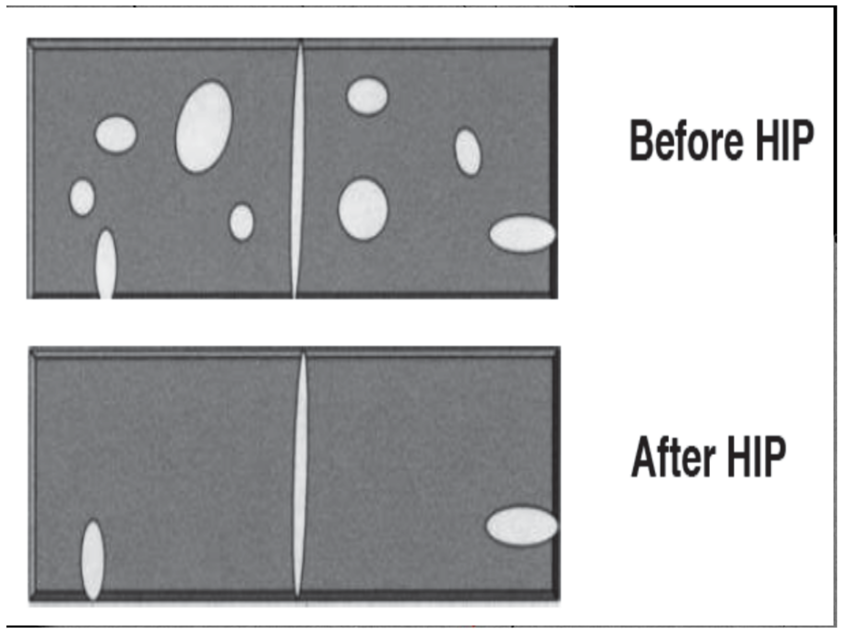
HIPping for Crack Closure (Post SLM)

CM247LC Ni-Superalloy

- HIPping cannot close the surface-connected cracks.



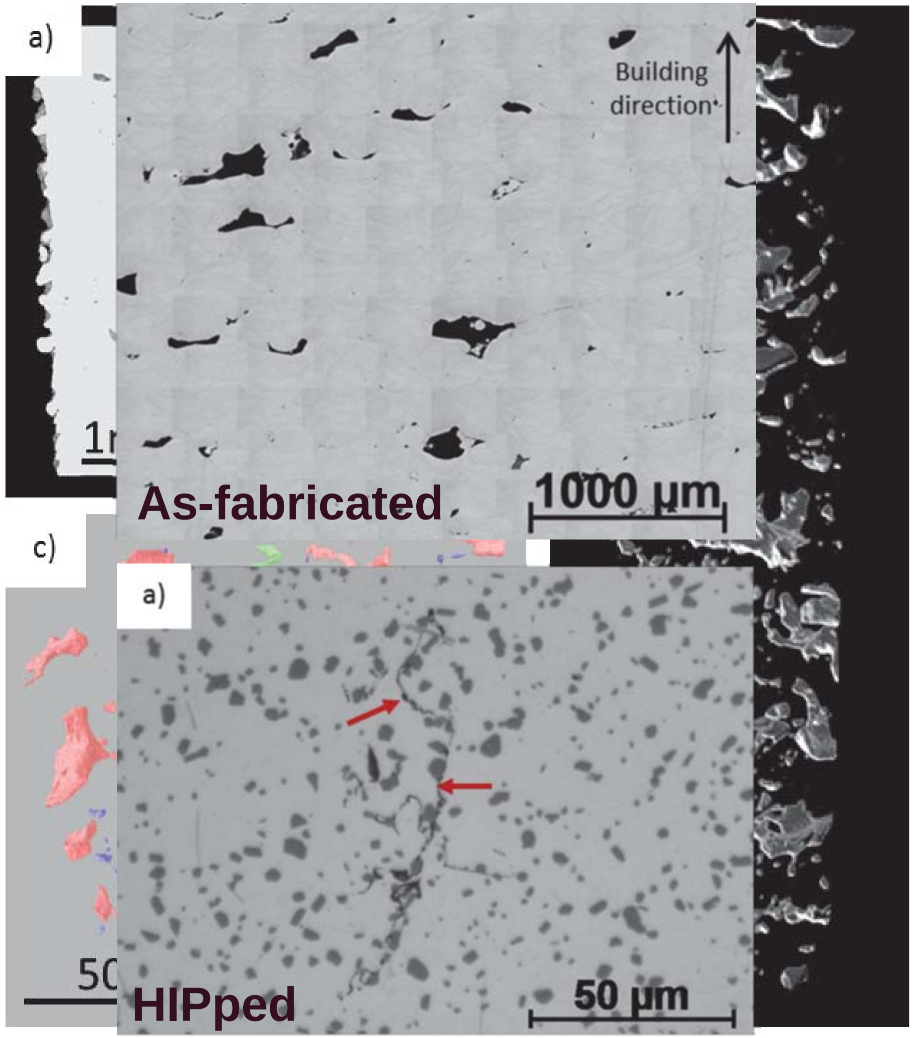
Outer region vulnerable to surface connected cracks (*Approx. 1mm-1.5mm wide*)



Post-Processing of Al-Alloys

HIPping of AlSi10Mg Alloys

- Highly susceptible to oxide film defects, resulting in poor wetting/melt penetration, and lack of fusion defects.
- HIPping collapses the oxide film defects, but remnants of the oxide films are visible.
- Post-processing reduces the strength due to the coarsening of the grain structure.



U Tradowsky, J White, RM Ward, N Read, W Reimers, **MM Attallah**: Materials & Design, in press, 2016.

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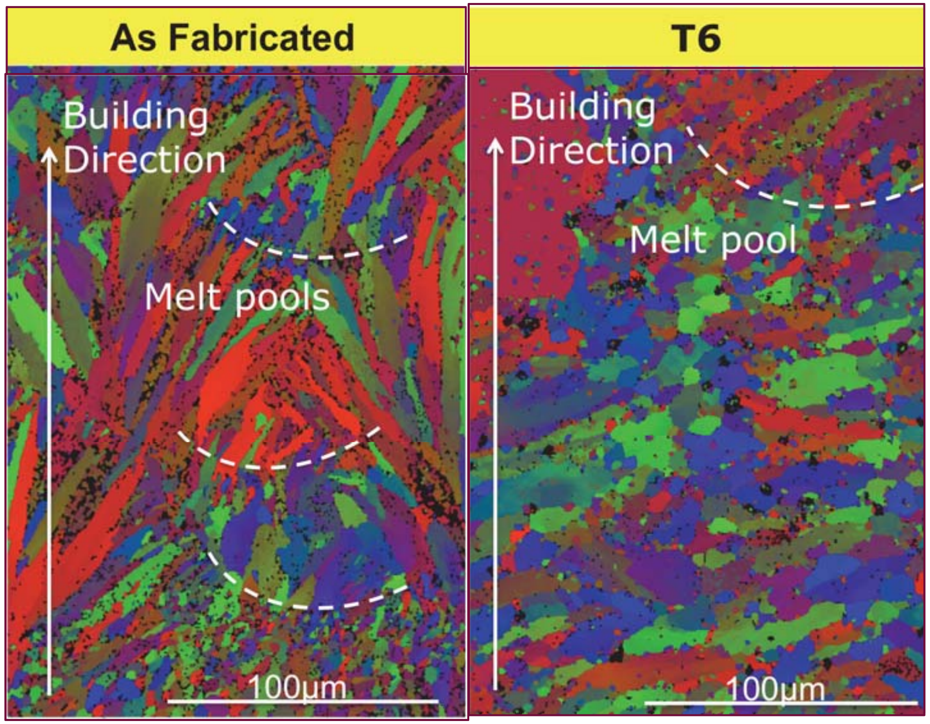

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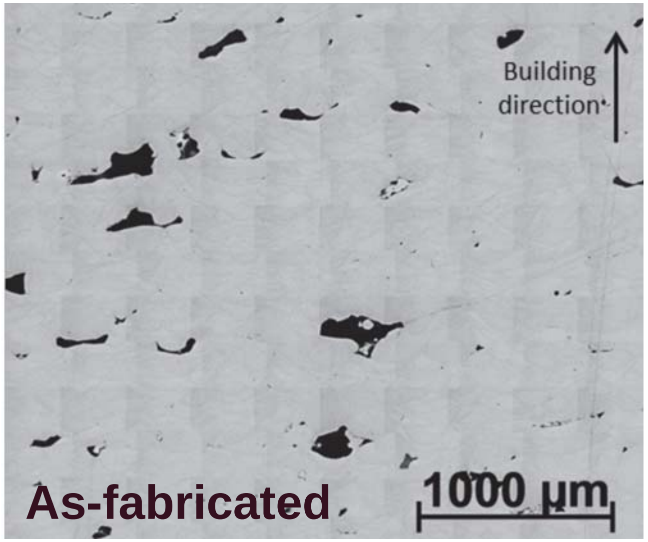

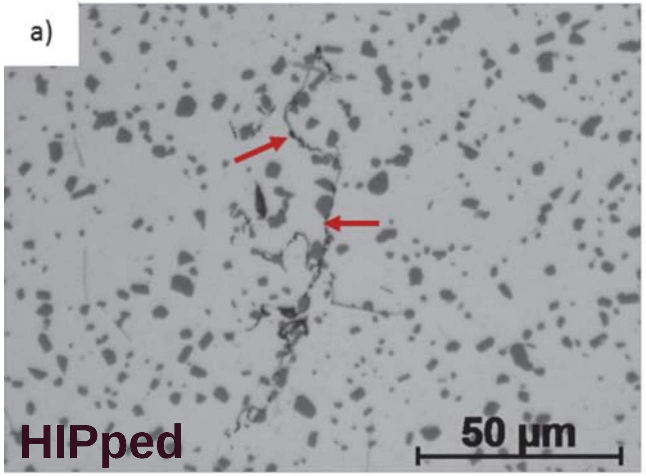

U Tradowsky, J White, RM Ward, N Read, W Reimers, **MM Attallah**: Materials & Design, in press, 2016.

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Research Highlights

Alloy Development

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Next Generation AM Materials

- The majority of metal AM work has focused on a limited alloy list: AlSi, IN718, Ti-64, & 316L, typically alloys for casting, forging, rolling, but not AM.
- Other investigated alloys were prone to defects:
  - Cracking (high γ' Ni-superalloys)
  - Residual stress
  - Gas porosity
- There is a need to develop AM-specific alloys, by tailoring existing alloys or using the flexibility of AM in alloy development.

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Alloy Development with Elemental Powders

SLM of low CTE Al-Si alloys

- Mixing of elemental powders (Al+Si) to create tailored CTE structures (in-situ), to avoid the need for pre-alloyed powders.

Alloy Development using Fine Powder Doping

SLM of Ti64-0.2Pd

- **Aim:** Develop modified Ti-based alloy using SLM to improve corrosion resistance.
- **Approach:**
  - Mix powder Ti-64 powder with Pd using a novel mix technique
  - Chemical analysis of as-SLMed samples
  - Evaluate corrosion behaviour with and without Pd addition

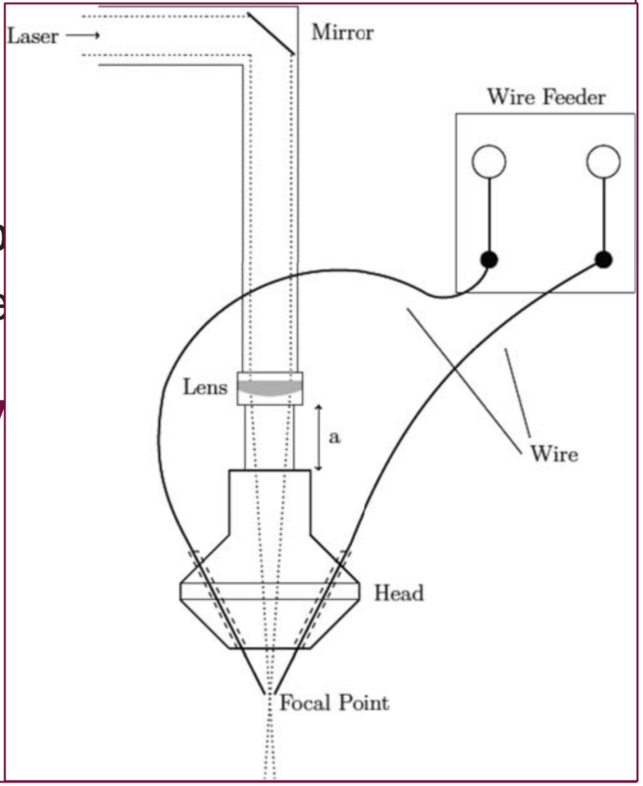
Alloy Development

Laser Combinatorial Synthesis

- **Combinatorial Synthesis (CS):** the production of a large number of alloy combinations in a simple process to identify new alloy combinations with interesting properties.

- **Wire-based combinatorial synthesis**
  - Developed in Birmingham
  - Laser beam melts elemental wires.
  - Composition is adjusted by wire-feeding sp
  - High-throughput: alloy buttons in 5 minute

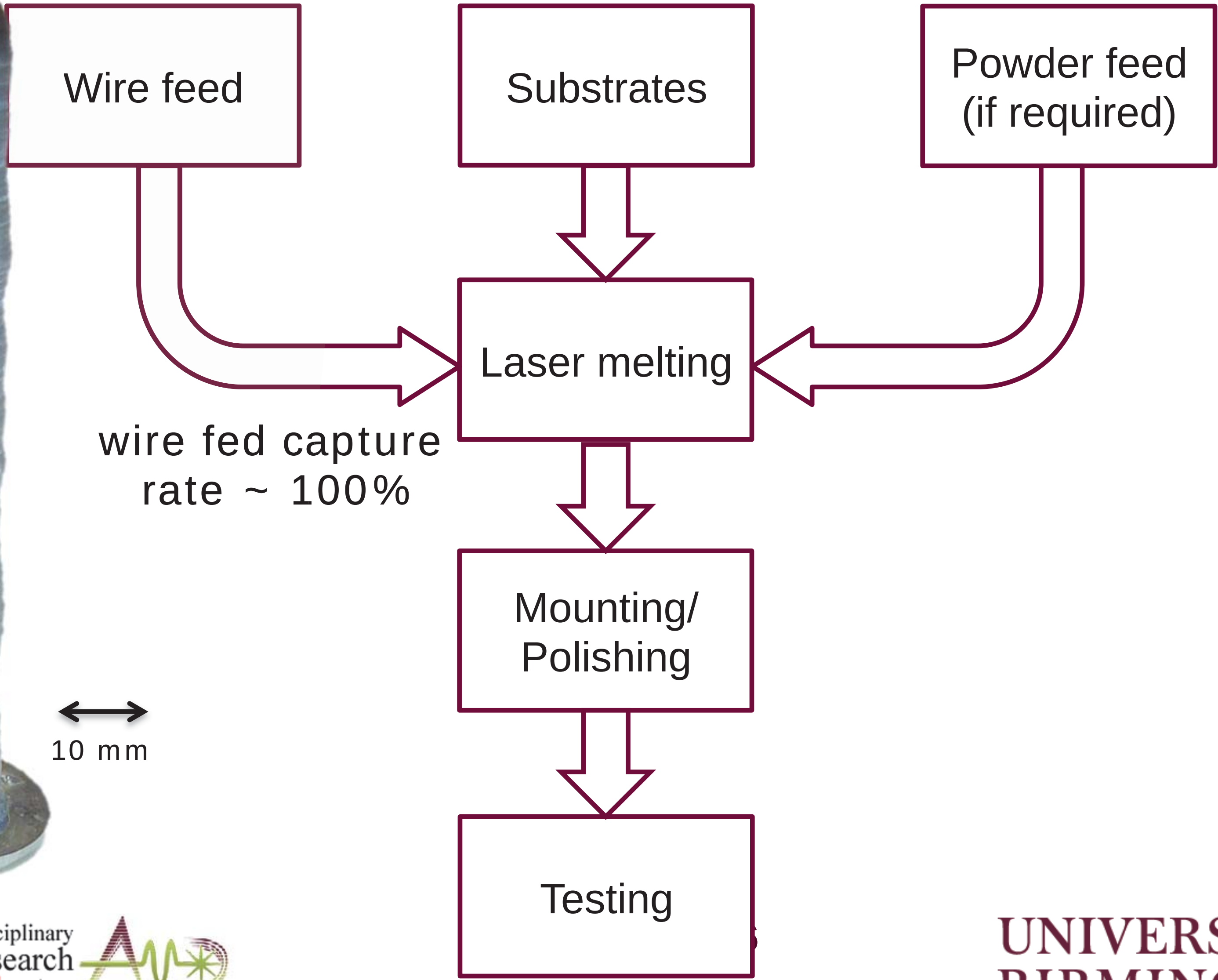
- **Current activities: design of metallic alloy**
  - High temperature smart materials
  - Thermoelectric materials
  - Superconductors
  - Corrosion-resistant materials



S Li, S Liu, NJE Adkins, MM Attallah: Proceedings of the TMS Annual Meeting, USA, February 2014.

High Speed Material Synthesis for M

The New Approach



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Concluding Remarks

Work In-Progress

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Work In-Progress

- Refractory metals AM for fusion applications (W, Cr, Mo, V).
- AM for materials for quantum metrology applications (permalloy, Invar36)
- Hybrid AM processing for Ni-superalloys.
- AM of PGM-modified superelastic TiNi alloys for medical applications.
- Modelling of powder spreading using discrete element modelling, combined with micro-CT validation.
- Meltpool modelling, as a function of laser tool path.
- Post-processing of electron beam melting in Ti-64.

Collaborators & Funding Agencies

SAFRAN
Microturbo

Rolls-Royce®

EPSRC

esa

Innovate UK
Technology Strategy Board

TWI

GKN AEROSPACE

ITP
GRUPO
Industria de Turbo Propulsores, S.A.

广东省工业技术研究院

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SEVENTH FRAMEWORK PROGRAMME

CCFE
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IHI

HORIZON 2020

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Those who have done the work

- **Above:** K. Gulia, A. Field, S. Megahed, M. Aristizabal, W Wang, P Jamshidi, T. Hanemann, N. Read, H. Baker, R. Jennings, S. Baker, S. Li, S. McCain, L. Carter, M. Glynn, JP White, H. Hassanin, U. Tradowsky, J. Macdonald, Y. Gaber, C. Qiu, RM Ward
- **Not present:** Ravi GA, M. Loretto, K. Essa, X Wang, S Liu, L. Parimi, C. Panwisawas, HC Basoalto, JW Brooks, NJA Adkins.

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Challenges Facing Metal AM

In Other Words*…

*Source Unknown