Metallic Additive Manufacturing Process and Materials Development at the University of Sheffield

The University Of Sheffield.

3rd June 2015

2nd Mexican Workshop on Additive Manufacturing 3D Printing
Queretaro Mexico

Dr Kamran Mumtaz

ADAM

Centre for Advanced Additive Manufacturing

RESEARCHER LINKS

BRITISH COUNCIL

CONACYT

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Presentation Overview

1) **About Me**
2) **University of Sheffield**
3) **Advanced Additive Manufacturing (AdAM) Centre**
   - -Facilities
   - -Academic Staff/Research Team
4) **Snapshot of Non Metallic Activities**
   - - Polymer, inkjet and composite technologies
5) **Overview of Metallic AM Research Areas**
6) **Detail into specific process and materials development projects**
   - Topology Optimisation
   - Stress Reduction
   - Novel Processes Development
   - Multi-Materials
   - Materials Development

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Background - Dr Kamran Mumtaz

Involved in Additive Manufacturing research activities since 2005

2004 – BEng (Hons) Aeronautical Engineering - Manchester
2005 – MSc Manufacturing Management - Loughborough
2008 – PhD laser powder bed fusion of Nickel alloys - Loughborough

2008-2011 - Research associate - Loughborough University/Industrial Secondments

2011 – Lecturer in Additive Manufacturing - The University of Sheffield
2012 - Co-founded AdAM Centre at the University of Sheffield

<u>Process and Materials Development for Metallic AM</u>

Understand limitations of current AM process/materials, develop more efficient processes, improved capability, novel processes, multi-materials, process simulation etc.

University of Sheffield

- Russell Group University
- Top 5 in UK for Mechanical Engineering
- Top 100 University 2014 world QS Rankings
- 7000 Staff and more than 26,000 students from around the world

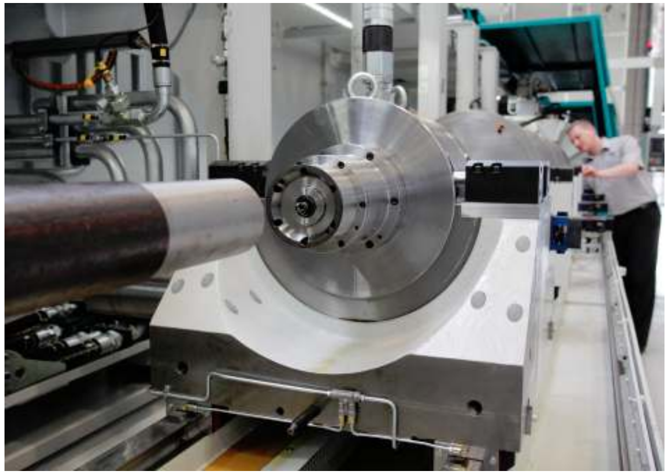
THE 1ST STUDENT EXPERIENCE SURVEY 2014-15

A WORLD TOP 100 UNIVERSITY

University of Sheffield

- **86% of our research assessed as world-leading or internationally excellent**
- **2014 Research Excellence Framework top 10% of all UK Universities**

- **Advanced Manufacturing Research Centre (AMRC) with Boeing, includes Nuclear & Medical AMRC**



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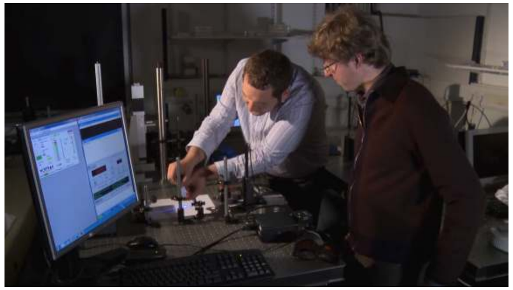
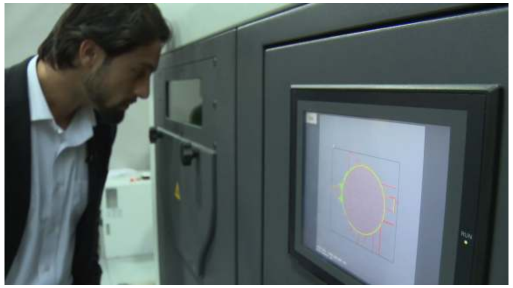
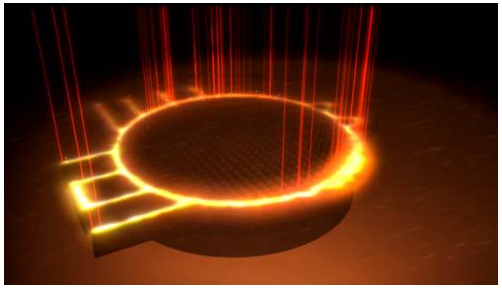
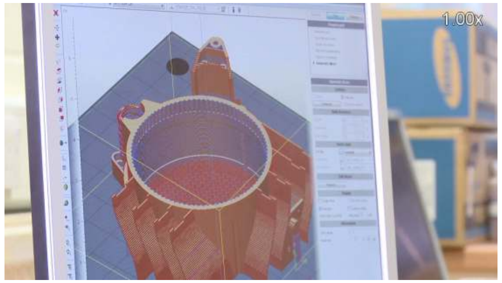
Advanced Additive Manufacturing Centre

- World leading AM research activities
- Multi-disciplinary approach, AM research activities and facilities spread across multiple departments, encouraging innovation in research
- Employs over 40 staff and researchers
- Over 20 commercial and bespoke additive manufacturing technologies
- Industrial work - Siemens, Rolls Royce, Philips, GKN etc.









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AdAM Centre Academics

Polymer Technologies

Prof N Hopkinson
(Head of Centre)

Dr C Majewski

Metal Technologies

Prof I Todd

Dr K Mumtaz

Design for AM

Prof M Gilbert

Jetting Technologies

Dr P Smith

Bio-Printing

Dr F Claeyssens

Dental AM Applications

Prof R Noort

Dr I Ortega

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AdAM Centre Facilities

Polymers
- X2 Object polymer jetting
- EOS Formiga Laser Sintering
- X2 custom High Speed Sintering
- Custom multi-laser sintering system
- X4 custom desktop 3D printers
- X2 custom micro stereolithography
- Custom Ink Jetting system
- Custom extrusion based 4-axis robot

Metals
- X3 Arcam Electron Beam Melting (customised)
- X2 Renishaw Selective Laser Melting (customised)
- ExOne Binder Jetting
- Optomec Aerosol Jet
- Custom multi-laser melting system
- Custom extrusion based system

Other Advanced Manufacturing
- Metal Injection Moulding
- Spark Plasma Sintering
- ProBeam Welder (electron beam)
- Post Treatment (HIP, Vacuum Furnace, shot blast etc.)

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Snapshot of Non-metallic AM activities

High Speed Sintering Polymers

Development driven by need to increase AM productivity and reduce the cost per part

Replaces conventional scanning lasers with a print head infra-red lamp to significantly increase build speed and increase build volume

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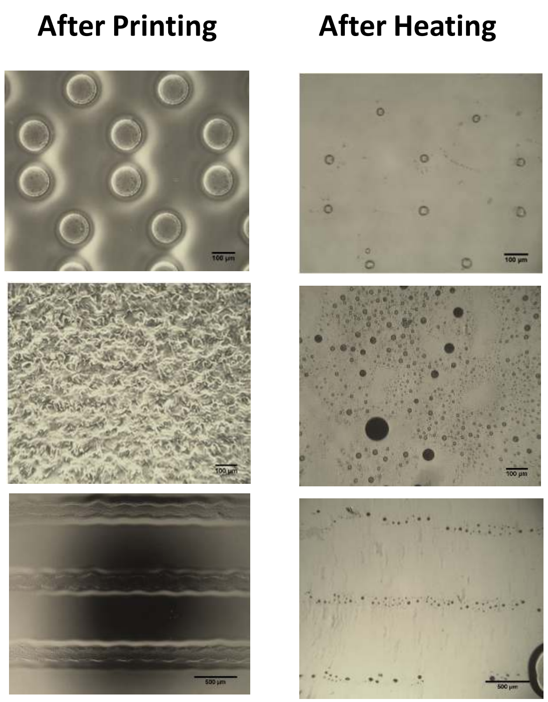
Snapshot of Non-metallic AM activities

Inkjet Technologies

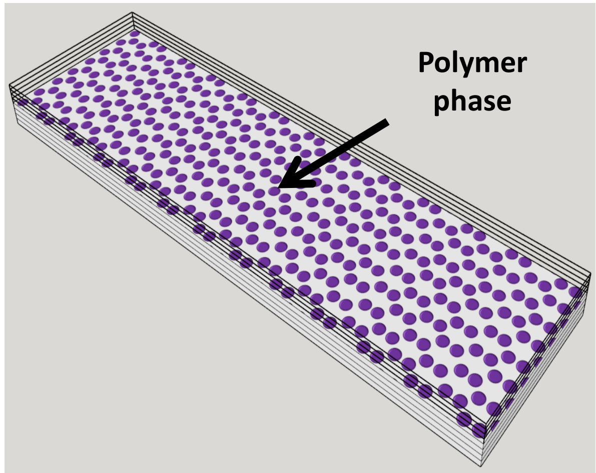
Effect of inkjet printed polymer on mechanical performance of Carbon Fibre Reinforced Polymers (CFRP)

Toughening CFRP by printing thermoplastic polymers between laminate sheets before curing

Polymer phases ease/arrest crack propagation. Minimise weight gain



A highly controllable size and geometrical distribution of the thermoplastic inkjet printed microphases are believed to be the contribution to the enhanced mechanical properties.



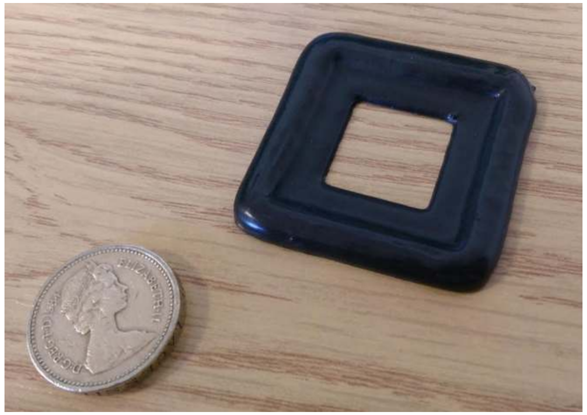
Snapshot of Non-metallic AM activities

Bio-printing with Stereolithography

Restoring damaged nerve function
Nerve guidance conduit (NGC)
Create scaffolds from a photopolymerizable liquid
that bio-degrades once nerve as been repaired

Non-Conventional AM Materials (often requiring process development)

Ceramic processing
Various composite materials (i.e SFRC)
Sustainable materials (i.e wood waste feedstock to create large structures, shelters)



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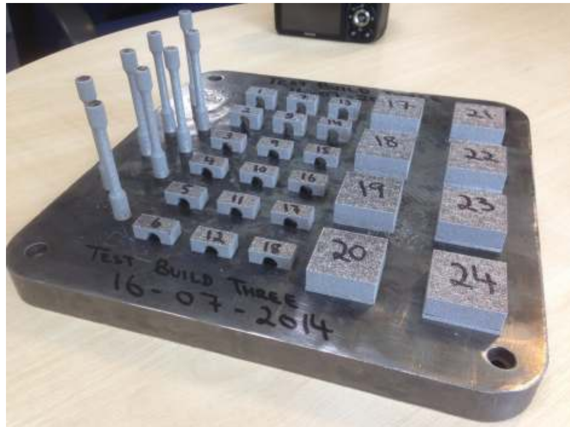
Overview of Metallic Activities

- **Understanding of existing processes (repeatability, process simulation etc.)**
- **Tackle common issues (i.e stress development, surface finish, speed, material variety etc.)**
- **Design Optimisation (i.e lightweight structures)**
- **New Materials (AM specific alloys)**
- **Novel Processes (faster, more efficient, introduce further capability advantage)**
- **Multi-materials**



Large list of materials processed/attempted. Steel, Nickel, Cobalt Chrome, Aluminium, Copper, Magnesium, Titanium alloys, graded materials etc.

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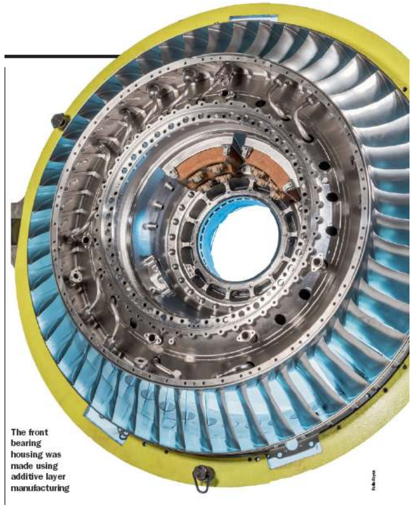
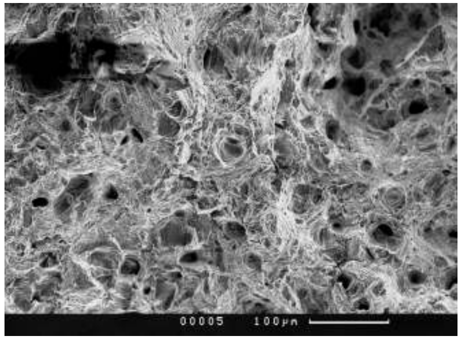
Understanding and Development of Process

Rolls Royce Engine Stator Vanes for Ring of Vanes

- **Build orientation and support structures**
- **Process optimisation- build quicker, eliminate defects**
- **Support to down stream processes e.g. machining, finishing & welding**
- **Pre-production repeatability**
- **Key process variables identified and controlled**
- **Increase in build process speed**





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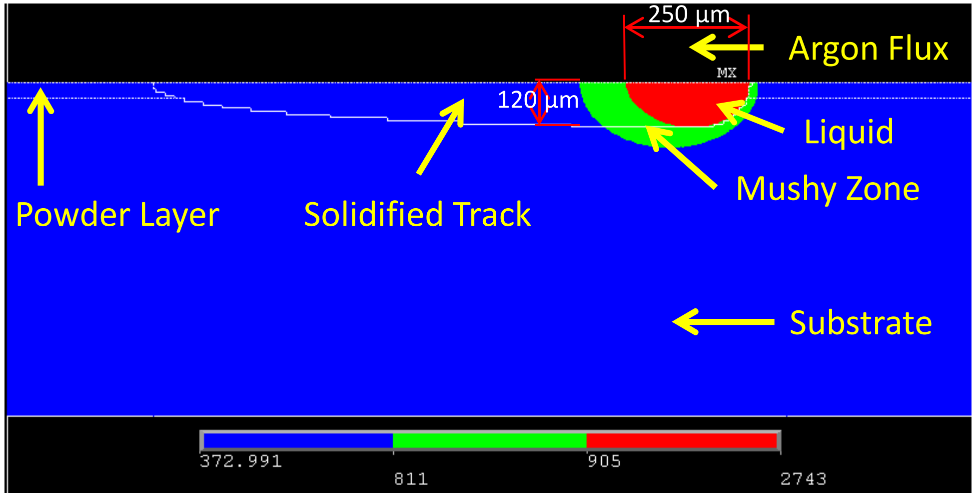
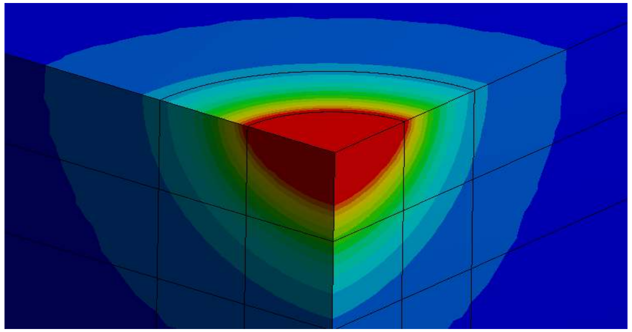
Understanding and Development of Process

Process Simulation

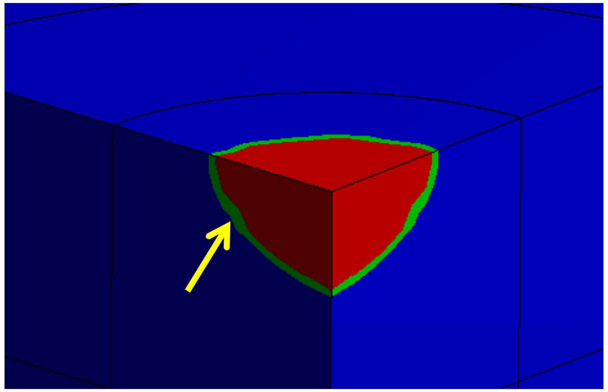
- **Numerical modeling used extensively in casting industry, nothing yet developed for powder bed AM**
- **Can assist with understanding of process and prediction of resultant microstructures, customisation, single crystal structure etc.**
- **Assists process parameter optimisation**



2D FEM Single Layer Solidification front tracking on melt pool (SLM).



3D Single Spot Temperature profile at the powder bed (SLM) developed with FEM.



3D Single Spot Solidification front tracking on melt pool (SLM) developed with FEM.

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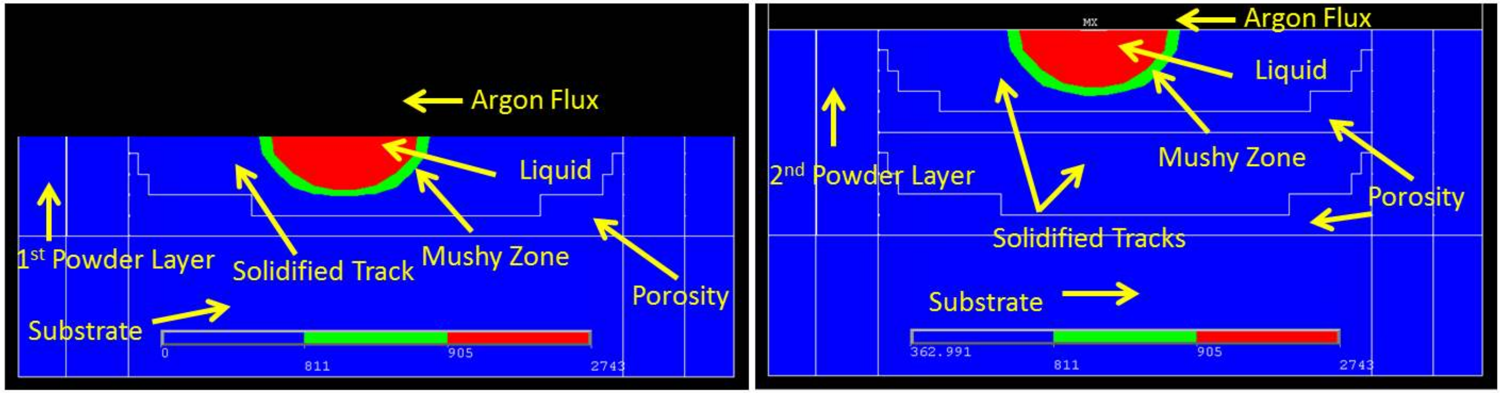
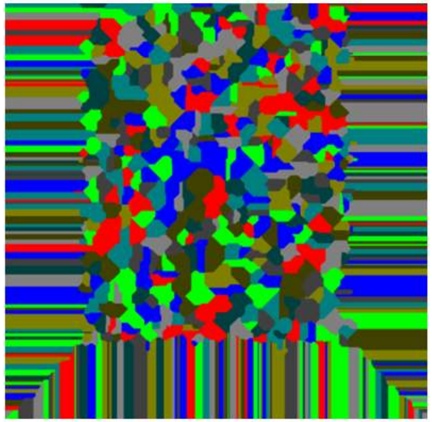
Understanding and Development of Process

Process Simulation



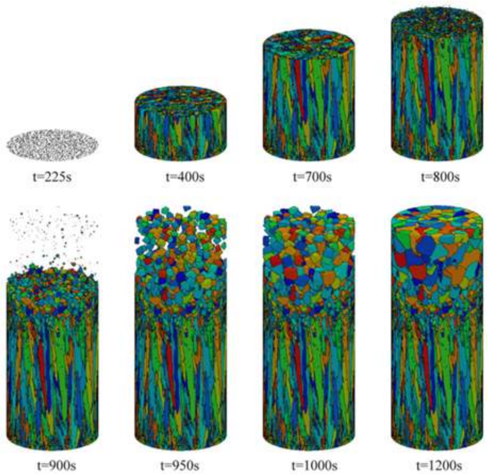
3D FEM Multi Layer Solidification front tracking on melt pool (SLM).

Next Step: couple FEM with CA in order to simulate microstructural development



2D Microstructure simulation of CET (columnar to equiaxed transition) with cellular automata.

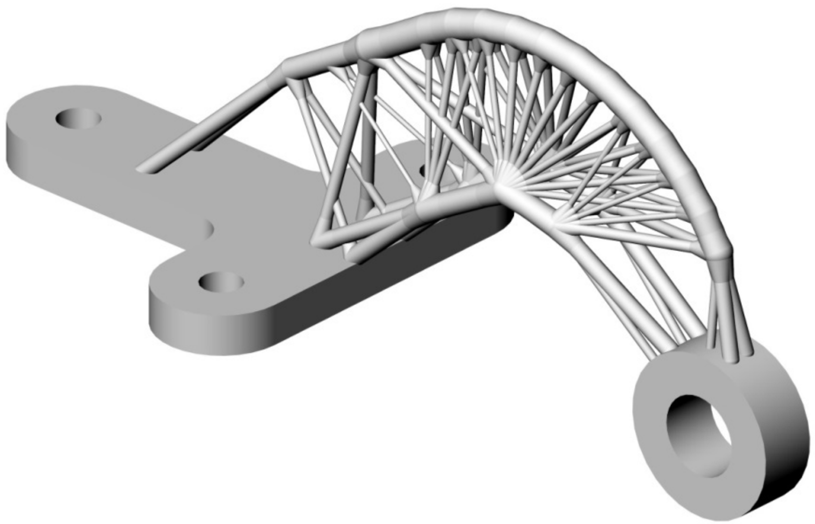
3D CAFE simulation of cylindrical ingot during CET in casting (Carozzani, Digonnet et al. 2012).



Topology Optimisation

Lightweight Structures

- **Minimal mass structures**
- **69% weight saving achieved using structural topology optimisation for bracket/hinge**



Topology Optimised Design

Original Design

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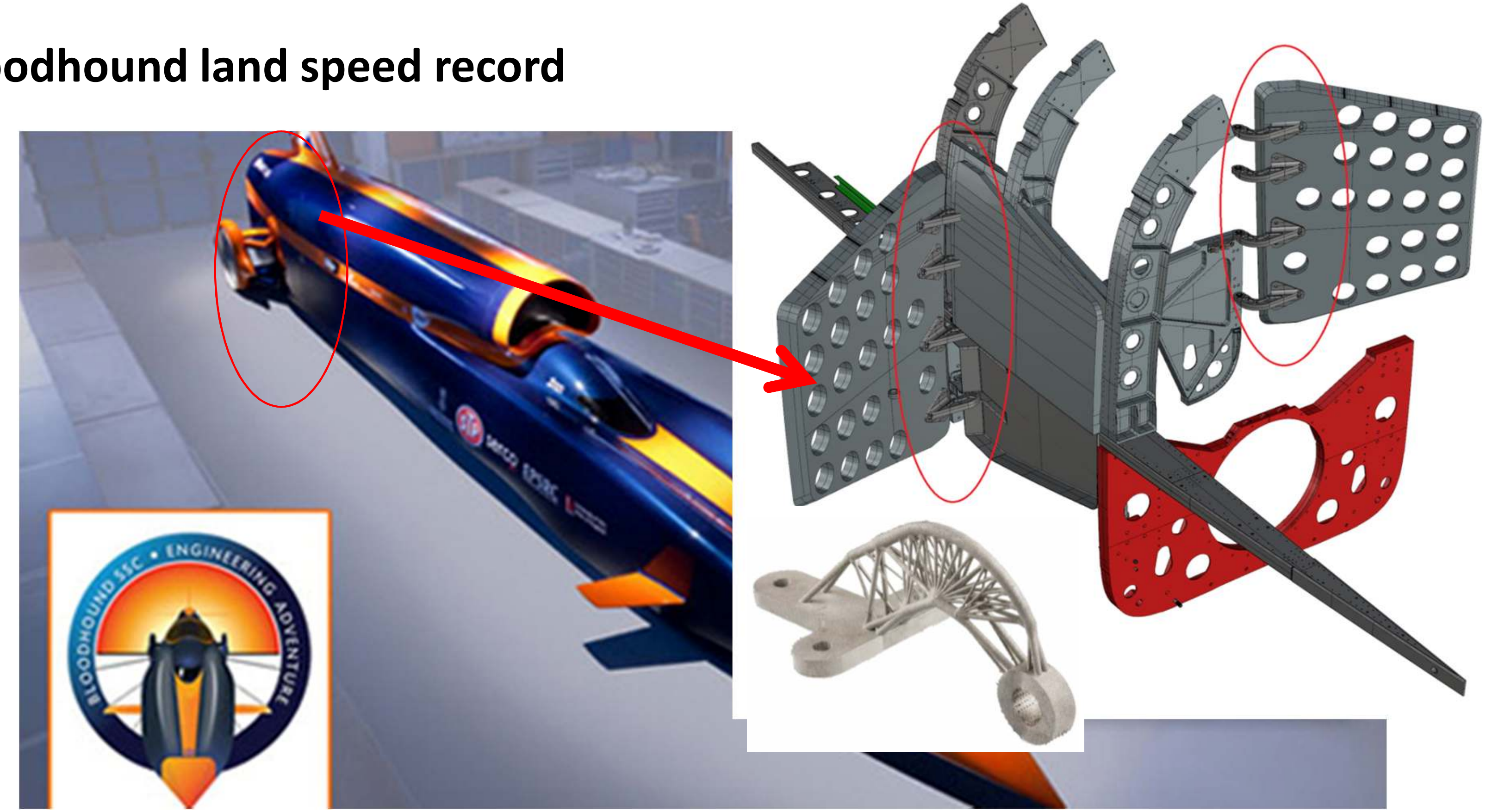
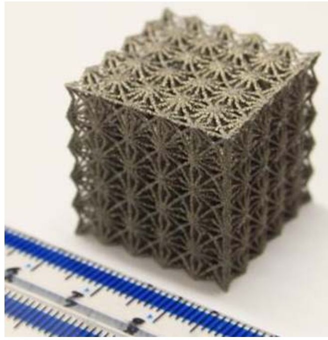
Topology Optimisation

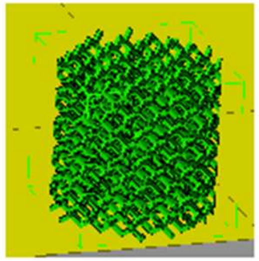
Lightweight Structures

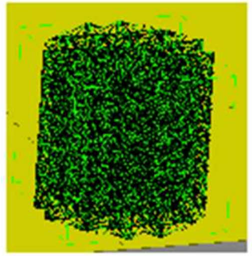
- **Bloodhound land speed record**



Topology Optimisation

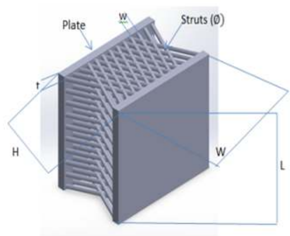


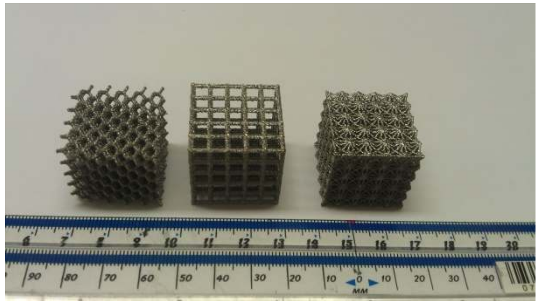


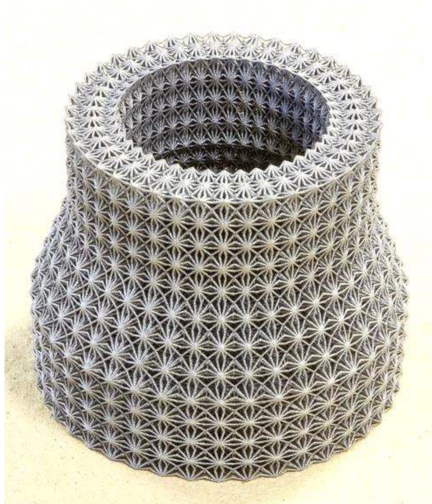


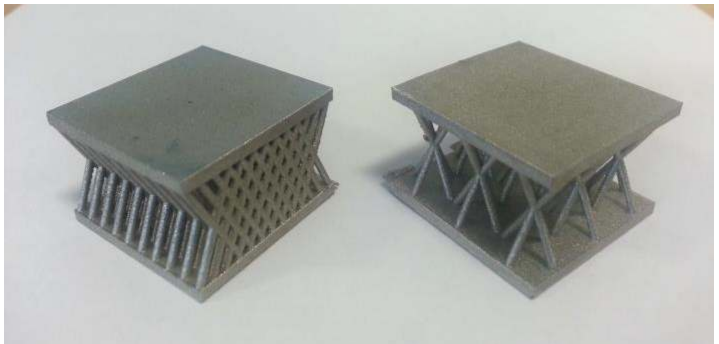
Lightweight Structures

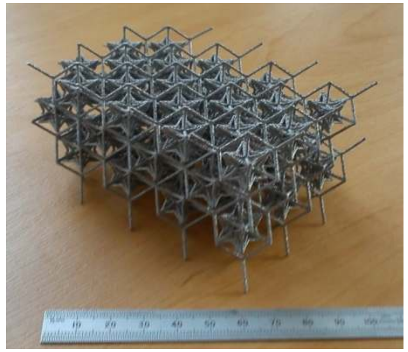
- **Lattice structures for testing impact loads**
- **Lattice like structures have high surface area making them ideal for thermal management applications**
- **Meta-material behaviours!**











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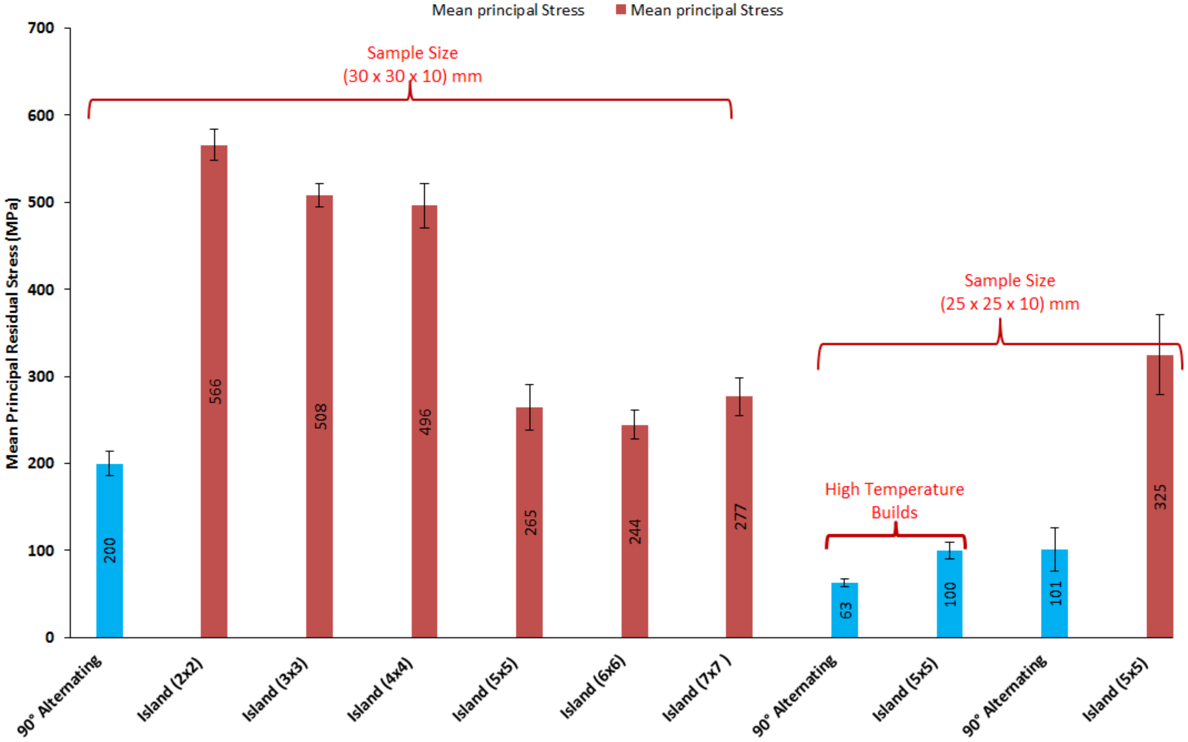
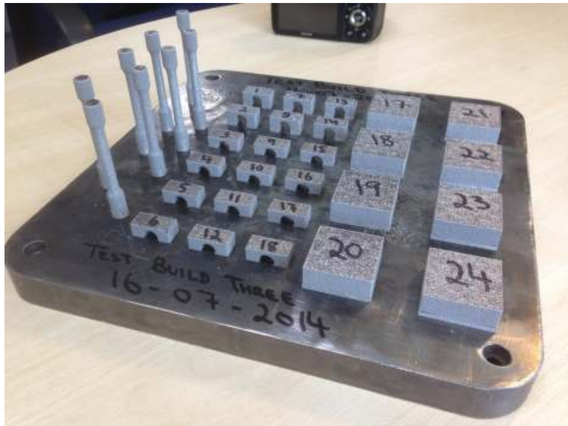
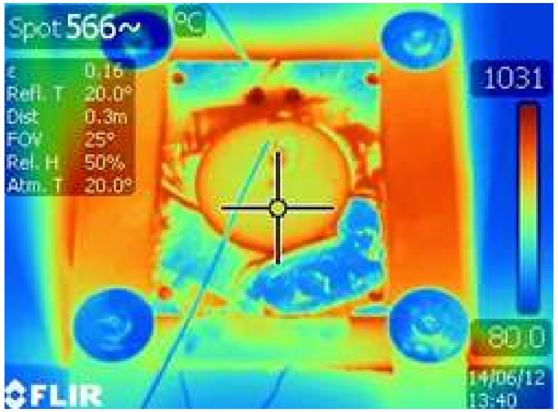
Stress Reduction

Methods to Reduce Residual Stress

- Parameter optimisation to reduce thermal variations across build
- Examine effects on mechanical properties







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Stress Reduction & Requirement for Supports

Some parts require support/anchors due to thermal warpage

Rapid heating/cooling

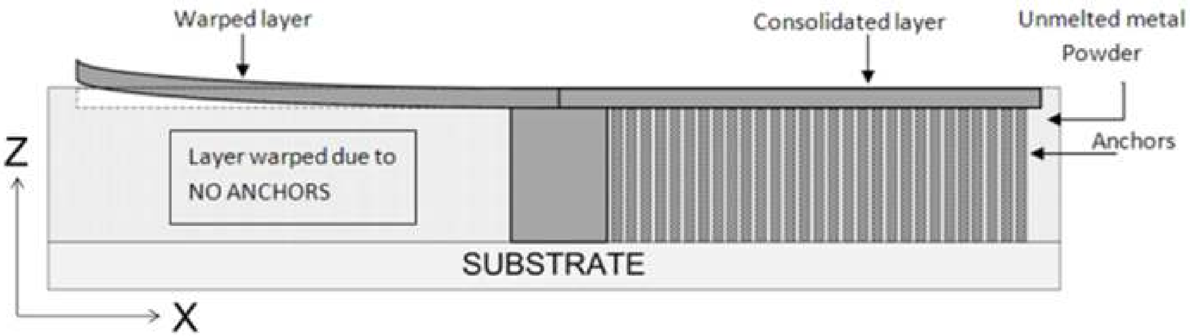
Large thermal variations

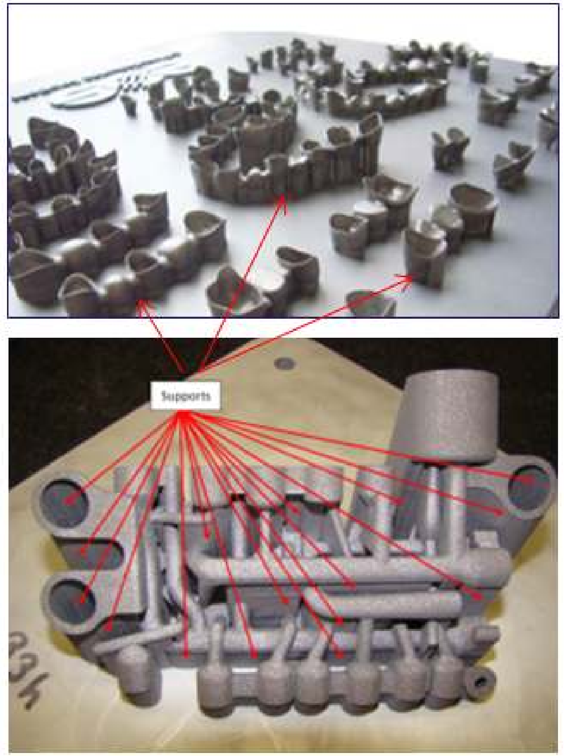
Stresses/warpage

Limits geometric freedom,

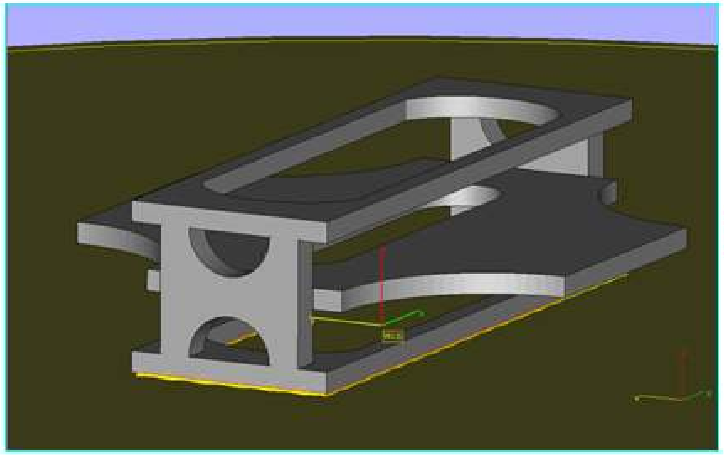
Incurs post processing and cost for anchor removal

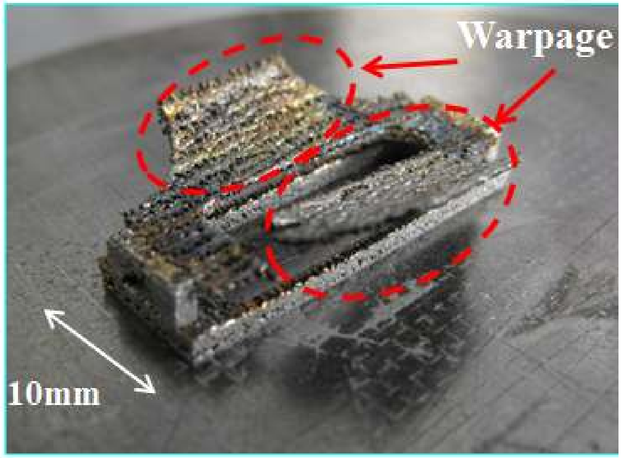
Cannot stack component on top of each other

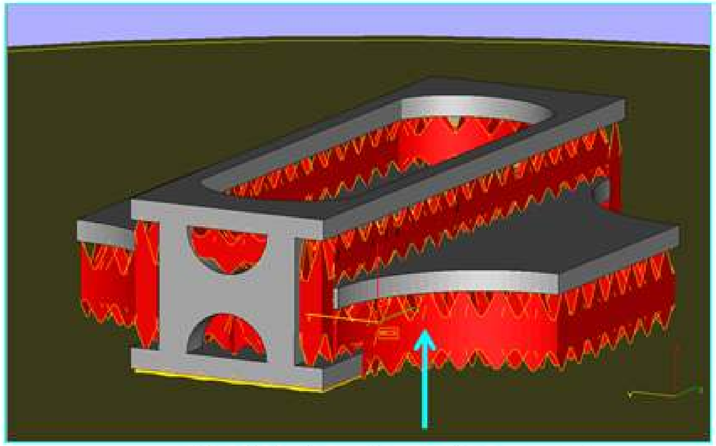




Stress Reduction & Requirement for Supports







Metal Anchors/Supports

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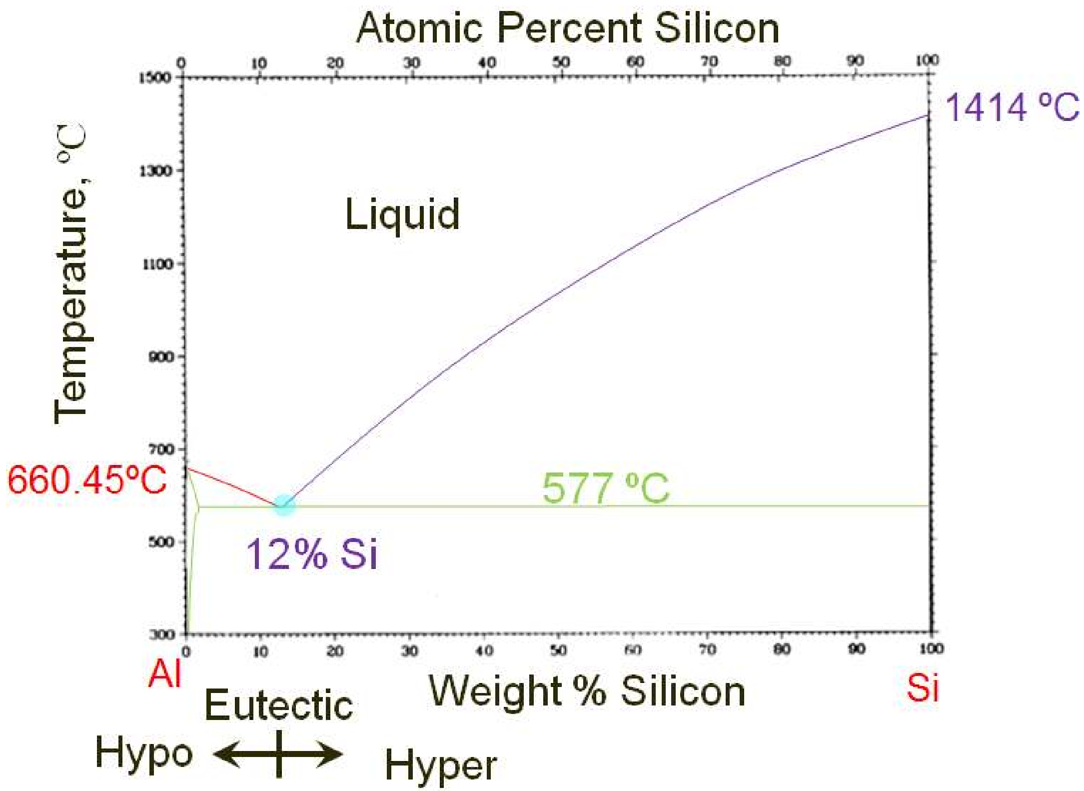
Stress Reduction using Anchoress SLM

Novel method to reduce stress and remove requirement for support structures

- Anchorless Selective Laser Melting
- Maintain material is semi-solid state throughout build, similar to SLS
- Combine careful custom elevated powder bed pre-heat with specially prepared elemental mix of materials



Stress Reduction using ASLM

Novel method to reduce stress and remove requirement for support structures

1

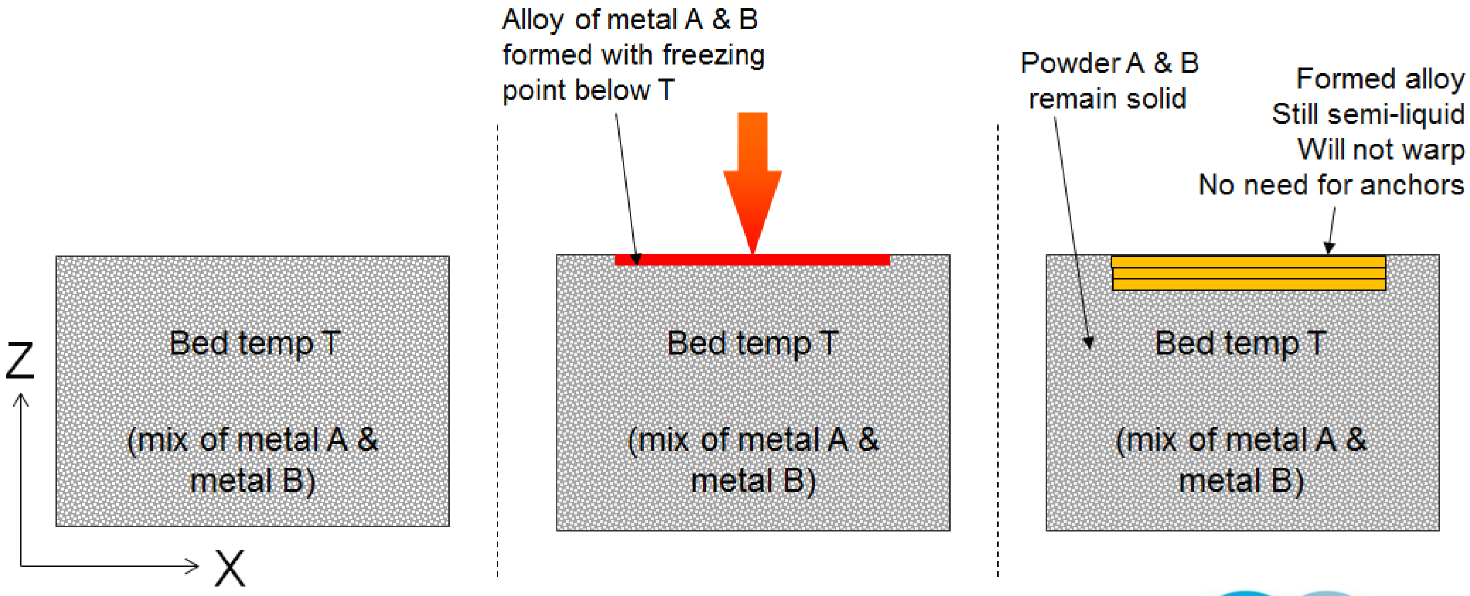
Heated powder bed, mix of un-alloyed powders A & B

2

Laser melts metal A & B forming a new eutectic (or hypo/hyper eutectic) alloy

3

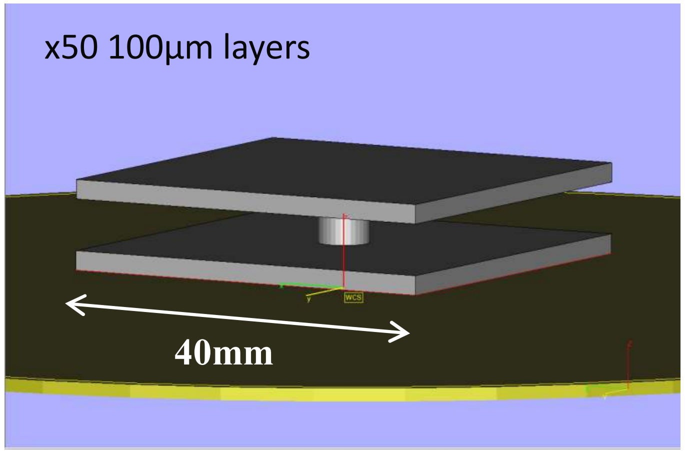
Bed temperature held at temperature T. Processed material cools but does not fully solidify

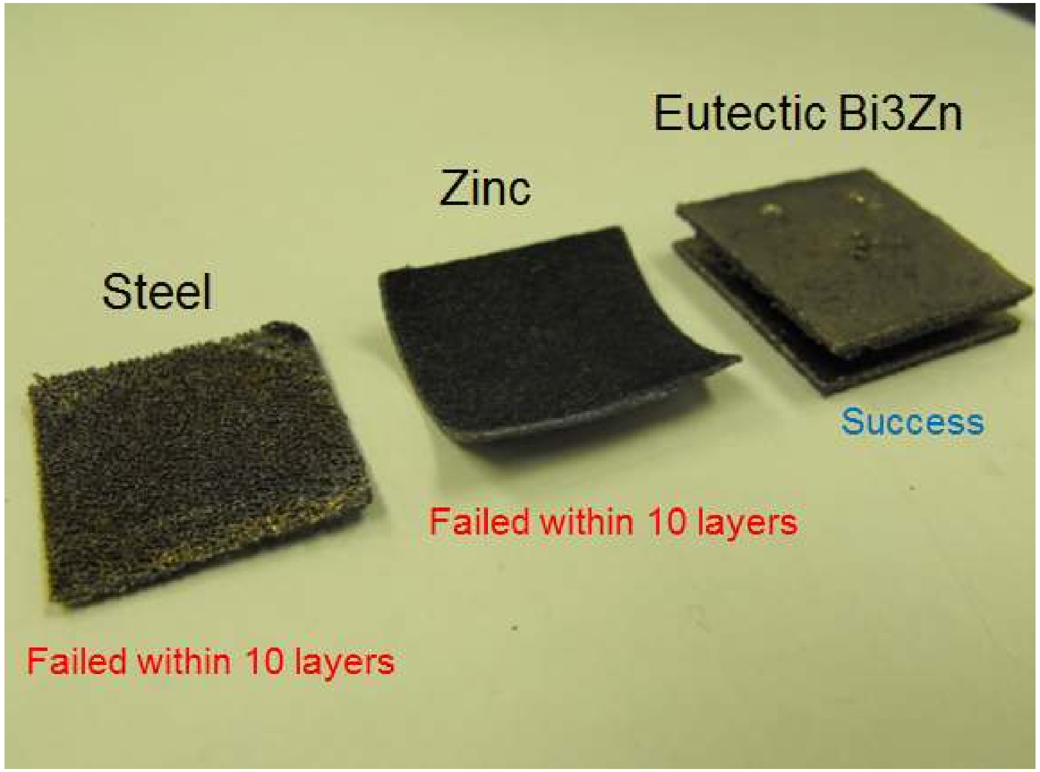


Stress Reduction using ASLM

Novel Method to Reduce stress and remove requirement for support structures

Large flat geometries impossible to build without support structures/anchors using conventional SLM/EM





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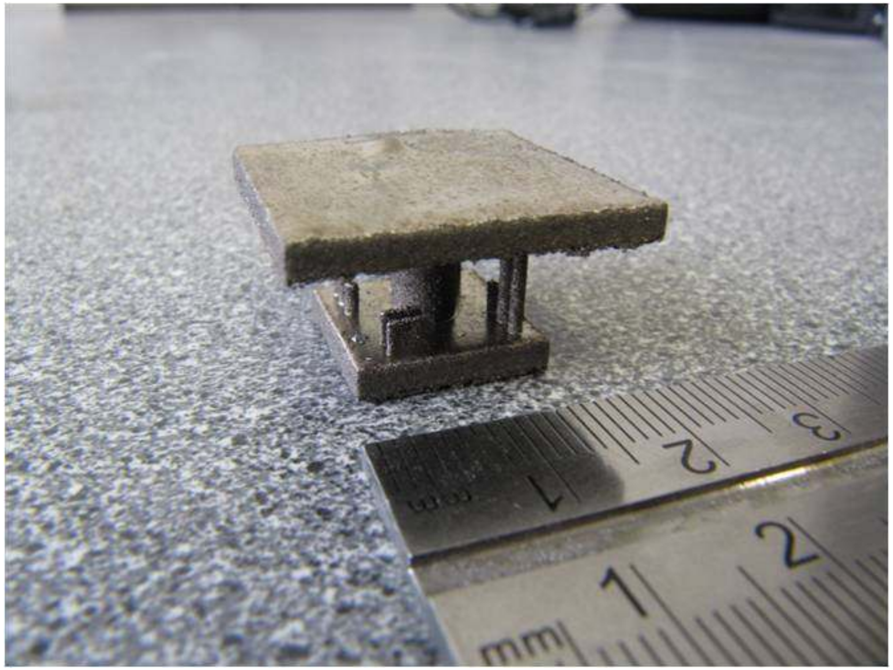
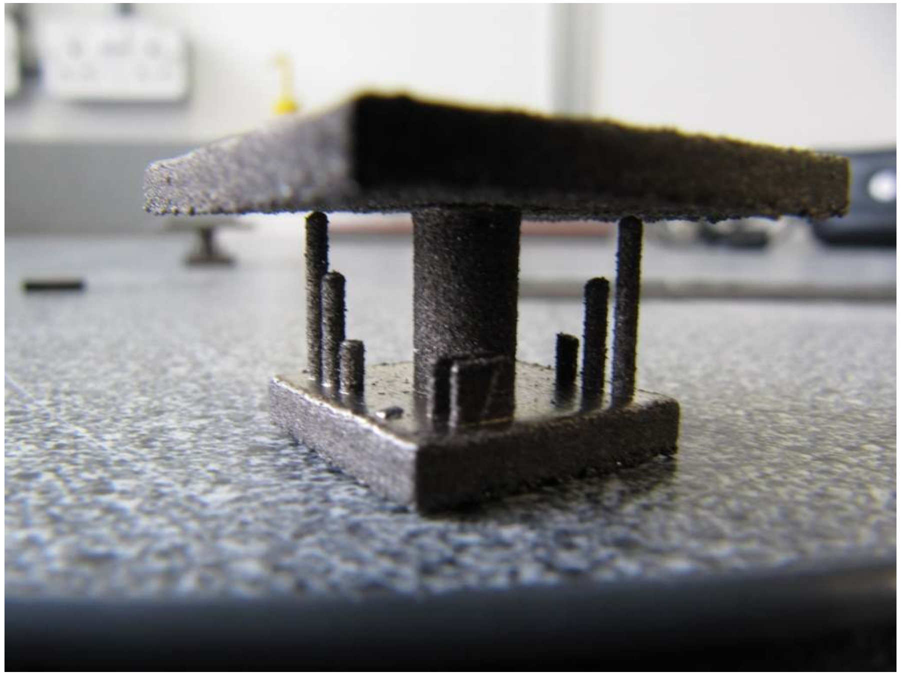
Stress Reduction using ASLM

Novel Method to Reduce stress and remove requirement for support structures

Large flat geometries impossible to build without support





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Stress Reduction using ASLM

Novel Method to Reduce stress and remove the requirement for support structures

Geometries within geometries

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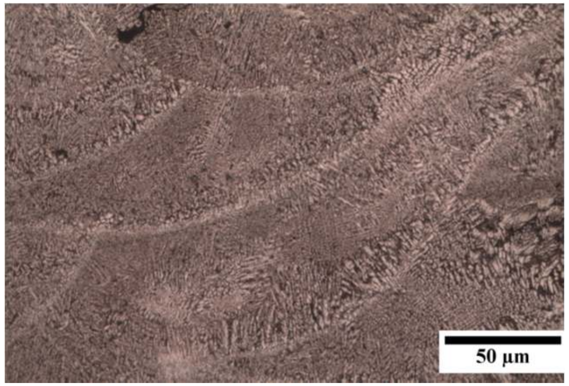
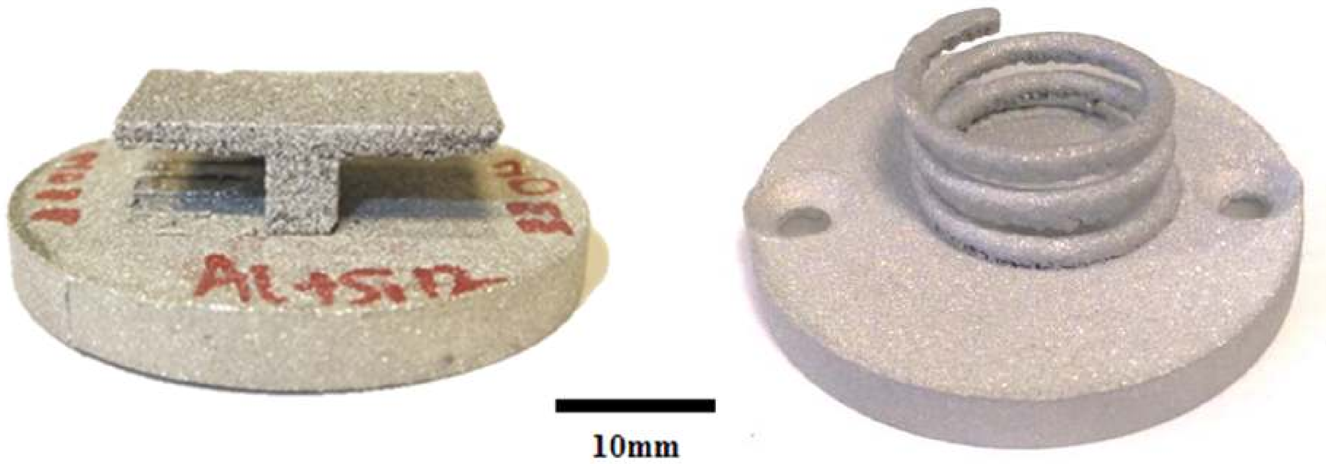
Stress Reduction using ASLM

Novel Method to Reduce stress and remove the requirement for support structures

Aluminium alloys, AlSi12, Al339, AlCu
Future work seeks to expand materials available

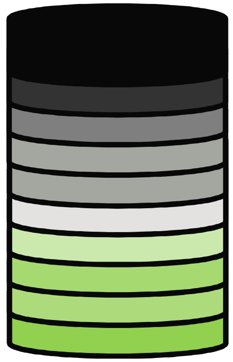


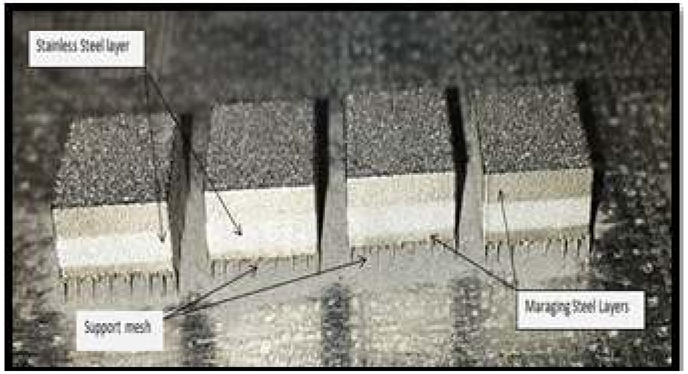


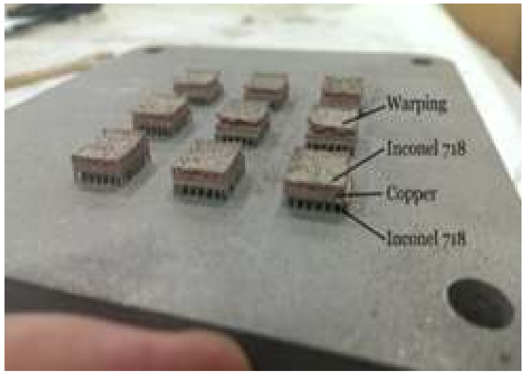
Multi-Materials AM

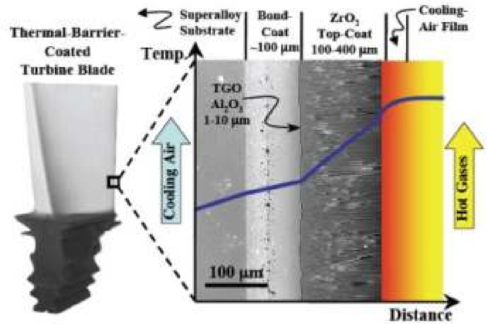
Enhance properties through grading of materials

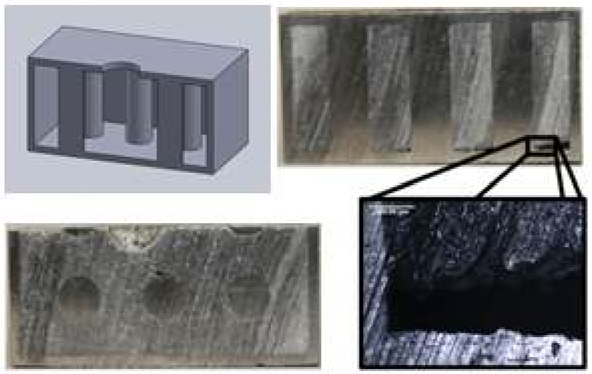
Prevent/design failure
Mechanical property control
Thermal management etc.

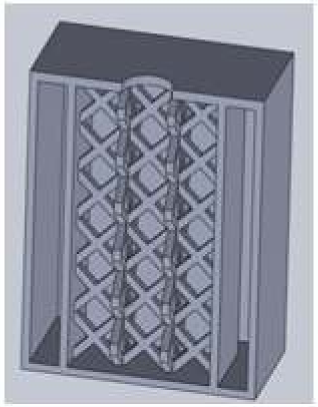


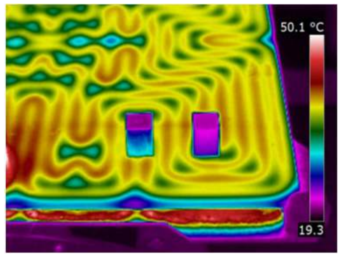












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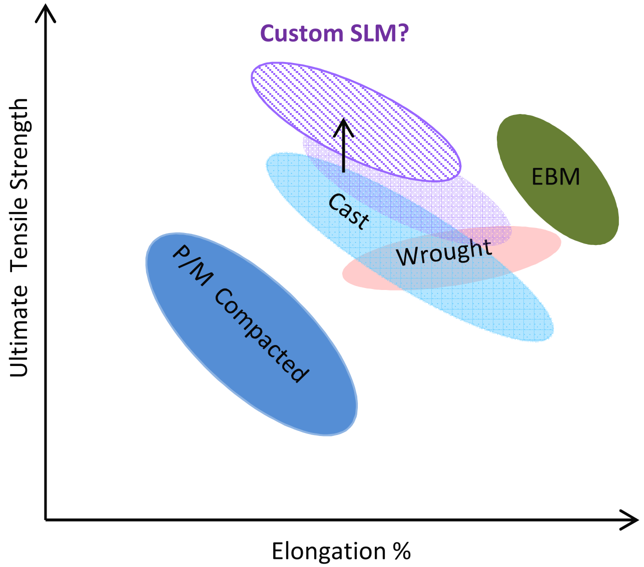
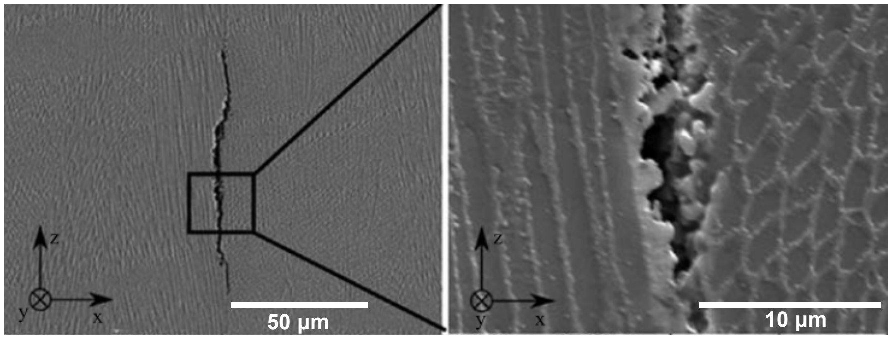
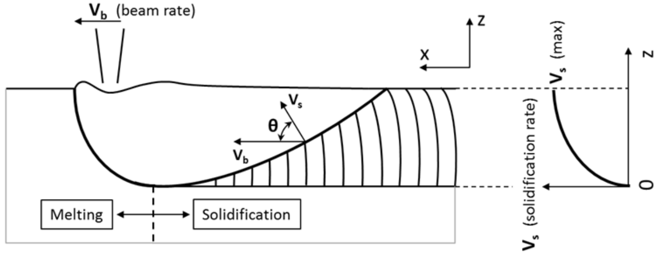
Custom Alloys for AM

Custom Materials Designed for AM

- Better Materials (improved performance, reduced processing issues)
- Growing research area
- Example of work - certain aerospace nickel alloys suffer from high crack susceptibility







Rickenbacher, L. (2013) Rapid Prototyping Journal **19**(4): 282-290.

Alloys for AM

Reduce crack susceptability in Nickel alloy

- **Calculated composition manipulation of existing alloy**

Alloy	Ni	Cr	Fe	Mo	Co	Mn	Si	W	C
MHX wt %	46.55	21.80	18.6	9.4	1.77	0.22	0.31	1.05	0.054
OHX wt%	47.87	21.3	19.5	9.0	1.04	0.48	0.32	0.56	0.057
Δc (At. Frac)	-0.01	0.007	0.0004	**0.003**	0.007	-0.003	-0.0002	**0.0016**	-0.0001
k (MPa At. Fraction-1/2)	-	337	153	**1015**	39.4	448	275	**997**	1061

$$\Delta\sigma_{ss} = \sigma_{ssMHX} - \sigma_{ssOHX} = \left(\sum_{iMHX} k_i^{\frac{1}{n}} c_{iMHX}\right)^n - \left(\sum_{iOHX} k_i^{\frac{1}{n}} c_{iOHX}\right)^n = 8.31\ MPa$$

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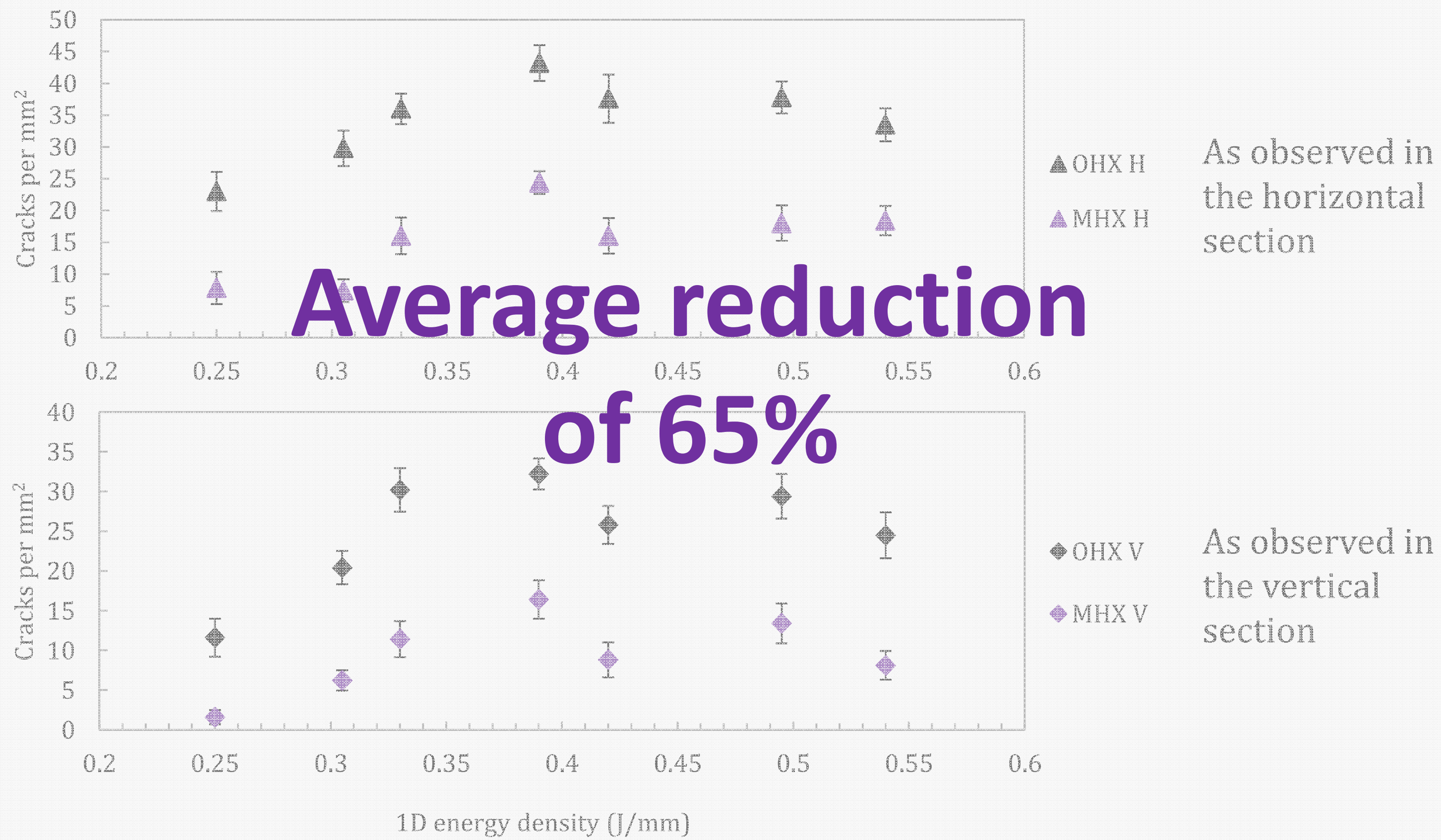
Custom Alloys for AM



Average reduction of 65%

Working with Mexico

- Currently supervise PhD students from Mexico (CONACYT)
- University of Sheffied already has a good relationship with Mexican research institutions and Universities
- Many Mexican students registered on our Advanced Mechanical MSc with AMRC/Boeing
- Initiated AM related collaboration with UANL, Mexico. If funded 18 month project will start in September 2015

Simulation of Microstructure within laser powder bed

Omar Lopez Botello

Stress free Aluminium AM components

Rafael A M Ramos

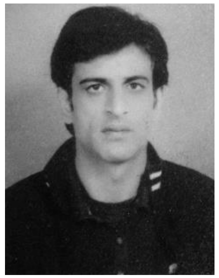
Machining of Ti64 AM components

Marco A Galindo

Novel multi-laser metallic powder bed processing

Miguel A Z Arredondo

Stress reduced Ti64 AM processing



Haider Ali

Bespoke nickel alloys for metallic AM

Neil J Harrison

The University Of Sheffield.

And Finally…

Visit www.adamcentre.co.uk

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The University Of Sheffield.