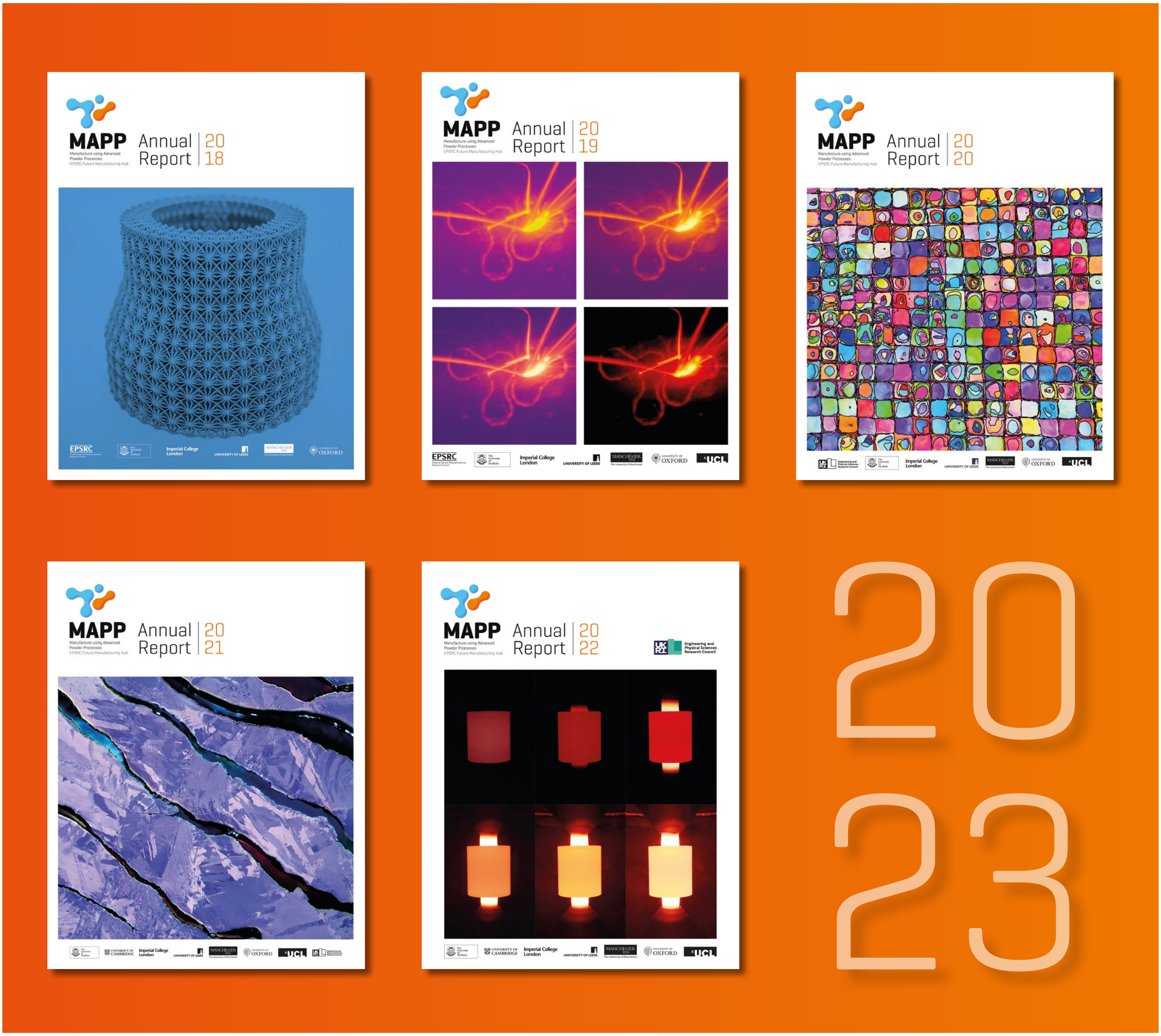
# MAPP Annual Report 2023

Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

Engineering and Physical Sciences Research Council

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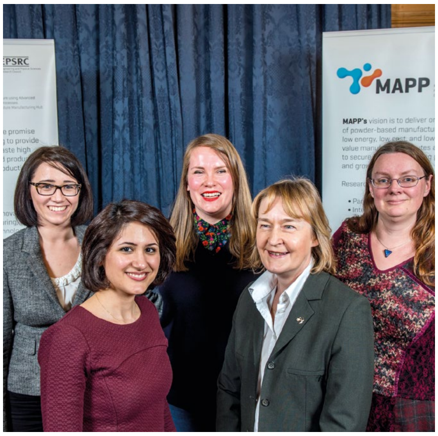
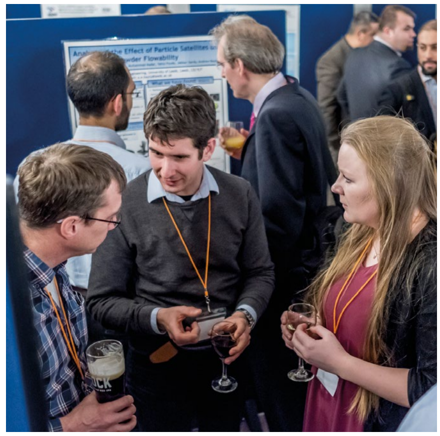
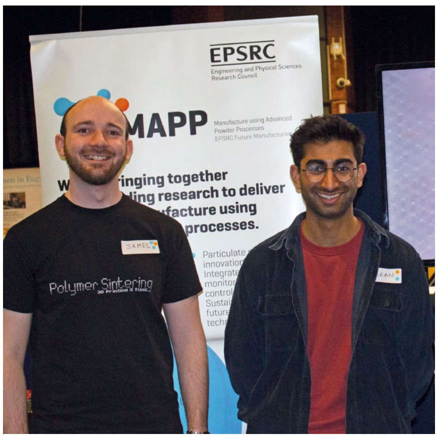
Front cover: **Montage of the front page covers from the previous MAPP Annual Reports. For details see page 4.**

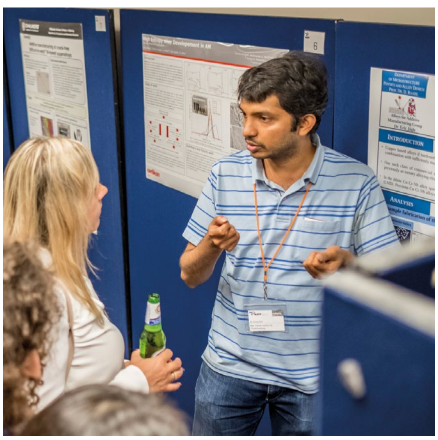




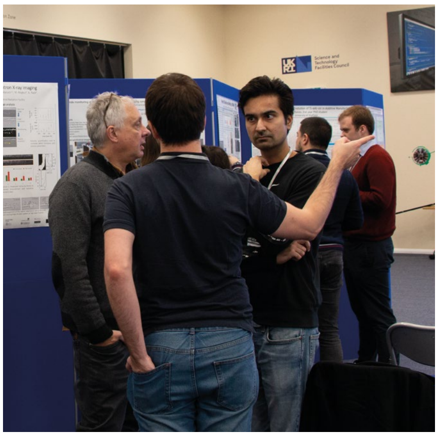











Images on pages 2 - 3: **MAPP events through the years**

# CONTENTS



**Front cover images:**

2018: Lattice structure built using Laser Powder Bed Fusion of Ti-6Al-4V powder.

2019: Nickel powder being sintered in a Renishaw Selective Laser Melting machine.

2020: EBSD map of 3D printed alloy that exhibits very low susceptibility to solidification.

2021: Polarised light micrograph of Ti-6Al-4V machining swarf before repurposing using FAST

2022: Images capturing Field Assisted Sintering Technology (FAST) for Ti-6Al-4V powder.

# WELCOME

## Welcome to the sixth MAPP Annual Report

At the start of 2022 we were all still emerging from the restrictions of the global pandemic and I am grateful to everyone in MAPP for their continuing research efforts throughout the challenges that we all faced.

Our Quarterly Review Meeting (QRM) in January was held safely online with updates from all MAPP partners and research programmes. In early May we held an in-person QRM at Manchester giving us all the opportunity to regroup, revitalise and finally meet with some that we had only seen on a screen. We were back online again for our meeting in July as the temperatures across the UK reached new record highs during the unprecedented heatwave. Our QRM with industry was held in the Research Complex at Harwell (RCaH) in mid November, at which MAPP researchers were able to update on their most recent findings through an interactive poster session and through presentations from each theme.

We have also held successful hybrid events including the MAPP lecture series and our second workshop on Artificial Intelligence in Additive Manufacture, which was run jointly with the Centre for Additive Manufacture – Metal (CAM$^2$). We continue to publish MAPP research in leading journals and these are listed in date and theme order on pages 32 to 39 together with the doi link to each paper.

This report highlights some of the many fantastic professional achievements of our colleagues in MAPP and I am pleased to see that we have been able to get back to attending, presenting and networking across a range of International Conferences and Workshops. Our focus now is on ensuring that our research is taken forward with industry, helping to deliver real economic impacts. We are continuing to work closely with our industrial partners making sure we are still addressing the most relevant research questions and challenges.

I hope you enjoy reading about some of MAPP's highlights of 2022. We look forward to continuing our work together and welcome you to join us and find out more at MAPP's Second International Conference on 28th and 29th June 2023.

**Prof. Iain Todd. MAPP Director**

**Professor Iain Todd**
**MAPP Director**

# ACHIEVEMENTS

# 2017 – 2023

MAPP's collaborative and interdisciplinary research and innovation programme continues to deliver on the new and fundamental understanding of powder-based manufacturing processes.

The academic, industrial and innovation partners continue to drive the hub's research which is needed to solve many of the challenges hindering the commercialisation of powder-based processes. A number of key outputs have been achieved over the past six years including:

- *In situ* research on Laser Powder Bed Fusion that paves the way for using synchrotron-calibrated digital twins for process prediction and suggests new ways to improve process reliability.
- Techniques developed using calibrated closed-loop monitoring and control of the Directed Energy Deposition process to achieve geometry-agnostic builds with more repeatable mechanical properties.
- Recommendation that a Spreadability Index is measured as a new property for Metal Powders used in Additive Manufacturing applications.
- Useful insights into the Hot Isostatic Pressing (HIPing) process of a novel Ti-Fe binary alloy via in-situ mimic HIPing experiments under synchrotron X-ray. For the first time, the whole densification process has been recorded by X-ray imaging.
- The extension of robocasting to the fabrication of ceramic composites and glasses.
- Work that opens new opportunities for the extension of digital light processing to non-oxide ceramics.
- Characterising a library of powders at the individual and bulk level.
- Methods to coat stainless steel powders to prevent oxidation.
- Using Field Assisted Sintering Technology (FAST) to optimise and improve process control.
- Developing deep-learning algorithms to enable rapid process parameter development, monitoring components as they are manufactured to enable 'right first time' manufacturing.
- The most in-depth understanding to date of porosity and pore formation as a result of varying levels of energy input in High Speed Sintering (HSS).
- New understanding in process models through the development of a laser powder bed Additive Manufacturing (AM) replicator, a Directed Energy Deposition (DED) replicator and an in-situ synchrotron rig for investigating the field FAST process.
- Use of machine learning to develop data driven approaches to predict printability in AM.

Some of our research has progressed more quickly through additional links with our aligned projects (you can find out more about these on pages 55 to 59), and we continue to successfully leverage funding to enable us to build a broader team and to retain key skills.

We are a hub that sets the research agenda in emerging technology areas including artificial intelligence (AI) in AM, in-situ and in-operando monitoring of advanced powder processes and processing and fundamentals relating to ceramics and multi-material.

Our leadership of the national agenda is highlighted by:

- MAPP Director Professor Iain Todd leading the Materials Made Smarter Centre (MMSC), launched in 2021 and set to revolutionise the way we manufacture and value materials in the UK.
- Continued involvement with the Henry Royce Institute agenda in Materials 4.0.
- Our partnerships with Catapults.
- Our partnerships with UKRI Critical Mass Activities.
- MAPP Executive member Professor Visakan Kadirkamanathan appointed as the Chair of the UK Automatic Control Council.

Throughout its duration, MAPP has collaborated with over 100 industrial companies (these are listed on pages 22 to 23) in both the UK and internationally, and we have continued to engage with academia through conferences, workshops, MAPP lectures and feasibility studies. Two of our feasibility studies continued with additional MAPP funding in 2022 and you can read more about

**Titanium Queen**
The winning photograph in the MAPP 2023 Image Competition was taken by Dr Simon Graham, University of Sheffield. Commercially pure titanium powder was cold isostatically pressed into shape using a silicone mould for further processing by Field Assisted Sintering Technology (FAST).

these on pages 26 and 28 to 29. Following its successful hybrid workshop in 2021, MAPP and the Centre for Additive Manufacture – Metal (CAM²) came together in October 2022 at the Leopold Hotel, Sheffield for an interesting and insightful workshop (pages 24 and 25) with talks from industry as well as academics from both hubs.

Our researchers have continued to support our online, in-person and hybrid events as well as deliver on our research programme. This year we saw our largest annual increase in MAPP and MAPP-aligned PhD students completing their theses and a number of MAPP researchers moving on to more senior academic posts, including fellowships.

A number of MAPP researchers have moved to new positions in 2022, including:

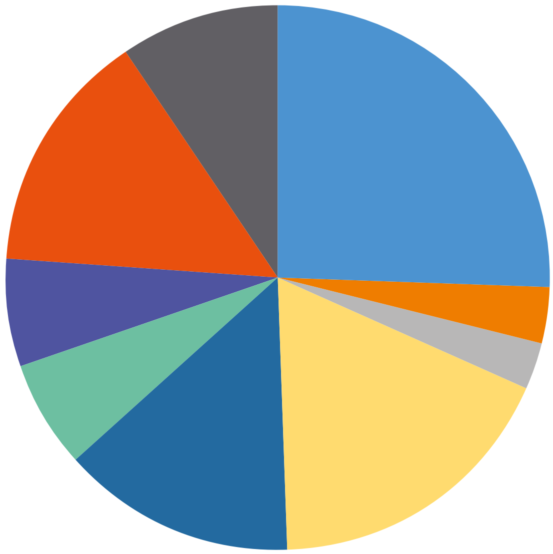
- MAPP Post-Doctoral Research Associate (PDRA) at Manchester, Dr Xun Zhang, is now a research fellow in the nuclear graphite research group (NGRG), Department of Mechanical, Aerospace and Civil Engineering at Manchester University.
- MAPP PDRA based at Harwell (UCL), Dr Hongze Wang, has now taken up a new role at Shanghai Jiao Tong University in China.
- MAPP PDRA at ICL, Dr Iuliia Tirichenko (née Elizarova), is now a research fellow in the Department of Mechanical Engineering at Imperial College London.

Fifteen MAPP-aligned PhD researchers successfully received their doctorates in 2022, these included:

- MAPP-aligned PhD's at Sheffield; Dr Florian Bushek, Dr Lova Chechik, Dr Alistair Lyle, Dr Sourabh Paul, Dr Silva Beatriz Fernandez, Dr Leigh Stanger, Dr James Wingham and Dr Kai Wu.
- MAPP-aligned PhD's at Oxford; Dr Ben Evans and Dr Zhouran Zhang

Our colleagues have taken part in a wide range of leading conferences and public engagement events both online and in person. You can read more about some of these activities on page 40. Rohit Malik, PDRA researcher, got the "Dame Julia Higgins Engineering Postdoc Collaborative Research Fund" for developing novel metal-ceramic joints using additive manufacturing from the Faculty of Engineering, Imperial College London. MAPP researchers were also successful in securing funding for two Henry Royce Institute Materials 4.0 Feasibility Studies.

## COMPONENTS OF MAPP'S FUNDING PORTFOLIO



- **Core EPSRC grant** £10,724,131
- **EU** £1,411,473
- **Facilities** £1,128,000
- **EPSRC** £7,417,423
- **IUK (inc ATI)** £5,719,910
- **RAEng** £2,687,000
- **Other** £2,742,975
- **Industry*** £5,959,329
- **Universities**** £3,912,500

## SOME OF MAPP'S KEY PERFORMANCE INDICATORS

145
International Journal publications

£22.7M
Aligned and leveraged income (from Industry and Academia)

11.463
Average Impact Factor^

239
Conference presentations including 86 keynote/invited talks

>100
Industrial collaborators across MAPP

42
Schools and over 1000 pupils engaged in Outreach events

>1200
Delegates at MAPP events (Industry and non-MAPP Academic)

^ The average journal Impact Factor is based on value from Academic Accelerator in January 2023

* Industry funding includes direct and indirect (in-kind) contributions

** University funding includes the total support from offer letters

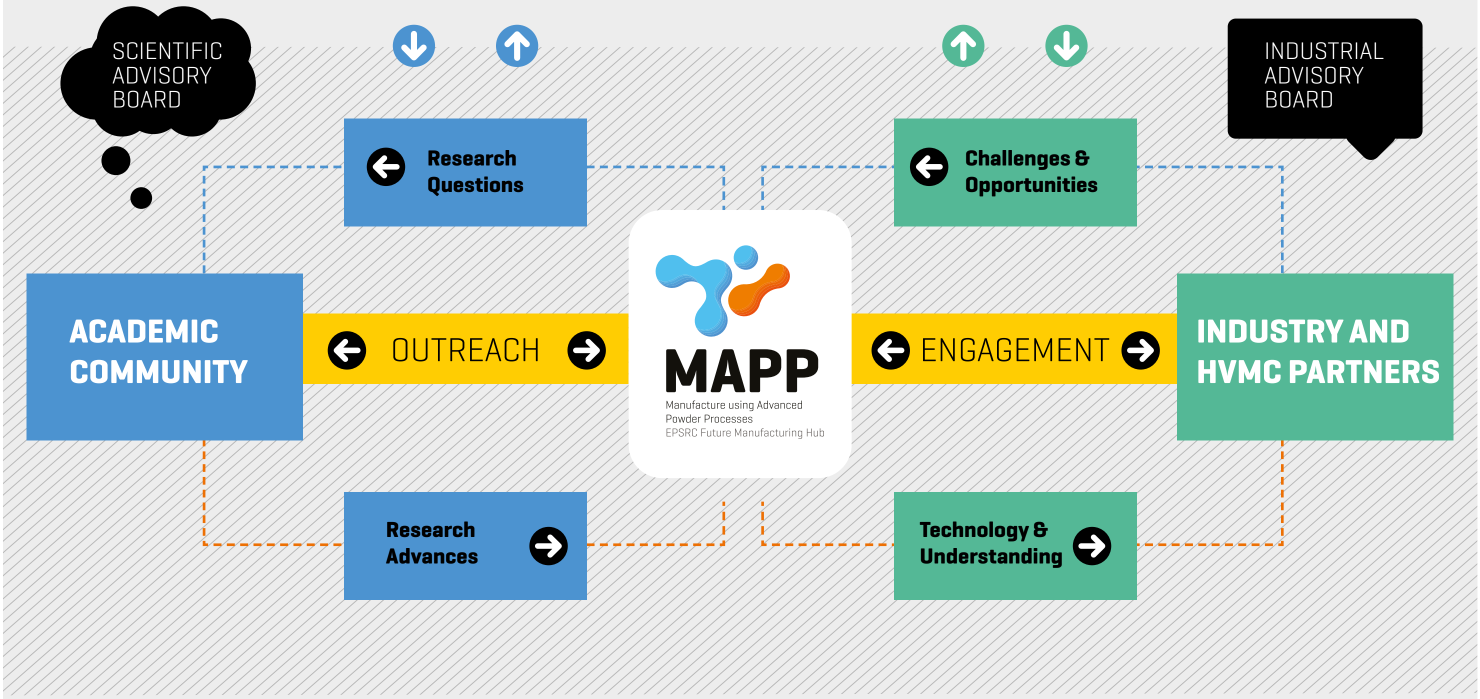
# PATHWAYS
# TO IMPACT

To ensure maximum impact on academia, technology, and the UK economy, MAPP established a range of pathways to impact.

Working with our partners and gaining insight from our advisory boards we delivered on promises of user engagement, commercial outputs, academic outreach, public engagement and the training of the next generation of engineers.

## ACTIVITIES

**International conferences**
**Research sandpits**
**Feasibility studies**
**International missions**
**High profile publications**
**Roadmapping workshops**
**Dissemination workshops**
**Technology demonstrators**
**Researcher secondments**
**Public engagement**



# RESEARCH PROGRAMME OVERVIEW

# CORE RESEARCH THEMES

## PLATFORM RESEARCH: POWDERS AND PROCESS BY DESIGN

Researching powders by design enables us to understand the complexity in powder systems and develop a systems level approach to deepen understanding of their morphology and interaction.

Our process by design research encompasses various powder processing systems, developed through advanced processing, control and monitoring to ensure consistent performance and enhanced manufacturing rates.

## GRAND CHALLENGE (GC) THEMES

### GC1: Right First Time Manufacturing

Ensuring we can deliver defect free and fit for purpose components.

Being able to predict porosity and microstructure evolution through multiphysics modelling. Accommodating variability through real time process control. Achieving pre-defined performance in components and reducing waste.

Working towards zero waste manufacture – processes which are cleaner, more efficient and generate less waste.

### GC2: From In-Process Monitoring and Control to In-Service Prediction and Performance

*In-situ* microstructural control, i.e. components which can be made with specific and controlled microstructures and properties, which will allow us to move from 'form on demand' (right first time) to 'performance on demand'.

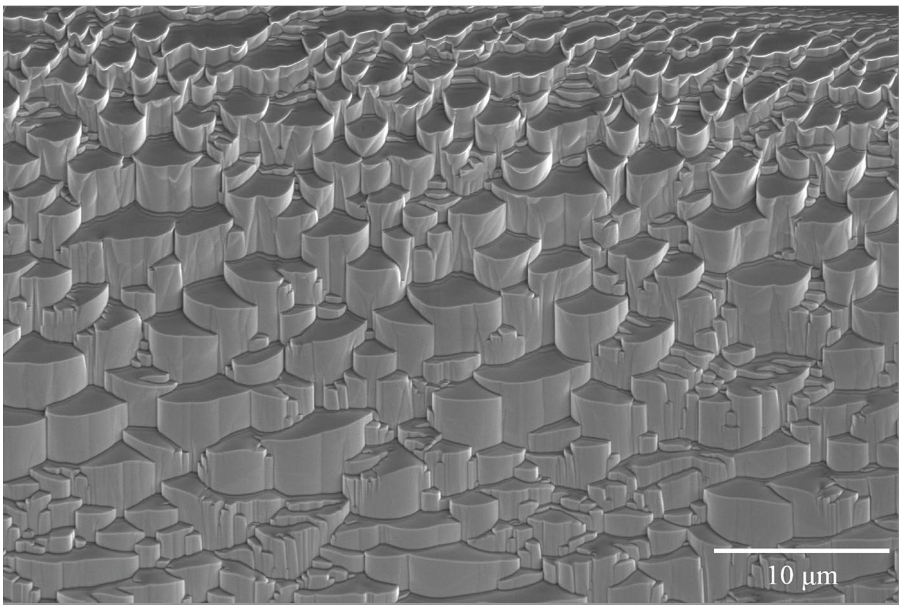
Prediction of component performance in subsequent manufacturing steps and service conditions from the original starting material and processing conditions.

### GC3: Enhanced Product Performance

Enhanced component performance through careful control of process and materials. Structural manipulation to enhance component performance and functionality – controlled hierarchical structures and components.

Development of starting materials which are tuned for process (e.g. 'alloys by design'). Development of processes for materials which are challenging to process or cannot be currently processed via existing powder processes.

Manufacturing of products with properties that are currently impossible.




**Steps to nowhere**

The runner-up photograph in the MAPP 2023 Image Competition was taken by Dr Max Emmanuel, Imperial College London. SEM image of SiC milled at 30kV 2.5 μA using a Xenon source on the Helios 5 Hydra DualBeam microscope captured in Secondary Electron mode.

## CROSS-CUTTING GRAND CHALLENGE THEMES

### Facilities and Demonstrators

We have developed a suite of advanced powder processing equipment and facilities as part of the Henry Royce Institute.

This includes a 'vertically integrated factory' with the ability to design and make new alloys and powder materials, and to process these materials via a wide range of advanced powder processes.

The facilities include small scale research equipment – highly instrumented systems – where we can develop new ideas and concepts, together with commercial scale equipment where we can demonstrate concepts and take them forward with our partners.

We have developed process replicators for use on beamlines (powder bed and blown powder AM) and are developing further replicator systems (e.g. FAST). We are also developing new manufacturing processes and systems including DAM and ceramic robocasting.

### Sustainability

Conventional material shaping and processing routes are often very wasteful and energy intensive, with typical 'buy-to-fly' ratios in aerospace manufacturing of 10- 20%.

Advanced powder processes offer the opportunity to reduce energy consumption and material use, contributing towards the UK's plans for net zero carbon.

Processes such as FAST offer the opportunity to use waste from other processes (e.g. machining swarf) as a starting material for high value products.

### Digital Twin

A central thread within MAPP's approach is the development of process models which can be used to predict and control process outcomes.

We are taking a systems engineering approach to build supervisory, predictive and interactive models of the powder processes and manufactured parts (our 'digital twins'). These models are a combination of both data-based and knowledge-based models with new metrology and *in-situ* monitoring approaches providing key inputs.

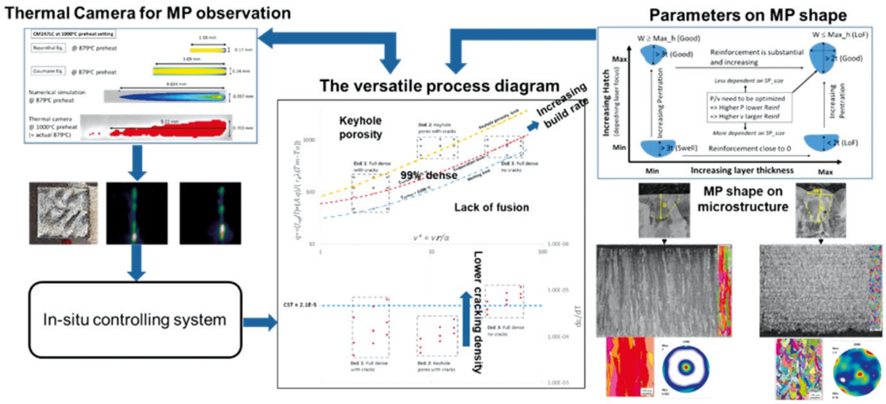
# RESEARCH PROGRAMME UPDATE

## P2.1 ADDITIVE MANUFACTURING

Investigators – Prof. Iain Todd (Sheffield),

Researchers - Dr Felicity Freeman, Dr Minh Phan, Dr Rob Snell, Dr Ben Thomas (Sheffield)

Collaborators – University College London (X1), University of Sheffield (X3), Royce Translational Centre (UoS), Sir Henry Royce Institute (UoM)




### A versatile process diagram for "right first time" LPBF parameter selection (Minh Phan)

A commonly used method to develop LPBF process windows for metallic materials is via the design of experiments (DoE). The procedure is reiterated many times until the optimal process window is identified. This has resulted in a large expenditure of material, time, and labour costs.

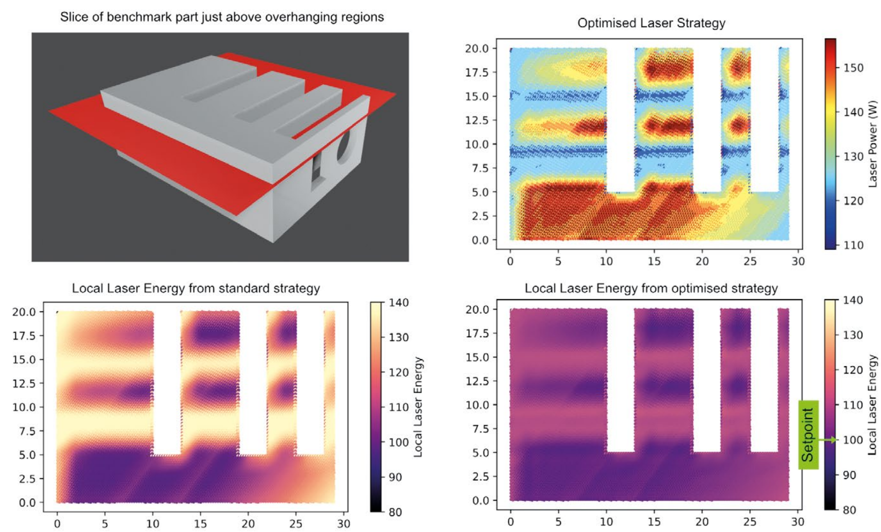
To expedite the progress and save resources, we develop a versatile LPBF process diagram that can predict the good process windows "right first time" based on previous work of laser welding. This is a holistic approach as multiple LPBF parameters and material thermo-physical properties are considered simultaneously by grouping relevant parameters into several dimensionless numbers (e.g., dimensionless beam powder and velocity).

The versatile process diagram shows high reliability in determining parameters corresponding to lack of fusion, keyhole porosity and 99% dense parts when plotting against literature data of LPBF for several metallic materials. We used the diagram to develop process windows for a novel material, ABD-900AM Ni-based alloy, and the results showed high fidelity. This has suggested that "right first time" parameter selection of newly developed materials can be achieved by the diagram.

The potential of the diagram can be expanded by adding more dimensionless numbers to further predict cracking density or towards achieving microstructure by desire. In addition, it can be incorporated with in-situ monitoring techniques to develop closed-loop process control.

### SmartSlicer - Predictive LPBF strategy optimisation software (Ben Thomas, Rob Snell & Henry Saunders (PhD))

The SmartSlicer has been developed over the course of the MAPP program. It optimises laser parameters to minimise heat accumulation and residual stress within parts built by laser powder bed fusion. The underlying algorithm combines traditional part slicing with a rapid laser simulation to predict where the energy density should be changed from conventionally optimised laser parameters. It was born out of thermal imaging work in MAPP where it was observed that certain geometrical features would overheat compared with bulk regions. We set out to mathematically define these regions and then developed software that could interrogate entire CAD files. These regions of interest can be defined by an 'insulation metric', which is analogous to a thermal conductivity. This value is tolerant of edges, corners, thin sections and overhangs, allowing the algorithm to be used across an entire geometry. Once these regions are identified the laser path is generated using whatever path strategy is desired e.g. meander, stripe, checkerboard or island. The predefined path is simulated using an approach that can be likened to a slimmed-down version of a finite-difference model. The simulation does not have the added overhead of modelling the full melt pool, nor does it require a full-field finite element approach to model heat flow. This results in software that can process an entire part without specialist workstation hardware and in a reasonable amount of time. A vector field, which has been termed a "Local Laser Energy" is generated for each of the part's layers at a constant laser speed and velocity. The laser power and speed is then changed for a second pass, this time using a multi-objective optimisation to obtain a thermal field centred around a desired Local Laser Energy setpoint whilst also minimising variations across the layer. As the laser hatch direction is normally rotated between layers, the algorithm can account for changes from the differing laser return times and minimises heat accumulation. The result is a vector path, with optimised laser parameters for every single hatch that can be written directly to a build file ready to be uploaded to an LPBF machine. Figure (see below) shows the modelled output for a single layer, which contains areas that are overhanging as well as thin and thick sections. The software is currently being developed as a product for a University of Sheffield spin-out company led by MAPP PhDs and PDRAs.



### BeAM - Closed Loop Control in Directed Energy Deposition (DED-AM) (Felicity Freeman & Ben Thomas)

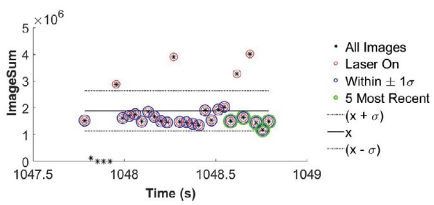
Closed loop control has long been a goal for metal additive manufacturing, as a route to smoothing out the impact of component geometry and stochastic process variation on thermal history. On the BeAM Magic 2.0 Directed Energy Deposition platform, the MAPP team have focused their efforts on developing an industrially-relevant approach, using off-the-shelf monitoring equipment and statistically rigorous data processing techniques to achieve control of melt pool temperature, and therefore deliver components with more uniform mechanical properties.

Image data is collected through a coaxially mounted thermal camera, filtered to remove laser back reflection. This is accompanied by machine metadata, including the position of all axes, local laser travel speed and the current laser power. The data from the camera is noisy, due to spatter which creates small, high intensity spots in the image, and the laser switching on/off at the ends of hatches and layers. The team uses statistical process control techniques to analyse batches of images, covering approximately 1 second of data, and screen out the noise, allowing the good quality images to be identified. This sub-set of images is processed to measure the width of the melt pool, which is then compared to a target value. The laser power is modulated to maintain a constant melt pool width through the duration of the build.

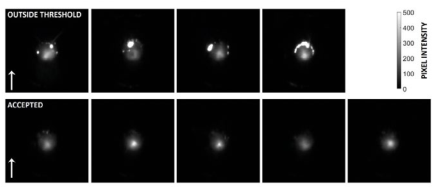
The team successfully applied this control algorithm to a range of component geometries, with build durations of 40 - 60 minutes. This allowed the control strategy to be validated while also confirming that the data capture, transfer and processing steps were sufficiently robust to support long, industrial-scale, build durations. Mechanical test samples were harvested from the components built with and without control, and analysed for flexural strength. The results showed less variation in strength when the control algorithm was applied, indicating a more repeatable material with less influence from the component geometry on the microstructure.

This is a significant step forward for DED, demonstrating that control can be achieved with off-the-shelf monitoring equipment, using statistical process control techniques to filter out process noise, and achieve a geometry-agnostic build with greater repeatability in mechanical properties.

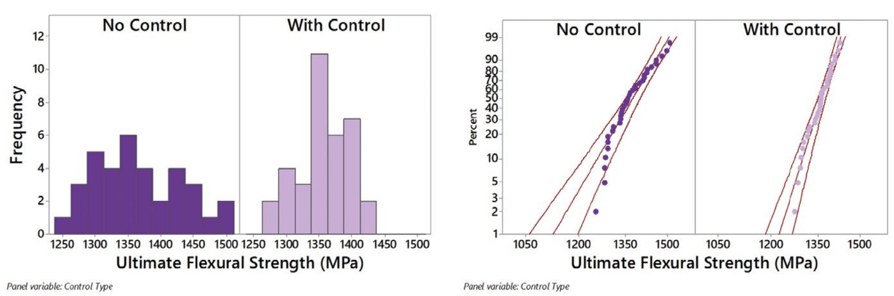
https://www.sciencedirect.com/science/article/pii/S092401362200334X




SPC-Based Image Selection Approach




Selected & Rejected Melt Pool Images




Histogram and Weibull plot of effect of control on flexural strength

## P2.2 SOLID STATE PROCESSING

Investigators – Prof. Martin Jackson (Sheffield), Prof. John Francis (Manchester), Dr Enzo Liotti, Prof. Patrick Grant (Oxford)

Researchers - Dr Simon Graham (Sheffield), Dr Rahul Unnikrishnan, (Manchester), Dr Yun Deng (Oxford)

Collaborators – University of Manchester (X2), Sir Henry Royce Institute (UoM & UoS), Swansea University, Carpenter Additive, ECKART GmbH, Tokamak, UKAEA

### Solid-state processing of metal powders (Simon Graham)

Research into solid-state processing of metal powders at Sheffield has developed considerably over the course of MAPP, with many successful outputs and case studies. There has been a range of research areas centred on the use of Field Assisted Sintering Technology (FAST), including:

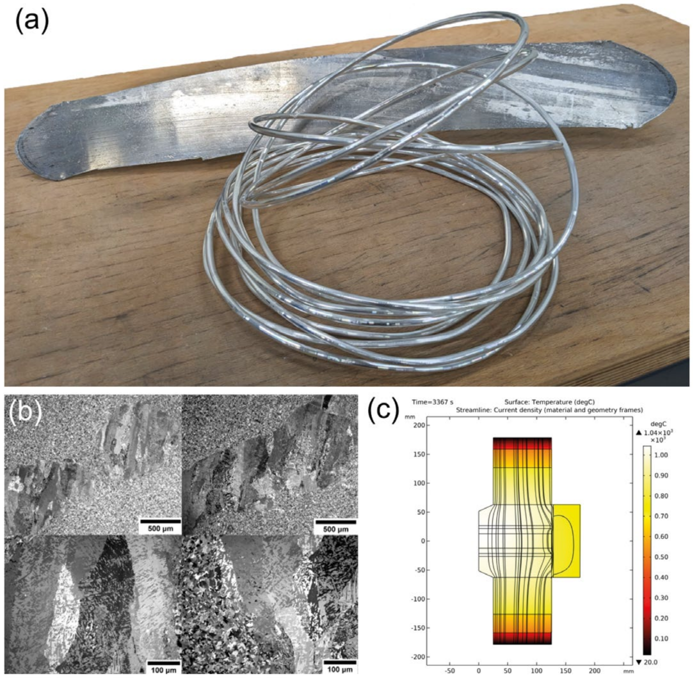
- Improving the fundamental understanding of FAST, both experimentally and using multiphysics modelling, for optimisation of parameters and right first time production
- Combining FAST with conventional metals processing techniques, e.g. forging (FAST-*forge*) and hot rolling (FAST-*roll*)
- Utilising sources of waste or surplus materials and converting them into useful materials/ products, *e.g.* processing of surplus gas-atomised aluminium and titanium powders, as well as using titanium machining swarf to produce automotive components via the FAST STEP 3 project
- Diffusion bonding of dissimilar alloys to produce high performance, multi-material components with site specific properties
- Using new, industrial scale equipment to produce larger samples/components, demonstrating the possibilities of FAST in industry
- Development of new alloys by using powders from novel extraction processes and through solid-state diffusion of blended elemental or alloy powders

Over the last year, there was a continued focus on the solid-state processing of surplus aluminium and titanium powders originating from gas atomisation. Powders outside the 20–63 µm range required for laser powder bed fusion are often deemed surplus. Field assisted sintering technology (FAST) and continuous extrusion are appealing technologies for the processing of these surplus powders into useful products.

There have been further developments on combining FAST with hot rolling (FAST-*roll*) to produce sheet from surplus powder in two steps. Hot rolling parameters were optimised for a FAST-processed A20X, an aerospace approved aluminium alloy. This resulted in defect-free, 1 mm thick sheet material, highlighting that defects observed previously were due to sub-optimal processing and not the material. Following this, FAST-*roll* has been trialled with titanium alloys, with promising results. The ability to easily convert surplus powders into high performance sheet material is desirable for several potential applications, such as in aircraft skins.

Combining FAST with additive manufacturing (AM) has led to the development of *Add*FAST – embedding AM structures into FAST material to create parts with different alloys/ microstructures in specific regions for site specific properties, whilst eliminating the porosity present in as-printed material.

The recent installation of a Conform$^{TM}$ machine at the Royce Translational Centre has enabled new research on converting surplus powders into wire. A20X powder has been directly extruded into 5 mm diameter wire, with no residual porosity and a good surface finish. Further investigation is required to understand the effects of processing parameters on the properties of the wire, whilst the use of alternative dies to produce different wire gauges and non-circular extrusion cross sections will be explored for several applications. For example, surplus powders could be repurposed into feedstock for wire arc additive manufacture, which requires a diameter of 1.2 mm. Another aim is to build upon previous work by researchers in Sheffield on extrusion of titanium alloy powders, which is challenging due to high temperatures and wear of tooling materials.




a) 1 mm thick sheet and 5 mm diameter wire produced from surplus A20X aluminium alloy powder by FAST-*roll* and the Conform$^{TM}$ process, respectively.

b) Polarised light micrographs of *Add*FAST Ti-6Al-4V samples sintered at 950°C, showing coarse grains originating from the AM strut and fine grains resulting from the surrounding powder.

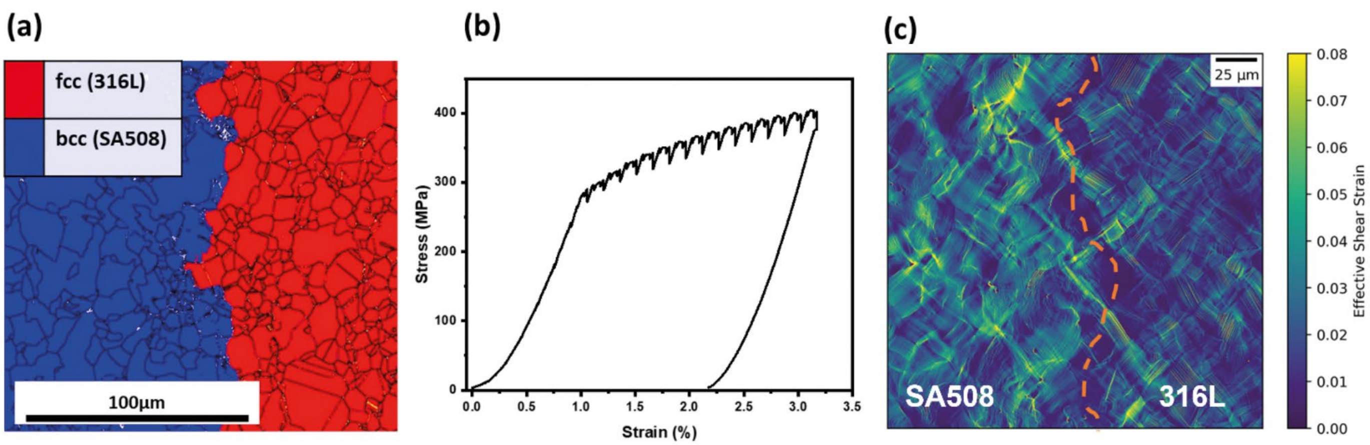
c) 2D axisymmetric model predicting the thermal gradient and current density present in tooling and sample during FAST processing of Ti-6Al-4V powder at 1015°C.

### Solid-state joining of dissimilar metal powders (Rahul Unnikrishnan)

The welding of metals with different physical and metallurgical properties gives rise to the potential for cracking, the formation of brittle intermetallic phases, and the generation of substantial residual stresses. When one of the materials is a hardenable steel, the joining procedure must also restore toughness without adversely impacting on the second material. Traditional approaches involve the introduction of intermediate (buttering) layers and a time-consuming manufacturing sequence. The ability to fabricate bespoke solid-state transition pieces would eliminate the need for in-shop joining of dissimilar metals and would also enable the deployment of advanced high-productivity welding processes.

The Manchester-led MAPP team are investigating the use of solid-state processes involving powders to create welds between type 316L austenitic stainless steel and SA508 Grade 3 pressure vessel steel, a common dissimilar weld that is found in the primary loop of a pressurised water reactor. Solid state processes, such as hot isostatic pressing (HIP), field assisted sintering (FAST), and powder interlayer bonding (PIB), have been explored to date.

In-situ mechanical tests on dissimilar joints were carried out in a scanning electron microscope, enabling researchers to better understand the deformation of joints at a micro-scale level. These tests revealed that powder-based joints showed promising strength at the interface, despite the presence of some pores. In fact, any porosity appeared to be traceable to the gas-atomised powders that were used in the process, and not to be related to the joining process itself. The viability of solid-state joining technologies has therefore been demonstrated. Currently, the focus is on optimising the deposition nickel-based interlayers, which impede the diffusion across the joint and to bridge the gap in the coefficient of thermal expansion between the materials being joined. The remaining challenge is to highlight the full potential for the pre-fabrication of transition pieces through combining additive manufacturing with solid-state joining.




EBSD Phase map (b) Tensile Stress-strain curve (c) 2-D Strain maps from Digital Image Correlation after tensile test of a type 316L-SA508 low alloy steel joint processed with FAST at 1100°C.

### New applications for powder-based manufacturing and Field Assisted Sintering Technology (Yun Deng)

The work at Oxford has focused on the investigation of novel uses of field assisted sintering for joining dissimilar materials and the fabrication of multi-material components with complex geometry.

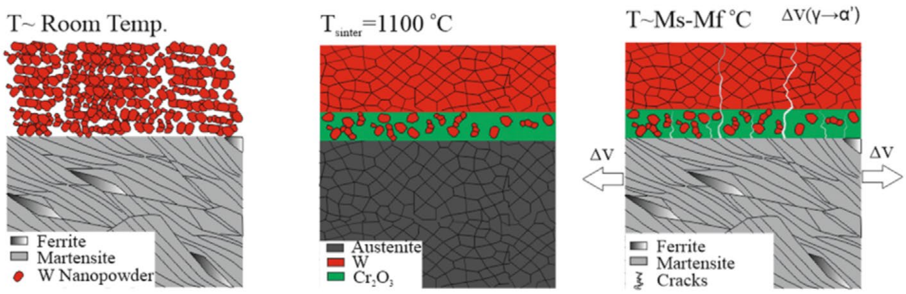
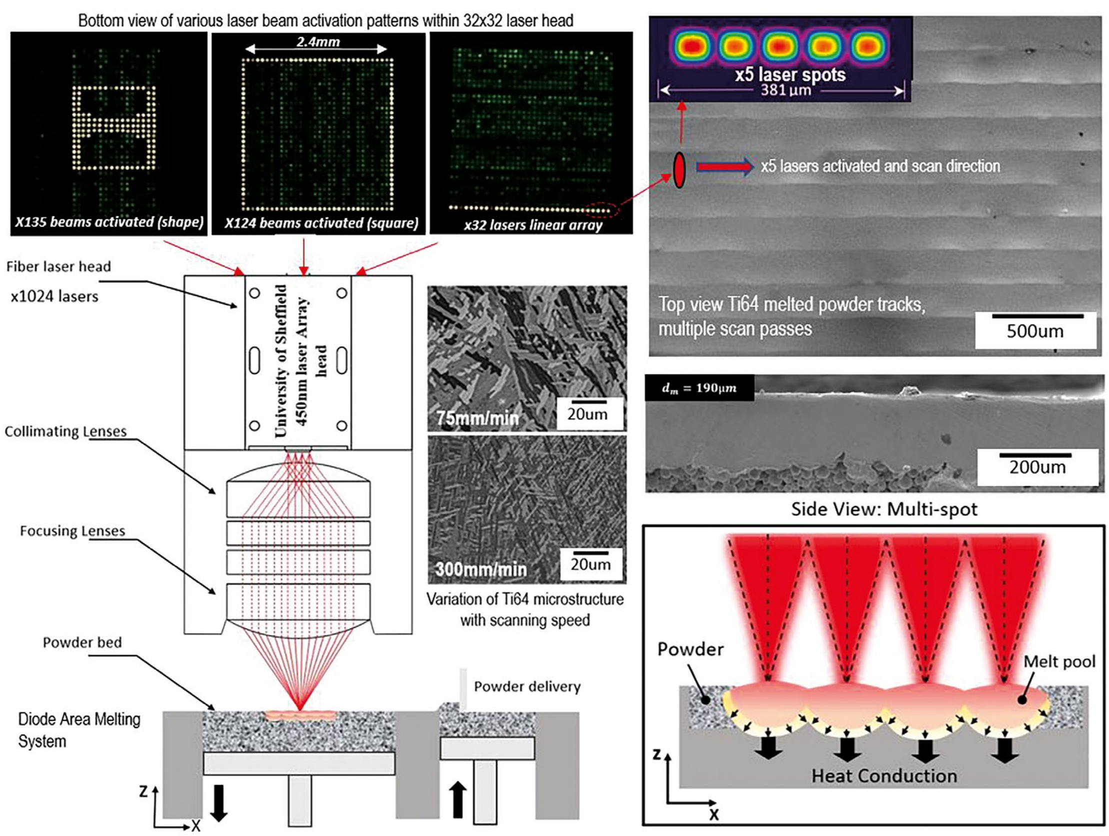



Figure 1: Schematic drawing of the sintering process and the mechanism for the apperance of vertically segmentation cracks (VSCs) W coating during the cooling stage

We have designed a powder metallurgy approach to directly sinter ultra-thick tungsten coatings on bulk steel substrates using field assisted sintering technique (FAST). Millimeter-scale tungsten coatings are needed for many plasma facing structural components in nuclear fusion reactors in order to withstand the extreme heat and radiation loads. However, joining such dissimilar materials is still an outstanding manufacturing challenge due to the following three reasons. Firstly, the very high melting points of tungsten compared to steel makes conventional diffusion bonding challenging. Secondly, the different thermal expansion coefficient between the two materials leads to a considerable build-up of stresses at the interface causing delamination of the coatings during fabrication or thermal cycling. Thirdly, the formation of brittle FeW intermetallic phases further embrittles the materials undermining the adhesion of the interfaces. By carefully tuning the FAST parameters and using nano-size tungsten powder we reduced the sintering temperature below the steel melting point and shortened the processing time limiting the formation of brittle intermetallic compounds. Furthermore, we designed sculpturing patterns on the substrate surface to deliberately segment the tungsten coating with a network of vertical cracks, which was proven to enhance the coating's durability through added in-plane strain tolerance. With this processing routine, we fabricated thick tungsten coatings (2mm) on the substrate of two martensitic steels. In the last year, we have extended the approach to ferritic steels and got a breakthrough in understanding the mechanism that could lead to higher coating thickness with a lower defect rate. Based on that, we have started to collaborate with UKAEA to deposit coating on Eurofer 97 steel. The approach also shows the potential of up-scaling for other industrial applications.

A second branch of research has explored novel processes for near neat shape and component functionalization, using a combination of approaches, such as 3D printing of sacrificial mould to design non-symmetrical geometries, and infiltration and functional graded approaches for multi-materials manufacturing.

## P2.3 FUTURE MANUFACTURING PLATFORMS




Diode Area Melting

## P2.3a Diode Area Melting (DAM)

Investigators – Dr Kamran Mumtaz and Dr Kristian Groom (Sheffield)

Researchers - Dr Ryan Brown (Sheffield)

The Diode Area Melting (DAM) process seeks to overcome the challenge of limited productivity and thermal control within current Powder Bed Fusion (PBF) additive manufacturing approaches.

DAM uses an architectural array of low power fibre coupled diode lasers to process pre-deposited metallic powder (e.g Ti64). The efficiently packed fibre arrays are integrated into a custom laser head designed to traverse across the powder bed. Each laser diode is individually controllable, enabling selective laser processing of powder bed cross-sections and layered fabrication of 3D net-shape components. The operating wavelength of each of these lasers (808nm) are shorter than standard PBF systems, the laser energy is more efficiently absorbed by the feedstock material allowing lower laser power to be used. This process is inherently scalable, within MAPP DAM has evolved from a basic x5 single laser array to an advanced x1024 laser head. The latest system has 32x32 450nm laser arrays enabling simultaneously parallel scanning across a build area with improved thermal control through strategic use of the laser arrays (activation patterns) for powder/melt-pool pre and post-heating.

The most recent work has shown further efficiency gains with the use of low power blue laser sources (450nm). It has shown the potential to control melt pool solidification, process challenging materials such as TiAl and create novel customisable microstructures with tailored site-specific mechanical performance.

## P2.3b High Speed Sintering and Polymer AM

Investigators – Dr Candice Majewski (Sheffield)

Researchers - Dr Ryan Brown (Sheffield)

Collaborators – University of Manchester (X2), University of Sheffield (X3), University of Nottingham, Malvern Panalytical, Netzsch

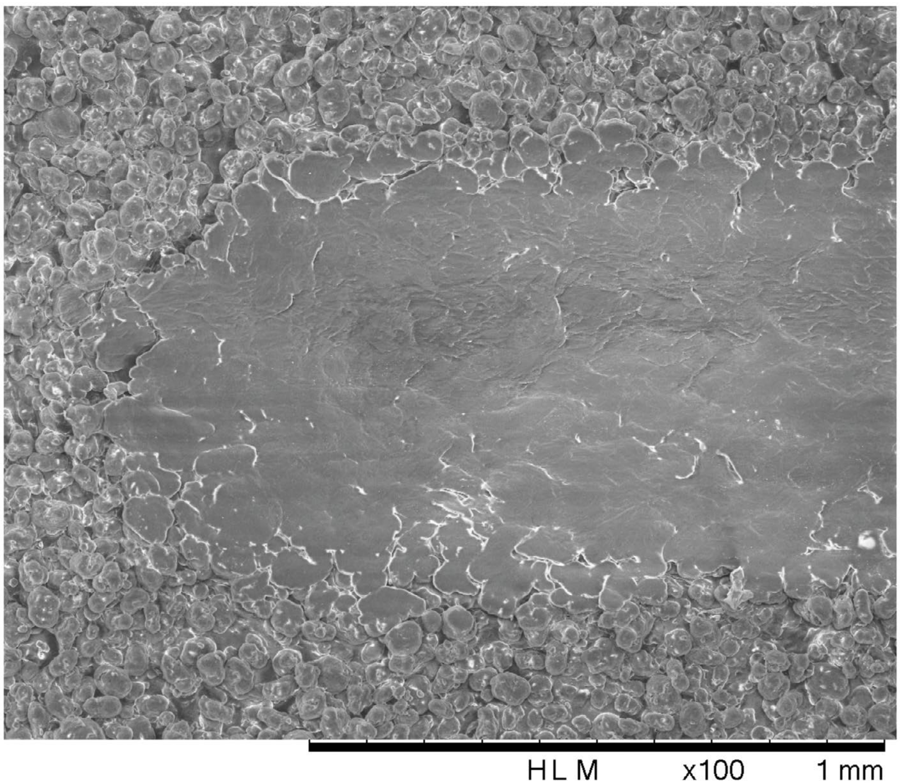
Powdered-polymer Additive Manufacturing (AM) processes are believed to be the most popular AM processes for the production of end-use parts, with polymer powders now the largest segment of the $2.6 billion AM materials market. Since the start of the MAPP programme, research into these processes (in particular Selective Laser Sintering and High Speed Sintering) has led to developments in several key areas:

An underlying aim of our research is to better understand the ways in which our materials and processes interact, in order to allow the design and optimisation of materials specifically for these processes and to improve part quality. Experimental work in this area (cross-cutting theme X2) includes the application of advanced scanning techniques to understand the effects of processing parameters on the development of porosity within AM parts. Modelling work (cross-cutting theme X3) includes the use of machine learning techniques to optimise process settings, development of a thermal model of the High Speed Sintering process, and Bayesian approaches to understanding the effects of material characteristics on their processability.

Characterisation of materials and parts has been a key theme throughout this area, with a focus on understanding how different techniques can be used to provide new insight into AM processes (cross-cutting theme X2). Work in this area has included the first ever use of Positron Annihilation Lifetime Spectroscopy to identify nano-scale structural changes at the surface of powdered-polymer AM parts, and an ongoing collaboration with Malvern Panalytical and Netzsch to understand the ways in which different techniques can combine to provide a deeper understanding of the effects of changes in intrinsic material characteristics on part quality. This latter work also led to the co-development of a full-day seminar relating to the use of advanced characterisation techniques for Additive Manufacturing.

A key barrier to increased uptake of AM parts is a lack of understanding of their real-life behaviour. Another key aspect of our team's research is to improve our understanding of this. Highlights include research into the effects of ultraviolet ageing on the aesthetic and mechanical properties of parts (including the underlying chemical changes causing these effects), successful demonstration of the inclusion of anti-bacterial properties into AM parts, and an understanding of tribological properties and ways in which they can be controlled.

As always there remains much more to discover, and our team continues to build on these research activities as well as exploring new research areas including the use of novel material types for powdered-polymer AM.




Detailed image of a wear scar on the surface of a polymer laser-sintered part. Image courtesy of Kieran Nar.

### P2.3c Ceramics

Investigators – Prof. Eduardo Saiz and Dr Finn Giuliani (Imperial College London)

Researchers - Dr Max Emmanuel, Dr Rohit Malik, Dr Erik Poloni, Dr Iuliia Tirichenko née Elizarova, Dr Siyan Wang, Dr Shitong Zhou (Imperial College London)

Collaborators – University of Sheffield (X3, P2.2, P2.3), University of Leeds (P2.1), University of Oxford (P2.2), University of Manchester (X2), European Space Agency, Manufacturing Technology Centre, Photocentric

#### Robocasting of alumina-based oxide ceramic matrix composites (Rohit Malik)

We have developed alumina Fibre (Nextel 610) reinforced alumina ceramic matrix composites using robocasting of hydrogel inks. The effect of processing parameters including, ink chemistry, solid content, Fibre content, Fibre length, and nozzle size on the printability of composites was investigated. The key findings are:

(1) The Fibre pull-out length determined from SEM micrographs was < 100 μm.

(2) The surface finish and Fibre alignment were found to improve with decreasing nozzle diameter.

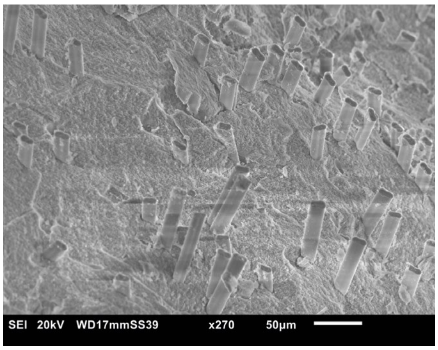
(3) A homogeneous distribution of Fibres was obtained till 30 vol% Fibre content.

(4) The flexural strength exhibits a gradual degradation in strength due to Fibre pull-out.

(5) Silica gel infiltration was investigated to reduce matrix porosity and increase the flexural strength of the composites. However, silica infiltration led to increased brittleness.

#### Digital light processing of alumina-based oxide ceramic matrix composites (Rohit Malik)

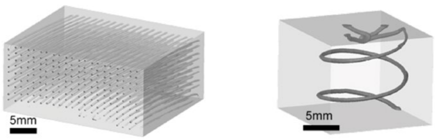
We did feasibility studies on direct light processing (DLP) of alumina-based oxide ceramic matrix composites. The composites with 5 vol% Fibre content exhibit a homogeneous distribution of Fibres, which were aligned in planes parallel to the printing plane. The printed samples also exhibited a high surface finish compared to their robocasted counterparts due to the relatively high printing resolution of DLP.




SEM micrograph showing fracture surface of 10 vol% alumina matrix composite.

#### Embedded printing and co-extrusion of composites (Shitong Zhou)

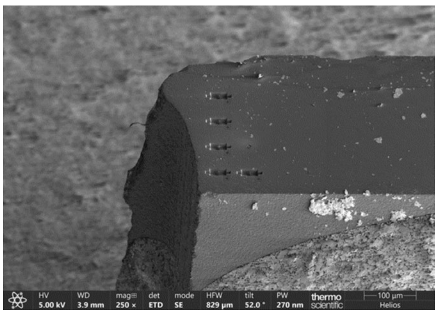
The application of robocasting on multi-material manufacturing, using embedded printing and co-extrusion. We previously analysed crack generation during drying in alumina parts with embedded steel reinforcements using X-ray tomography in collaboration with the University of Manchester. This technique was also employed to create microchannel arrays in ceramics for thermal management. In addition, coextrusion of multi-material ceramic pastes allowed the introduction of intricate networks of weak interphases to improved fracture resistance. These techniques open new possibilities in fabricating inorganic composites with designed architecture.




X-ray tomography of microchannel arrays (left) and spirals (right) in alumina. In collaboration with the University of Manchester.

#### Micromechanics (Max Emmanuel)

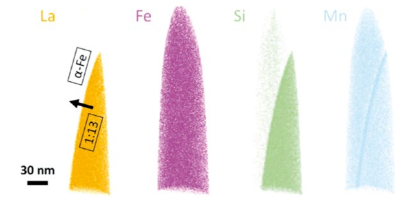
We are attempting to determine the possibility of crack healing in a vacuum environment following microscale fracture tests performed in-situ in a SEM. Furthermore, work is also being done to examine crack growth behaviour in a TEM. Finally, analysis is being performed on EBSD data from WC-Co samples to determine the effect of chromium doping on creep.



SEM image of DCBs milled on SiC single single crystal for crack surface healing experiments in a SEM.

#### Micromechanics (Siyang Wang)

We employed in situ micromechanical testing and characterization with electron microscopy to understand the failure mechanisms of a wide range of structural and functional materials, including nuclear fuel claddings for fission reactors, magnetocaloric materials for next-generation cooling systems, high entropy alloy-based protective coatings, and energy storage materials in Li-ion batteries. We provided a mechanistic understanding of failure processes essential for improving structural design against degradation. Our research outcomes help ensure the damage resistance of materials in novel clean energy systems, of which stability is critical for meeting the target of net zero.




APT element maps of a phase boundary in a La(Fe,Mn,Si)13-based magnetocaloric material

#### Strong and tough bioinspired composites out of silicon carbide for high-temperature applications (Erik Poloni)

In this project, we aim to manufacture strong, tough and thermally-resistant bioinspired composites out of silicon carbide platelets. We are exploring different processing routes to synthesize alpha silicon carbide platelets, which are not commercially available. Once the platelets will be synthesized, we will magnetically functionalize them so that they can be aligned with the aid of a rotating magnet following an establish method to replicate the brick-and-mortar architecture of nacre. The green body will be sintered with a glassy phase and their mechanical and thermal properties will be characterised.

#### Use of graphene as an universal additive to promote direct laser-based processing of ceramics and reflective metals – Iuliia Tirichenko née Elizarova

After demonstrating the feasibility of using graphene to promote the laser-based processing of silica, we have been working on the development of mixing processes to generate graphene-containing feedstocks with the right characteristics (flowability, laser adsorption) for these processes. Dry and wet mixing using different graphene sources have been used. A collaboration with Graphene First in Manchester has been initiated. They have provided different graphene materials. It has been observed that graphene flake size is critical. Small graphene nanoplatelets do not form uniform powder beds when mixed with copper. Future work will centre on the formulation of a copper-graphene feedstock to quantify the increase in efficiency brought by the introduction of graphene.

## CROSS-CUTTING X THEMES

Cross-cutting (X) themes underpin our core research themes. Elements of each of the three themes run through the platform research activities to enable a deeper understanding that allows MAPP to deliver on outcomes.

## X1 *In-Situ* Process Monitoring

Investigators – Prof. Peter D. Lee and Dr CL Alex Leung, University College London

Researchers - Dr Samy Hocine, Dr Kai Zhang, Dr Wei Li, University College London

Collaborators – University of Manchester (X2, P2.2), University of Sheffield (P2.1 & P2.2), University of Leeds (P2.1), Imperial College London (P2.3), University of Oxford (P2.2)

The focus of X1 is to develop unique physical twins of powder processing and component performance that can be probed on synchrotron beamlines to calibrate process digital twins. These physical twins are providing new insights into how to improve the processes and, through machine learning, we are starting to develop low-cost monitoring and control systems. The physical twins have been applied to new materials, from moon rock (Regolith) to reduced graphene oxide (rGO) printability additives, and to new processes such as magnetic field flow control. Two main streams have been explored for synchrotron process calibration, Laser Powder Bed Fusion (LPBF) and blown-powder Directed Energy Deposition Additive Manufacturing (DED-AM).

### Laser Powder Bed Fusion

AM products may exhibit imperfections that lower their mechanical performance. There is a lack of fundamental understanding of how these imperfections form during manufacturing. There are two key ways to improve our understanding, one is to use real-time, *in situ* observations, and the other is via computational process simulation. In this work, our team first uses ultra-fast X-ray imaging coupled with a physical replica of a LPBF machine (a.k.a. physical twin) to visualise and quantify the process dynamics during AM. Working with Renishaw, we combined their RenAM500Q scanning head with UCL's in-house in-situ printing chamber to create a system enabling concurrent ultra-fast correlative imaging including X-ray, optical and other modes to gain many new insights into LPBF. Working with all the MAPP partners, the additive manufactured parts were examined by post-modern electron microscopy to extract microstructural information. After that, we synthesised our experimental data and fed them into a process simulation (a.k.a. digital twin) developed by Rolls-Royce plc. Combining the application of both physical and digital twins, we successfully quantified the pore evolution kinetics, pore size distribution, waviness, surface roughness, and melt volume during LPBF of a nickel alloy. Our work paves a new way to use synchrotron-calibrated digital twins for process prediction and suggests new ways to improve process reliability.

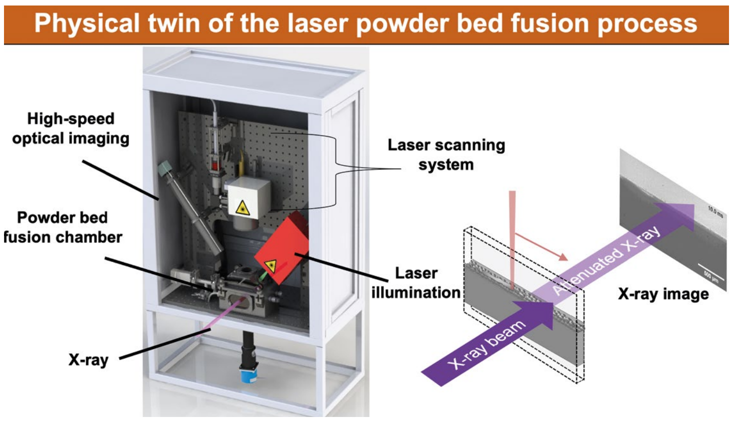
### Directed Energy Deposition Additive Manufacturing

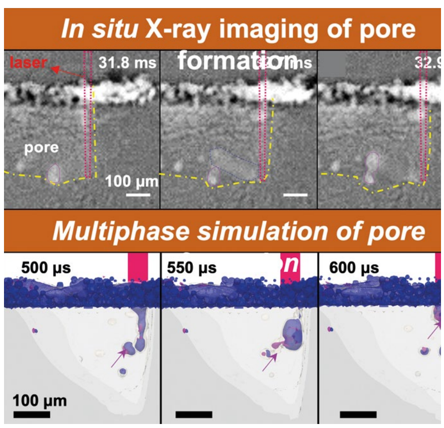
Another key powder manufacturing process is blown-powder DED-AM, where a stream of powder is blown into a laser melted pool building much larger tracks than in LPBF, enabling larger part production. Here we created a second generation Blown-powder Additive Manufacturing Process Replicator; BAMPR-II. Working with Industrial Collaborators, we first used this physical twin to optimise the processing condition of key new aerospace alloys. We then began to look at how we could disrupt the processes to minimise the number of potentially detrimental features forming via applying external forces such as magnetic fields. The work demonstrated that these external forces can significantly alter the flow patterns in the molten pool, providing another process parameter to apply to obtain high quality builds.

### Impact

The X1 theme has been disseminated widely, generating ca. 40 publications in international journals and over 150 engagement activities, from plenary talks at conferences to news articles. Many of MAPP's industrial collaborators were fully engaged throughout the project, with one patent filed and a licensing agreement agreed for sale of some of the physical twins for radiography and tomography.

See pages 30 and 31 for further insights into the MAPP-funded research that has been undertaken by UCL at RCaH.




We used UCL's custom-built physical twin coupled with high-speed X-ray imaging to study the pore evolution mechanisms during the laser powder bed fusion (LPBF) additive manufacturing (AM) process. New insights gained in our study explain how pores were formed; they were then used to calibrate a multi-phase process simulation model, a.k.a. digital twin, for the LPBF AM. This digital twin can be used to predict and optimise processing conditions to achieve a print quality that minimises both porosity and surface roughness.

## X2 Advanced Characterisation

Investigators – Prof. Philip Withers, Prof. John Francis (Manchester), Prof. Andrew Bayly, Prof. Ali Hassanpour (Leeds)

Researchers – Dr Mozhdeh Mehrabi (Leeds)

Collaborators – University of Sheffield (P2.1), Imperial College London (P2.3), University of Edinburgh, University of Greenwich, Swansea University, Carpenter Additive

### Powder spreadability

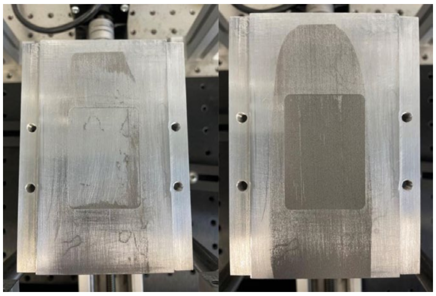
The research at the University of Leeds aimed at understanding powder spreading behaviour for Additive Manufacturing and key descriptors that could predict their behaviour.

Our objective was to understand spreading dynamics, the role of powder characteristics, and the spreading systems and to finally find appropriate quantitative metrics for assessing powder spreadability.

To achieve this goal, we analysed a wide range of AM powders:

1. To systematically study powder spreading behaviour and to come up with a unique description of powder spreadability index using a standard procedure.
2. To fully understand the effect of powder's characteristics on the powder spreadability to identify the key descriptors of the raw materials.
3. Identification of the most reliable method to characterise powder flow behaviour in correlation with the conditions of powder spreading in additive manufacturing
4. To investigate the effect of external variables such as humidity, temperature, blade geometry and velocity on the powder spreadability.

We have found that the measurements using commercial flowability measurement techniques can only partially correlate with the powder spreadability, and in some cases, have led to contradictory results. The study in this work has revealed the shortcomings in correlating the flowability of powder and their spreadability under real process conditions. It became evident that to identify and choose the appropriate powders, the direct assessment of powder spreading is the most suitable approach, for which a standard **powder spreading instrument** shall be developed. Therefore our focus and effort for future work will be on further developing a standard spreading machine capable of systematically quantifying the term powder spreadability under different process conditions, close to those of real process.



Marked differences were observed in the spreading behaviour of two 316L powders that had similar flowability.

## X3 Modelling, Optimisation and Control

Investigators – Prof. George Panoutsos, Prof Visakan Kadirkamanathan (Sheffield), Prof. Phillip Stanley-Marbell (Cambridge)

Researchers - Scott V. Notley, Emad M. Grais (Sheffield)

Collaborators – University of Sheffield (P2.1, P2.3b), University College London (X1), Royce Discovery Centre, Sir Henry Royce Institute (Sheffield)

### Robust Data-Centric Cyber-Physical Systems For Materials 4.0 (Scott Notley & Emad Girgis)

In this project, the feedback control is to be provided by a machine learning (ML) entity, a Reinforcement Learning (RL) strategy. A model-free algorithm is created that iteratively learns via interacting with the environment (additive manufacturing process) towards controlling the process (meltpool depth). We developed a computational framework based on Proximal Policy Optimization (PPO) RL. For simulation purposes we *replace* the real PBF environment with a physics-based simulation model for the PBF process as shown in Figure 1. The PPO RL framework requires many thousands of interactions with the environment to derive a control policy, hence the use of the model here.

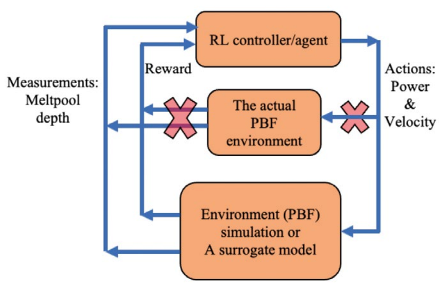



Figure 1: Using Reinforcement Learning with the simulation of the Powder Bed Fusion environment.

The process output to be controlled is the depth of the meltpool, while the process parameters; beam power and velocity are used to achieve a predetermined meltpool depth target. The aim of the RL agent is to find good values for the process parameters, i.e the power and velocity that can achieve a stable meltpool depth (55 μm over the build). The reward for the RL agent is how close the measured depth is to the required depth of 55 μm with a regularisation term that penalises the distance between the minimum and maximum melt depth during the RL episode.

Figure 2 shows the meltpool depth for the case of using RL with and without control. In the same figure, the control actions (selected power and velocity values) are also shown. As it can be seen from Figure 2, the meltpool depth is closer to the target value with control compared to using fixed values for the power and velocity of the laser beam, as expected. We can also see that, when the meltpool is deeper than the target (usually around the edges of the build) the RL policy reduces the power and increases the velocity simultaneously to reduce the heat applied to the build. This power and velocity control compensation strategy can be used for any arbitrary target of meltpool depth (or other control metric, meltpool temperature, cooling rate etc.). The overall control performance is also summarised in the form of a histogram in Figure 3, where process stability around the target (55μm meltpool depth) is demonstrated.

Physics based models are computationally expensive and introduce a prohibitive amount of lead time even in an offline optimisation paradigm. As a solution to this problem, fast surrogate models based on neural networks can be used to approximate the physics model. Surrogate models are computationally cheap models that approximate the dominant features and responses of more complex high fidelity models. A new modelling framework was developed, based on neural ensembles, to estimate the inherent epistemic uncertainty of the surrogate model. We consider uncertainty due to two sources: (a) non-identifiability of models due to multiple local minima for a given dataset and (b) inherent data randomness. The standard method of minimum cross-validation error, in this case, may not be suitable as we require a measure of performance that is consistent across networks. In this case we use an adaptation of a method previously developed as part of the MAPP programme, that estimates a statistically principled measure of goodness-of-fit, to ensure commensurate performance across networks enabling the use of an ensemble of neural networks to provide robust predictions, with an estimate of uncertainty on those predictions and requires no prior assumptions on data distributions and covariance.

The surrogate models were built using a reduced training dataset composed of discrete and constant power and velocity combinations over whole builds mapping to meltpool depth. Despite this shortcoming of the training data, the surrogate model is able to respond robustly to unknown process parameter combinations and dynamic input transitions providing a measure of the reliability during these periods.

Figure 4 shows example results comparing the performance of the surrogate model (solid line) to the ground truth physics model (dashed line); grey shading shows the surrogate uncertainty of prediction. Figure 3a shows the response of the surrogate when transitioning between two previously seen laser powers (100 to 150 Watts) used in the training data with increased uncertainty at the point of transition. Figure 3b shows the response found when transitioning from a previously seen laser power to an unseen laser power. In this case there is increased uncertainty both at the transition time and post-transition.

Using the surrogate ensemble modelling approach, we can now replace the computationally expensive simulations (numerical models) with cheap to run surrogates, hence further enhancing the effectiveness and efficiency of the RL strategy.

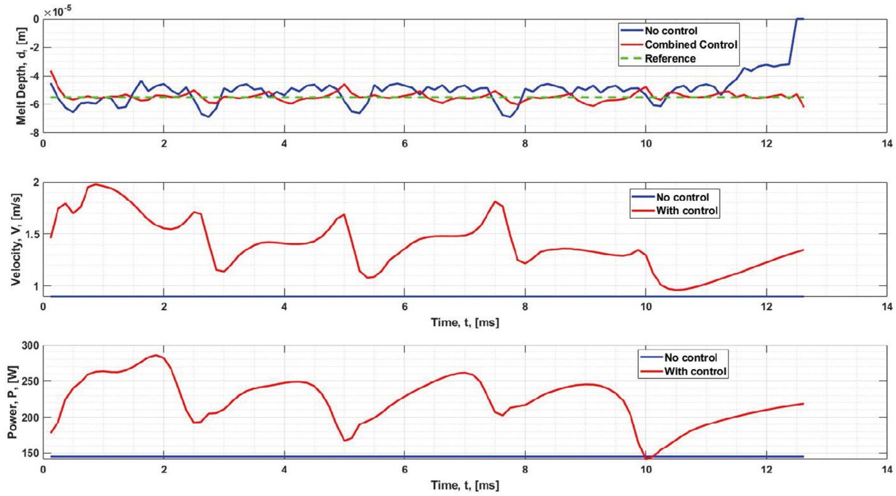



Figure 2: The meltpool depth for using RL controller (red lines) and without control (blue lines) and the corresponding actions (velocity and power) in the control case (in red) and without control (in blue).

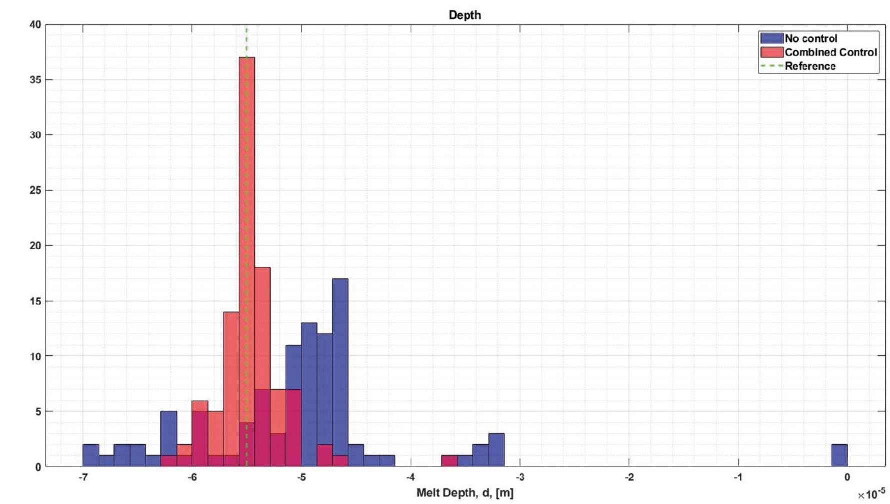



Figure 3: The histogram of the meltpool depth for using RL controller (red bars) and without control (blue bars).

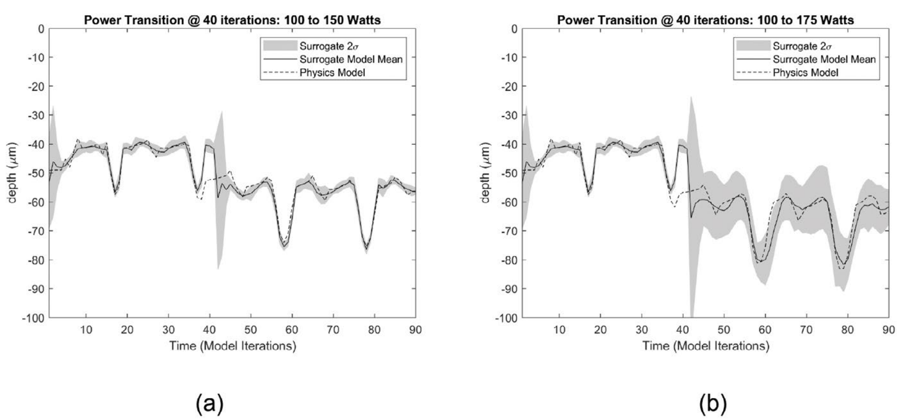
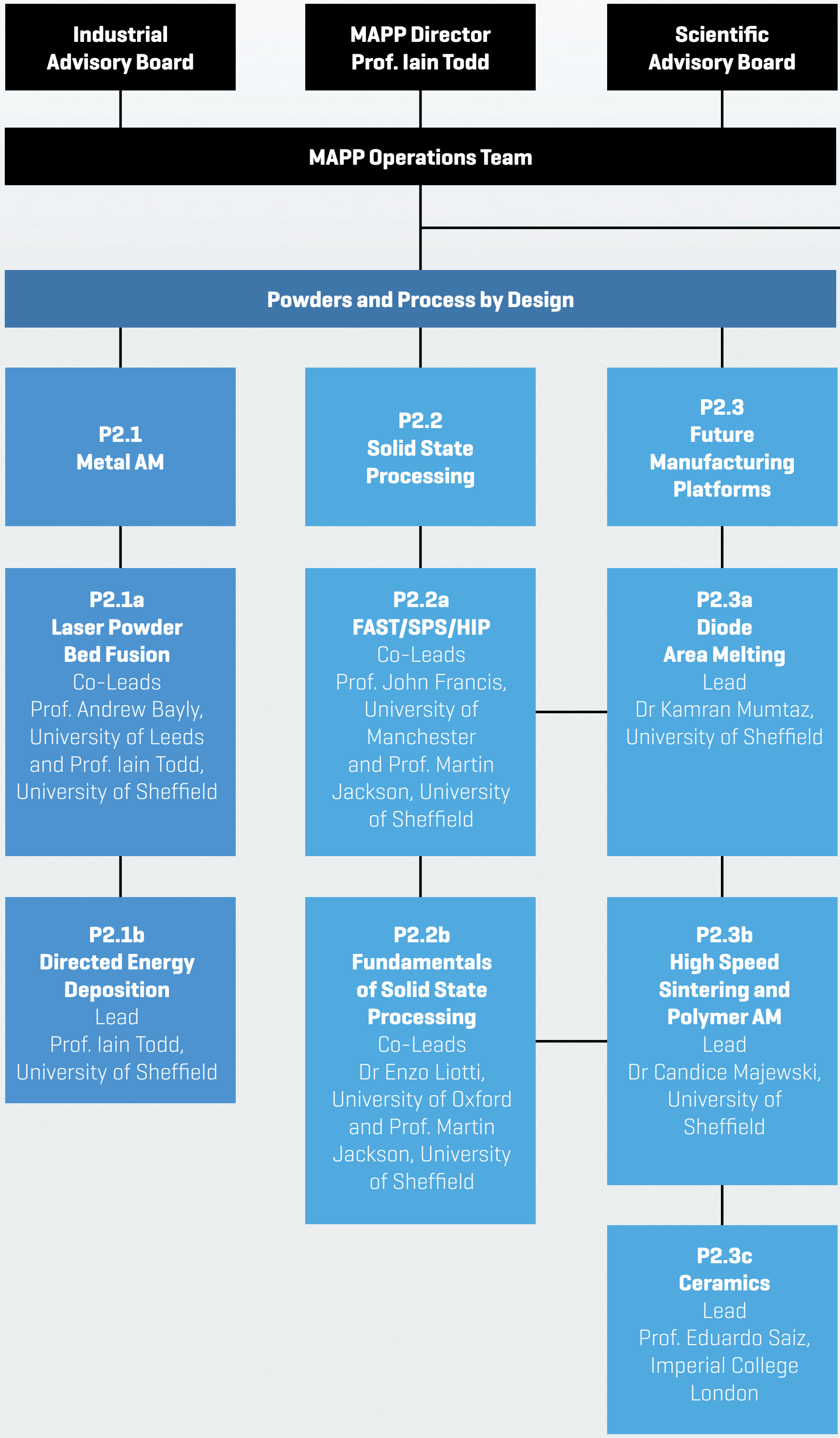



Figure 4: Surrogate model performance vs Physics based model with transitions in laser power. (a) Transitions between laser powers contained within training data. (b) Transitions between laser powers from a 'known' power contained in the training data to an 'unseen' laser power of 175 Watts.

# MAPP PROJECT ORGANISATION CHART




**Co-Investigators in Powders and Process by Design**

- Dr Finn Giuliani, Imperial College London
- Prof. Patrick Grant, University of Oxford
- Dr Kristian Groom, University of Sheffield
- Assoc. Prof. Ali Hassanpour, University of Leeds
- Prof. Andrew Mullis, University of Leeds
- Prof. Philip Prangnell, University of Manchester
- Prof. Luc Vandeperre, Imperial College London
- Dr Jon Willmott, University of Sheffield

## University Partners

University of Sheffield · University of Cambridge · Imperial College London · University of Leeds · Manchester 1824 The University of Manchester · University of Oxford · UCL

### X1 *In-situ* Process Monitoring
Lead Prof. Peter Lee, University College London

**Co-Investigators**

- Prof. John Francis, University of Manchester
- Dr Finn Giuliani, Imperial College London
- Prof. Patrick Grant, University of Oxford
- Dr Chu Lun Alex Leung, University College London
- Prof. Andrew Mullis, University of Leeds
- Prof. Iain Todd, University of Sheffield

### X2 Advanced Characterisation
Lead Prof. Philip Withers, University of Manchester

**Co-Investigators**

- Prof. Andrew Bayly, University of Leeds
- Prof. John Francis, University of Manchester
- Dr Finn Giuliani, Imperial College London
- Dr Candice Majewski, University of Sheffield
- Prof. Mark Rainforth, University of Sheffield
- Prof. Luc Vandeperre, Imperial College London

### X3 Modelling, Optimisation and Control
Co-Leads Prof. Visakan Kadirkamanathan and Prof. George Panoutsos, University of Sheffield

**Co-Investigators**

- Prof. Andrew Bayly, University of Leeds
- Assoc. Prof. Ali Hassanpour, University of Leeds
- Prof. Andrew Mullis, University of Leeds
- Prof. Philip Prangnell, University of Manchester
- Assoc. Prof. Phillip Stanley-Marbell, University of Cambridge

**In tribute to Prof Luc Vandeperre**

# MAPP

# PROJECT PARTNERS

University of Sheffield
University of Cambridge
Imperial College London
University of Leeds
Manchester 1824 The University of Manchester
University of Oxford
UCL

MAPP is led by the University of Sheffield and brings together leading research teams from the Universities of Cambridge, Leeds, Manchester and Oxford, Imperial College London and University College London, together with industry partners and the UK's High Value Manufacturing Catapult Centres.

## HIGH VALUE MANUFACTURING CATAPULT CENTRES

AMRC Advanced Manufacturing Research Centre / The University Of Sheffield.
AFRC Advanced Forming Research Centre University of Strathclyde
Catapult High Value Manufacturing
cpi
mtc Manufacturing Technology Centre
National Composites Centre
Nuclear AMRC
WMG Innovative Solutions

## INDUSTRY PARTNERS

Atomising Systems Limited
Eastman
element six
Carpenter Additive
freeman technology
GKN Aerospace
JM Johnson Matthey Inspiring science, enhancing life
Maher
Metalysis
Morgan Advanced Materials
Photocentric
PSI
Renishaw apply innovation™
Rolls-Royce
Safran Messier-Bugatti-Dowty
SECO
Wayland Additive
WEIR
XAAR
ZEISS

## ADDITIONAL COLLABORATING AND CONTRIBUTING INDUSTRIES

Throughout the six years of research, MAPP has worked with additional industries through; collaboratively funded aligned projects (some of which are listed at the end of this report), directly funded programmes and projects or through indirect and in-kind industrial funding. In total, over 100 companies have collaborated and contributed to the MAPP and MAPP-aligned research across a wide range of powder-based processes.

**Additive Industries**
**Addmaster**
**AddUp**
**Airbus**
**Alloyed**
**Amexci AB**
**Arcelor Mittal**
**AREVA Group**
**Argonne National Laboratory**
**Aubert and Duval**
**Autodesk**
**BEAMIT**
**Bentley Motors**
**Boeing**
**Braskem**
**Britishvolt**
**Carbolite Gero**
**CCFE**
**Central Laser Facility**
**CFMS**
**Cidetec**
**Constellium**
**Diamond Centre Wales**
**Diamond Light Source**
**Dr Fritsch**
**DSTL**
**Eckhart**
**EDF Energy**
**ESA**
**ESRF**
**Force Technology**
**Ford**
**Granutools**
**Heita**
**HRL Laboratories**
**Illika**
**Inovar Communications**
**Insphere**
**Jaguar Cars**
**Kanthal**
**KTN**
**Liberty Powder Metals**
**LSN Diffusion**
**Lucideon**
**Malvern**
**Materialise**
**McClaren**
**Metron**
**Multilase**
**Netzsch**
**Northern Automotive Alliance**
**NPL**
**Oerlikon**
**Olympus**
**Oxford Instruments**
**Oxford Lasers Ltd**
**Phoenix Materials Testing**
**Qdot**
**Relequa**
**Reliance**
**Reliance Precision**
**Retsch UK**
**Rheinmetall BAE Systems Land (RBSL)**
**SABIC**
**Sandvik Osprey**
**Siemens**
**Solar Turbines**
**St Gobain**
**STFC**
**Tata Steel**
**Thermocalc**
**Thinklaser**
**Timet**
**TISICS**
**Tokamak**
**Transition International Ltd**
**Tripal**
**TWI**
**UKAEA**
**US Office of Naval Research Global**
**Verder Scientific**
**Victoria Drop Forgings Ltd**
**WH Tildsley**
**Wilde Analysis**

The ACONITYLAB (ACONITY3D GmbH) Laser Powder Bed Fusion (LPBF) machine at the Royce Discovery Centre (RDC) in Sheffield

# MAPP AND CAM$^2$ SECOND JOINT WORKSHOP ON AI IN AM

**The joint Centre for Additive Manufacture event was held at the Leopold Hotel in Sheffield on 5th October 2022**

Delegates and speakers shared the latest thinking on additive manufacturing in industry at our second joint workshop with the Centre for Additive Manufacture – Metal (CAM$^2$) in October 2022.

The event included interesting speakers from Siemens, AMEXCI, Carpenter Additive, Rolls-Royce, Themo-Calc Software and academia.

About 80 delegates attended the hybrid event, held online and in Sheffield. It followed 2021's successful workshop on Artificial Intelligence in Additive Manufacture (AM).

It provided an opportunity to connect with about 45 colleagues in person and 35 online delegates to address some AM monitoring, control, and data challenges.

The joint workshop on Artificial Intelligence in Additive Manufacture, covered the following topics:

- In-process Control in Additive Manufacture
- Data handling in AM
- Process Modelling and Simulation
- Digital qualification of processes and materials

The programme included MAPP Director Prof. Iain Todd, Prof. Eduard Hryha, director of CAM$^2$, and speakers from Chalmers, University of Sheffield, Carpenter Additive, Amexci AB, Siemens, the University of Cambridge, and Rolls-Royce plc.

AM allows almost unlimited freedom of component design for designers and engineers, enabling the direct manufacture of complex components that are not possible or feasible to produce by other technologies.

AM also has rather unexploited potential to offer materials engineers and metallurgists the freedom to control microstructure and materials properties in ways that were previously also seen as being "impossible".

However, practical utilisation of this potential requires an extremely high degree of control over the AM process on the micro-and macro-level. This requires the development of machine control and sensor technologies in combination with modelling and machine learning tools to enable process control and its tailoring to utilise the benefits of material and component design as well as to assure process robustness.


Researchers, at CAM$^2$ and MAPP, have been deeply involved in the development of new methods and strategies and their application to the control of the AM processes and components manufactured by AM. This workshop focused on this research and the opportunities that the digitalisation of the AM process offers and the continuing research challenges that it presents.





MAPP



Engineering and
Physical Sciences
Research Council
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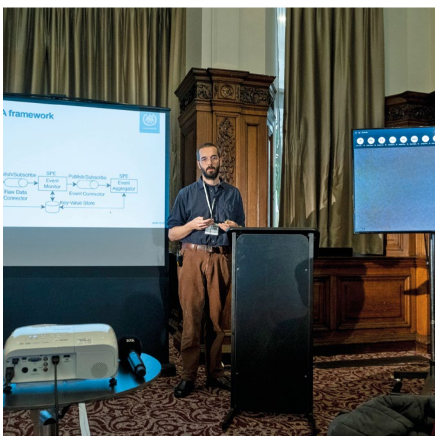



# ACCES

# GRANTED

## Reviewing the Feasibility funded research of Kit Windows-Yule at Birmingham University

Article by Rachel Park, RP Editorial Services, from a recent interview with Dr Kit Windows-Yule

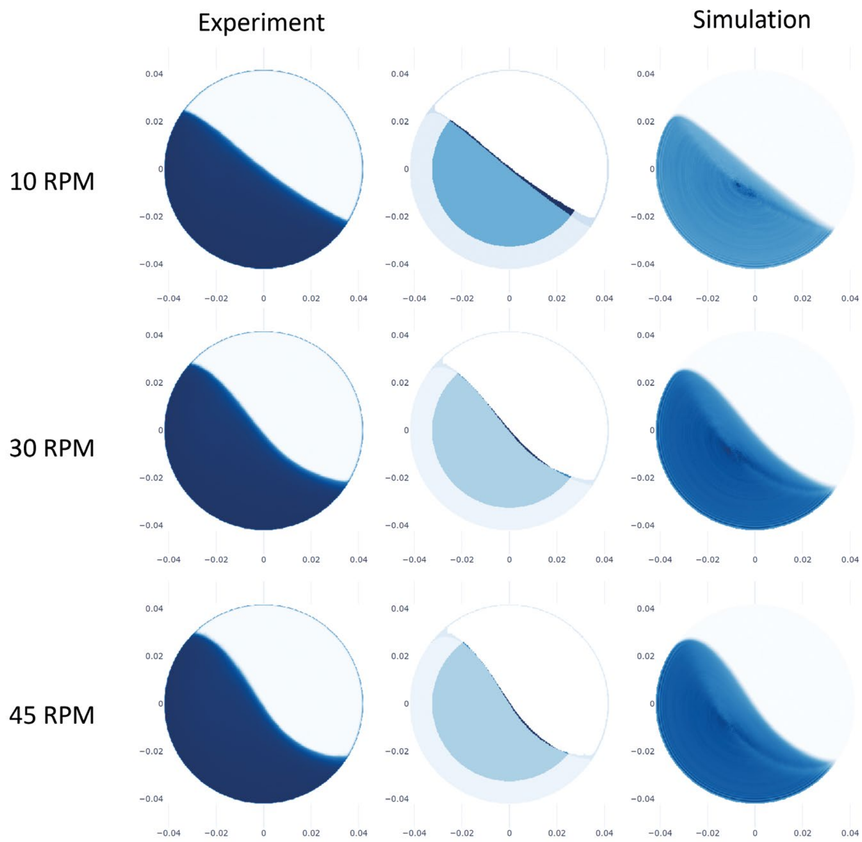



Image caption: ACCES can calibrate *multiple parameters* against *multiple measurements* within a single instrument. For example, GranuDrums at different RPMs, Shear Cells, FT4 etc.

### JUST TO CLARIFY – NO, THAT TITLE IS NOT A TYPO.

This is a fascinating progress report for the 2023 MAPP annual report on the ground-breaking feasibility research being undertaken by Dr Christopher (Kit) Windows-Yule at Birmingham University. To recap quickly, Dr Windows-Yule's research is focused on the use of the Discrete Element Method (DEM), specifically its current use in industry and improving implementation and outcomes.

According to Dr Windows-Yule: "DEM is a very powerful technique but people are using it very poorly. DEM is a technique that allows you to use simulation to prototype industrial processes and optimise them to do what they need to do. Hypothetically, it should work brilliantly. However, in order to get it to work optimally, you need to feed it the right parameters – the ***real*** properties of the materials that you are modelling."

The DEM research started with an International Fine Particle Research Institute (IFPRI) funded project that led to a feasibility study called CoExSiST, funded via MAPP's second round of feasibility funding (November 2019). A key feature of CoExSiST was the development of the Autonomous Characterisation and Calibration using Evolutionary Simulation (ACCES) tool, also developed with MAPP funding and driven by two of Dr Windows-Yule's students, Leonard Nicusan and Dominik Werner.

Dr Windows-Yule explained how CoExSiST and ACCES have coalesced over the last 12 months: "[they] are two halves of the same coin, but we have merged both of those projects together and are calling it ACCES moving forward."

The goal of ACCES is to address the limitations of DEM by making it simpler, less labour-intensive and more cost-effective. ACCES is a software ecosystem, and it is generating a great deal of interest across the powder manufacturing sector. This can be seen most clearly through the follow-on funding ACCES has received, notably from Granutools, Europe's foremost powder characterisation specialist.

Dr Windows-Yule commented: "Characterisation and calibration go hand-in-hand. If you want to calibrate a DEM simulation, you need good characterisation of the powders that you are using. However, the tools that you measure powders with provide values corresponding to bulk powders. DEM needs to know how a particle behaves."

As a result, the project with Granutools is focused on the development of DEM digital twins for all powder characterisation devices. This allows the creation of mapping relations and thus effective measurements using the Granutools devices. These can then be run through the digital twin to produce the microscopic parameters of the powder.

This is a four-year project with £50k of additional funding from Granutools. According to Dr Windows-Yule: "We are just over a year in and the goal is to develop the World's first microscopic powder characterisation device – a real revolution for the field that provides actual powder properties with physical meaning."

To date, the project has produced digital twins of three of Granutools' five devices.

Rounding up his experiences with MAPP, Dr Windows-Yule commented: "When I went into this MAPP project, I had one PhD student funded by the government. Now I have a team of 17 people — enabled by the research funded by MAPP. So, MAPP will live on – even after it ends."

# MAPP SUPPORTED WAYLAND ADDITIVE ON THE JOURNEY FROM TECH START-UP TO MACHINE SALES

Article by Rachel Park, RP Editorial Services, from a recent interview with industrial collaborators, Will Richardson and Ian Laidler, at Wayland Additive

The Wayland Additive and MAPP collaboration dates back to 2017. Wayland, based in Huddersfield, was then an additive manufacturing (AM) technology start-up focused on solving the many industrial challenges of the eBeam metal powder bed fusion (PBF) AM process for production applications.

Wayland brought together a small team with a wealth of knowledge and experience from the semiconductor industry, where electron beam widths are measured in nanometers and process instabilities are unacceptable. The team was convinced that their collective experience could improve the eBeam process for AM and this is the primary focus of the company.

Today, that conviction is bearing success. With a strong order book and a growing team, Wayland is continuing to scale up its manufacturing operations and has started shipping its Calibur3 metal AM systems, featuring its proprietary NeuBeam process.

Scaling-up production of the Calibur3 Metal AM System to meet growing global demand. Image courtesy of Wayland Additive.

## MAPP COLLABORATION FROM AN INDUSTRIAL PERSPECTIVE

Speaking with CEO, Will Richardson and CTO, Ian Laidler about the Wayland journey, Richardson said: "We have worked with MAPP in a number of different ways. Initially, this was through an Innovate UK funded collaboration called Project MIRIAM."

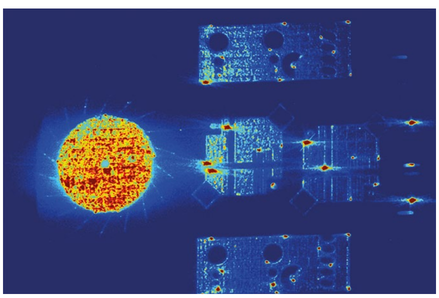
Laidler further elucidated: "The Miriam project was very much focused on in-process monitoring. Specifically, around research focused on the application of infrared (IR) imaging techniques and developing a bespoke camera lens."

The success of the Miriam project led to subsequent projects. These have spanned the existence of MAPP and are now becoming visible both technically and commercially. Laidler confirmed: "Our in-process monitoring capabilities, as they exist on the Calbur3 system are a direct consequence of our collaboration with MAPP."

Wayland's exploration into Artificial Intelligence (AI) has also been through collaborative efforts with MAPP, specifically with Professor George Panoutsos (MAPP Primary Investigator). The company is currently sponsoring one of his PhD students.

## TECHNOLOGY & PEOPLE

As a deep-tech start-up, Wayland is operating across a broad spectrum of scientific and engineering disciplines. The in-house Wayland team cannot cover every aspect to the expert level as required and this is where MAPP meets a fundamental need. Laidler explained: "As a start-up, we cannot scale the team with ***all*** of the knowledge required. This means that we absolutely ***have*** to feed off the universities. MAPP is a superb conduit, providing access to the expertise that we need."



Thermal image of Calibur3 melt phase showing individual melt pools.

Indeed, Wayland has been very well positioned to transition expert AM personnel from academia into industry. According to Laidler, "this is absolutely fundamental and one of ***THE*** most successful outcomes of MAPP in terms of how it has funded and trained core staff for industry." The Wayland team now includes several staff hired from MAPP — experts in their respective fields who all joined the company as a result of the MAPP collaboration.

Summing up the importance of MAPP to Wayland, Richardson said: "This type of programme in the UK is incredibly helpful and important for tech companies starting up, as a means of accessing deep technical expertise while also having the funding mechanism in place to support this kind of work."

# FEASIBILITY PROJECT REPORT:

# DEVELOPMENT AND DEMONSTRATION OF A CHEMICAL POWDER RENEWAL SYSTEM

Principal Investigator (PI): **Dr James Murray**, Senior Research Fellow, Advanced Component Engineering Laboratory, University of Nottingham


## Abstract

In Laser Powder Bed Fusion (LPBF), high value powders which do not end up in the final part are gradually oxidised as they are recycled until they are unfit for purpose and discarded for close to zero value. Previous work at Nottingham funded through MAPP demonstrated a new chemical method for the renewal of used metal powder, removing damaging oxides and allowing high quality parts to be generated from heavily used powder (Figure 1). In this current feasibility study, we developed a new *electro*chemical method for powder processing and have produced a bespoke rig to allow processing of larger volumes of powder. The rig can also be purposed for etching of powder using conventional acids without electrification.

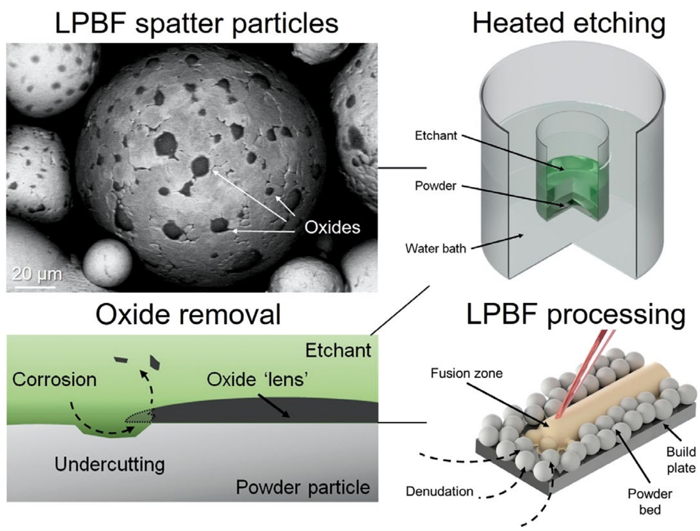




Figure 1 SEM image of oxidised steel powder, along with etching procedure and LPBF processing

## Context

In metal LPBF, powder quality is critical to the production of parts with good density and accuracy. Despite the process taking place in vacuum conditions with a low ppm of oxygen, the high temperatures reached means that oxidation can still occur. In addition, partially melted particles can join with other particles in the powder bed, substantially altering the average powder size present. Both of these factors can significantly alter the quality of parts produced, reduce the powder life and often be expensive.

Oxides present on powder reduce the mechanical strength and generally alter properties away from the intended or nominal properties of the material. Currently, sieving is performed to remove agglomerates, often referred to as spatter, from the powder bed. As well as being inherently wasteful, this process does not necessarily remove chemically modified particles from the powder bed. An alternative process to renew powders is plasma spheroidisation. This, however, is a capital and energy intensive process modifying the overall powder size distribution through complete remelting.

The present approach of a surface-only modifying chemical process aims to be a low-cost approach that can be performed rapidly using low capital investment and in the vicinity of the LPBF process.

Previously we developed a chemical approach for powder renewal based on use of an acid. This work proved that dissolution of the near-surface of oxidised powders is possible. However, to enable scaling in a cost effective and safe manner, an *electrochemical* solution has now been proposed and devised.

## Principle and preliminary data

An initial rig design was based on a simple electrochemical cell. The main challenge was to ensure good current flow by minimising the distance between both electrodes, without direct contact between the powder particles and the cathode but with good contact between particles and the anode. Hydrogen gases are produced from the ECM process and the electrolyte must be evenly distributed around particles, therefore the cathode, and insulating plate beneath, were made permeable through hole drilling.

The principle of our preliminary experimentation is illustrated in Figure 2 (a) and (b). The anodic dissolution is used to remove the near-surface of material in contact with a copper anode. In this setup, current flows to the anode permitting a chemical reaction enabled by the use of a simple NaCl based electrolyte. Used stainless steel powders were sandwiched between an anodic metal base and a permeable insulating plate. The permeable plate allows electrolyte flow to and for gas to be released from the powder. A cathode is placed on top which is also liquid permeable and permits current flow.

The nature of the preliminary setup is such that little movement of the powder takes place during processing. In addition, the powder is deliberately held in place to ensure contact with the anode and therefore effectively allowing the powder to become the anode. Chemically etched particles were observed and this provided proof that the principle was of powder ECM was sound. However, the proportion of particles produced that were successfully etched entirely was small compared to articles remaining unetched. This is because direct contact with the anode is required for a sustained period of time to enable etching.

In this preliminary design several issues were exposed which were to be tackled with the next iteration and these are listed in the next section.

## Considerations for final design

The preliminary design, despite demonstrating the principle of electrochemical etching, did not allow scaling up of powder volumes or processing in any continuous manner.

To solve this, we designed a system to allow semi-continuous processing of larger batch sizes. The design had several key requirements:

- To ensure contact of all powder particles with the anode
- To randomise particle motion to ensure uniformity of current flow
- Adjustable speed
- Adjustable current and voltage

Several iterations of the design were developed with the final design shown in Figure 2 (c). A centrifugal barrel approach was taken using the anode as the external surface of the barrel to ensure contact of powder with the anode without use of another surface to apply force to the powder.

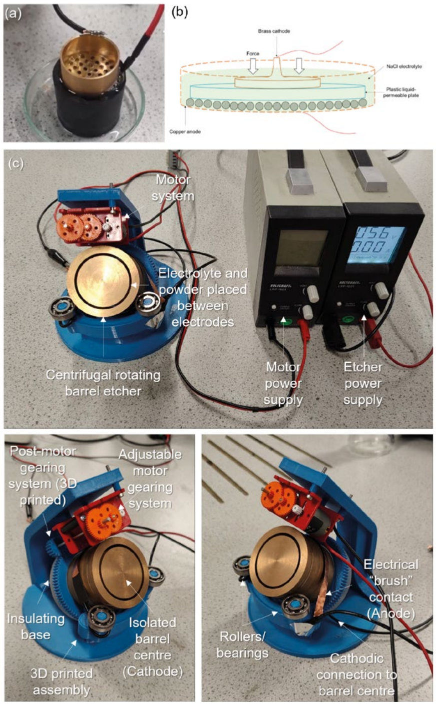



Figure 2 (a) Preliminary rig to test principle, and (b) Principle used for electrochemical etching in both the initial rig and adapted to the centrifugal rig. (c) Designed centrifugal barrel etcher setup to allow semi-continuous etching of powder in an electrolyte.

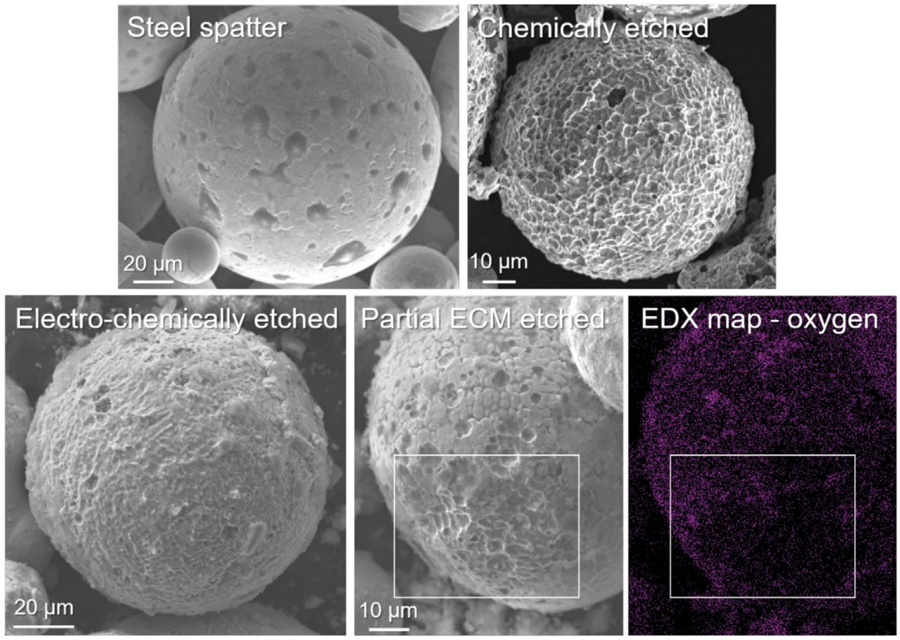



Figure 3 SEM images of an initial oxidised steel spatter particle, a chemically etched (non-electrochemical) particle, a successfully electrochemically etched particle using rig developed here, and a partially etched particle along with EDX map, revealing reduction in oxygen in etched areas.

One particular challenge with the rotating design was to ensure constant electrical contact from the power supply to the rotating anode. A single copper flexible tape was used to fit the shape of the barrel and ensure good contact. This design is not expected to last indefinitely and wear of the tape will eventually occur.

A simple DC motor was powered by power supply from which voltage and current can be adjusted. The motor drives an adjustable gearing system as shown in Figure 2 (c). The central part of the barrel is fixed to the system and electrically isolated from the anode. A cathodic connection is made from the power supply to the metallic pin on which the cathode is resting and rotating against. Two bearing systems are used at the front of the system to allow fluid motion.

Electrochemical testing was performed using an electrolyte of 2 molar NaCl, with current supplied by an adjustable power supply.

The results of latest testing using the etcher rig demonstrated that powder ECM is feasible and that evidence of oxide removal is present. Figure 3 shows an example oxidised steel spatter particle prior to etching. For reference, a chemically etched powder particle is shown demonstrating the effectiveness of an acid based approach (in this case using Kalling's solution). The bottom row shows an electrochemically etched particle with the majority of the near-surface removed, revealing a grain based etched surface. A partially electrochemically etched particle is also shown, with the initial surface remaining at the top. An EDX map is shown of the same partially etched particle, revealing a drop in oxygen in the clearly etched regions. In all cases some evidence of NaCl precipitates can also be seen remaining on some particles. The proportion of particles successfully etched is still low and requires further experimentation to enhance etching effectiveness.

## Summary and next steps

The key results and next steps of the feasibility study can be summarised as the following:

- The principle of electrochemical etching has been demonstrated on 316L steel particles.
- Oxide islands typical of used spatter powders from the LPBF additive manufacturing process can be removed.
- Static electrochemical etching is not as effective as acid based chemical etching (e.g. using Kalling's / Ralph's etchant), given the difficulty in uniformly supplying current to all particles.
- A centrifugal rig was developed using power supplies driving current supplied to the electrodes, as well as to a motor system driving the motor.
- 3D plastic printing was extensively used to create the assembly and gearing system to allow the heavy brass barrel to rotate.
- This system allows particles with electrolyte to be agitated and centrifugally forced against an anode. Provision of current to the rotating barrel via a copper-tape type brush contact functions although more advanced iterations will be required for further intensive operation.
- Electrochemical etching is feasible with this setup using a 2M NaCl electrolyte, however the proportion of particles successfully etched must be increased in current and future experimental work.
- It is possible that a hybrid acid-electrolyte approach may compensate for downsides to the pure ECM method, without requiring a particularly unsafe acid. Continuing experimental work will investigate this.

# MAPP AT RCaH:
# PROVIDING A VITAL LEGACY

Article by Rachel Park, RP Editorial Services, from a recent interview with Professor Peter D. Lee and Dr Chu Lun Alex Leung shedding light on the MAPP research at RCaH

One of the core MAPP teams from University College London (UCL) was established at the Research Centre at Harwell (RCaH) in 2017 with a remit to lead research that focused on x-ray imaging and computational simulation of powder materials for advanced manufacturing processes at a microstructural level. The principal investigator (PI) is Professor Peter Lee (UCL) who also serves on the MAPP Executive Team.

The exceptional resources available to the UCL team at RCaH, notably the synchrotron facilities at the Diamond Light Source (DLS), set it apart as unique in its capabilities in the UK.

## HISTORICAL OVERVIEW

From the beginning, the MAPP team at Harwell has met and exceeded expectations with its Additive Manufacturing (AM) research. Across its 6.5-year history, the RCaH team has won 18 grants, totalling £6.8m in funding. Significantly, 15% of this funding came from industrial partners, illustrating the commercial value of the research. The team has 38 peer-reviewed publications with 20 more currently in preparation; participated in 146 engagement activities; holds one commercial license and has filed one patent, with more in progress.

Professor Lee was keen to emphasise the importance of the people involved:

**"MAPP has provided the stability and funding to train a new generation of scientists, industrialists and large-facility workers who are now impassioned by AM and who are themselves carrying on projects. So, MAPP won't finish, as this new generation of researchers will carry on the work."**

"Chu Lun Alex [Leung] is a perfect example: he joined MAPP as a postdoc. Within 18 months, he became a lecturer and now runs his own research programmes, and we co-direct a group of 20 scientists working on powder processes."

In total, eight early career researchers (ECRs) funded through MAPP are now academics at universities worldwide. Three others now work at synchrotrons and others have gone out into industry. Three ECRs have graduated with a PhD, including Dr Lorna Sinclair, whose work on in-situ imaging of AM processes was detailed in the MAPP 2022 Annual Report. There are currently 14 PhD students aligned with MAPP at RCaH.

## RESEARCH FOCUS

The unique proposition of the RCaH team in terms of using synchrotron imaging is their ability to calibrate low-cost in-situ monitoring devices. Common in-process monitoring technologies can only understand the process from the surface – not inside the process. The DLS and other synchrotron light sources provide x-ray imaging with unsurpassed spatial and temporal resolution. Up to 1 million frames per second and down to 1 micrometre resolution.

## COLLABORATION WITH AND TRANSITIONING TO INDUSTRY

As progress continues with digital twins, there is a need to develop next-generation **physical** twins in order to inform and validate the digital replicas, according to Professor Lee. Both Professor Lee and Dr Leung lead **physical twin** projects.

Dr Leung explained: "For example, one research focus is directed at trying to understand the impact of recyclable powder for the Laser Powder Bed Fusion (LPBF) process, specifically powder contamination and how that affects the AM process and finished components."

He continued: "The formation of keyhole pores is detrimental to LPBF part properties, but they are sub-surface. Low cost optical and infrared imaging techniques cannot see pores form, but they do give a variation in signal. We use the synchrotron to see when they actually form and then correlate that to the surface data produced by low-cost sensors. It thus provides a 'ground truth', so when a pore has occurred, we see a fluctuation in a spectral (e.g. infrared) signal from the surface. This methodology has allowed us to calibrate a low-cost technique that can be put in any — or every — AM machine."

As a result, superior understanding can be delivered to help modelling groups. Indeed, Dr Leung has worked with the Rolls-Royce modelling group to help calibrate a digital twin to predict the formation of imperfections during a build.[1] (See image 1).

A second physical twin project within MAPP at RCaH has focused on the Direct Energy Deposition (DED) process. This work has also been jointly funded by industry and focuses on minimising porosity and maximising microstructures. Professor Lee explained: "The in-situ imaging capabilities of the DLS have been able to identify how, when powders are gas atomised with Argon, tiny bubbles can form in the feedstock and go into the melt pool. Our in-situ imaging shows that these small pores can coalesce into a bigger pore, potentially reducing quality of builds. The really exciting part though is that we have identified a solution to eliminate these pores by applying external forces. We are now exploring how to implement this in commercial systems."

Professor Lee and Dr. Leung are heavily involved with another industry-focused project in collaboration with Imperial College London, which has led to filing a patent for a powder additive that enhances powder feedstocks for AM. Laser AM is energy hungry and relatively inefficient. The UCL team, together with Eduardo Saiz & Iuliia Tirichenko (née Elizarova) from Imperial have identified reduced graphene oxide (rGO) as a solution. By adding a very small amount of rGO onto the surface of the powder feedstock, it significantly enhances the laser light absorption during the build. Early indications suggest for the least absorbing powders, the fraction of laser energy absorbed could go from ca. 5% to 80% - if this is the case it could make this portion of the process 20x more efficient. This could make processing highly reflective materials, such as aluminium and copper alloys, much more efficient for AM.

As MAPP concludes, the vast legacy that it has seeded at RCaH will continue with more than 20 people — PhDs and post-docs — who will continue to innovate with powder processes supported by new project funding.

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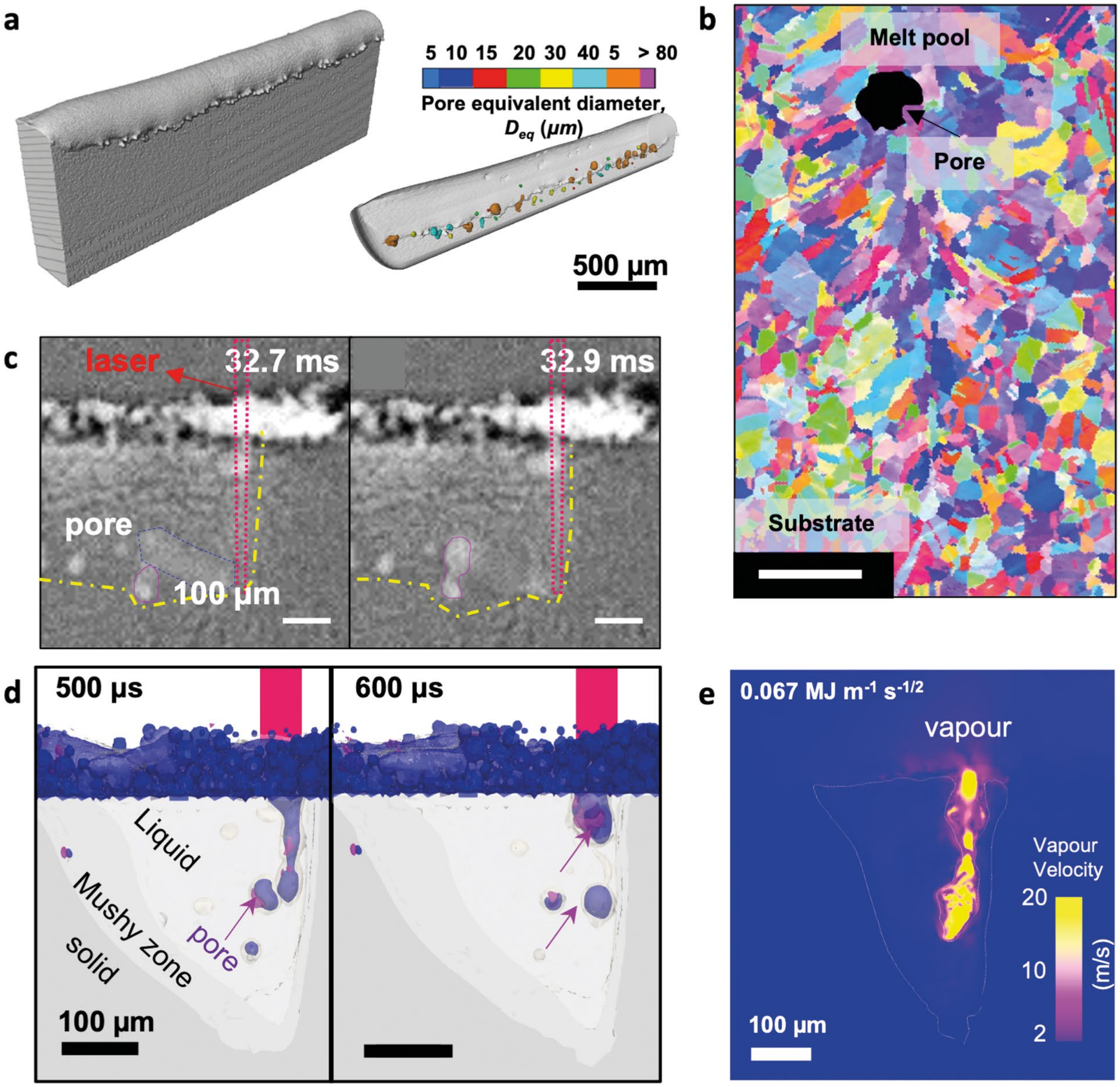


Image 1: UCL team combined (a) 3D X-ray computed tomography, (b) electron microscopy, and (c) high-speed X-ray imaging results to calibrate and verify an industry's digital twin of laser powder bed fusion additive manufacturing (AM) process. This digital twin is capable of predicting (d) melt pool dynamics and (e) multiphase interactions, e.g., solid-liquid-metal vapour-argon gas, during AM.

# PUBLICATIONS

2022 - 2023 has seen the publication of an additional 34 MAPP Journal and Conference papers, bringing further understanding to a wide range of advanced powder processes across our research themes including *in-situ* process monitoring, advanced characterisation, enhanced product performance, and modelling, optimisation and control.


### 2017 (THEME: P2.1)

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### 2017 (THEME: X1)

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### 2018 (THEME: P2.1)

Todd, I., (2018), Metallurgy: Printing steels, *Nature Materials*, **17**, 13-14, https://doi.org/10.1038/nmat5042

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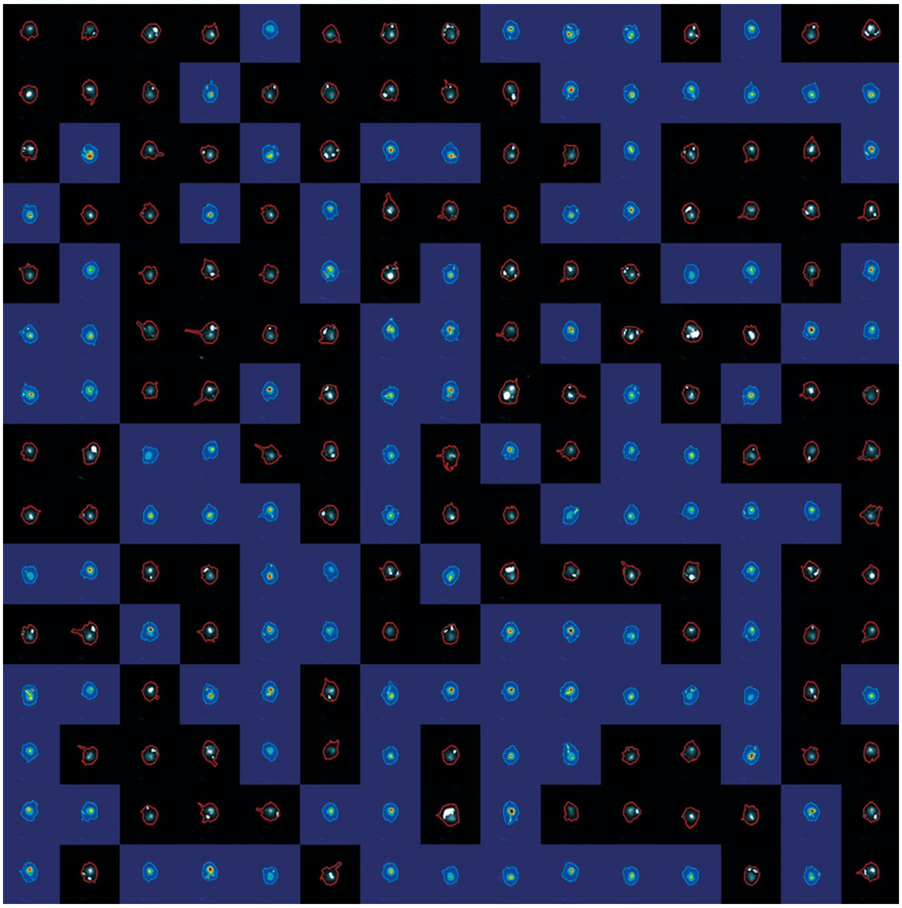

**Melt Pool Pacman**

Third prize in the MAPP 2023 Image Competition was taken by Dr Felicity Freeman and Dr Ben Thomas. This photo montage of images is from a BeAM Magic 2.0 Directed Energy Deposition build using gas-atomised 316L steel powder. The images, collected by a coaxial optical camera, are live processed by a closed-loop control algorithm, which uses selection criteria based on skewness and circularity to screen out images with spatter. Images which passed are shown in false colour; images which failed are shown in grayscale with the melt pool boundary contour superimposed.


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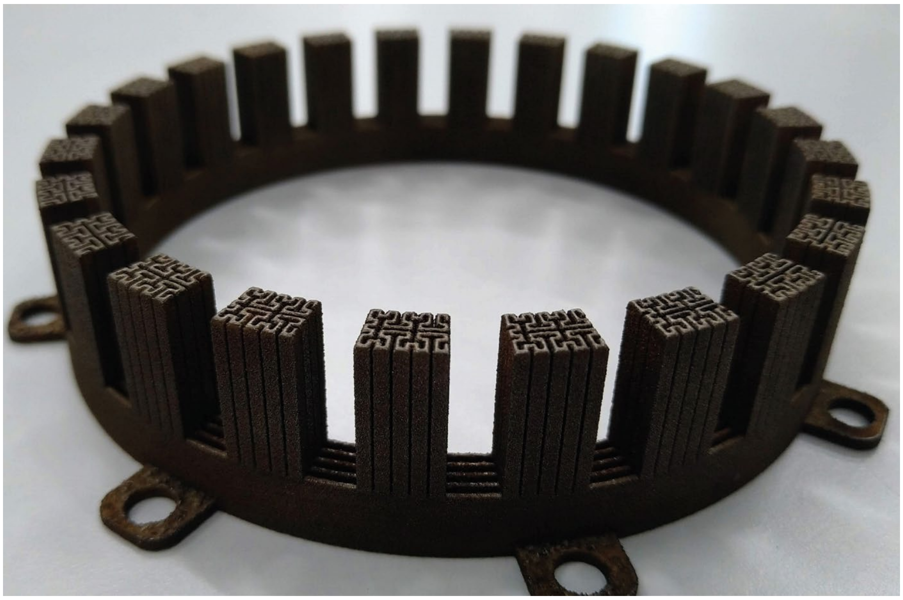

**Electric Machine Stator**

Alex Goodall won fourth prize in the MAPP 2023 Image Competition. An electric machine stator created from soft magnetic electrical steel, with a Hilbert cross section to limit eddy current losses.

## 2020 (THEME: P2.2)


Matthews, G.A.B., Santra, S., Ma, R., Grovenor, C.R.M., Grant, P.S., Speller, S.C., (2020), Effect of the sintering temperature on the microstructure and superconducting properties of MgB2 bulks manufactured by the field assisted sintering technique, *Superconductor Science and Technology*, **33**, 054003, https://doi.org/10.1088/1361-6668/ab7c53

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Ostergaard, M.B., Zhang, M., Shen, X., Peterson, R.R., Konig, J., Lee, P.D., Yue, Y., Cai, B., (2020), High-speed synchrotron X-ray imaging of glass foaming and thermal conductivity simulations, *Acta Materialia*, **189**, 85-92, https://doi.org/10.1016/j.actamat.2020.02.060

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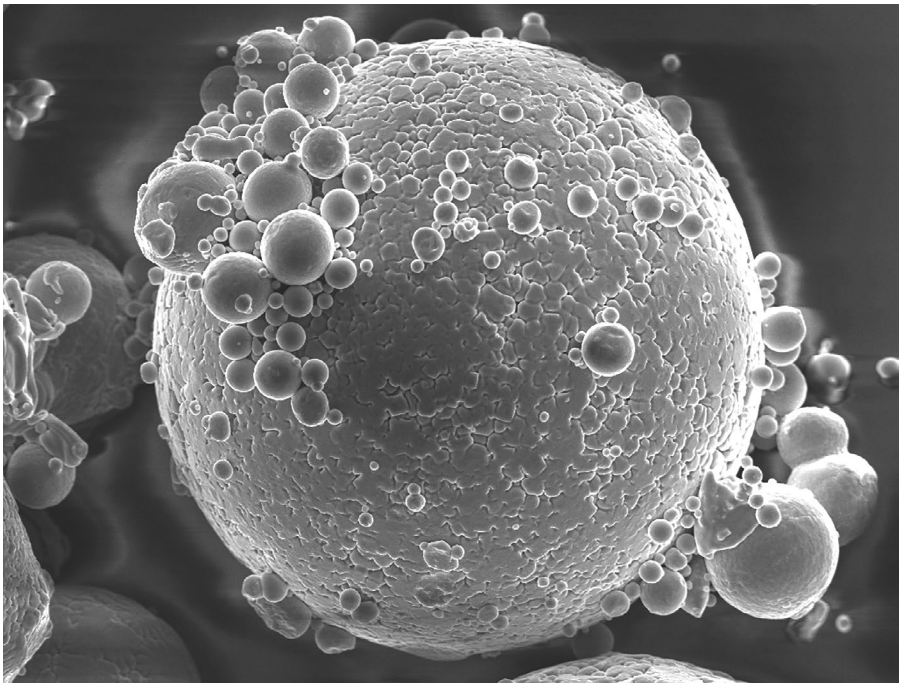

**Satellites** from Simon Graham. Secondary electron micrograph of a coarse aluminium alloy powder particle surrounded by finer particles.


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**Titanium wheel** from Simon Graham. Ti-6Al-4V powder cold isostatically pressed into shape using a silicone mould, for further processing by Field Assisted Sintering Technology (FAST).

## 2022 (THEME: P2.2)

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## 2022 (THEME: X3)

Aftab, M., Rossiter, J.A., Panoutsos, G., (2022), Predictive functional control for difficult second-order dynamics with a simple pre-compensation strategy, *2022 UKACC 13th International Conference on Control (CONTROL), Plymouth, United Kingdom*, 12-17, https://doi.org/10.1109/Control55989.2022.9781367

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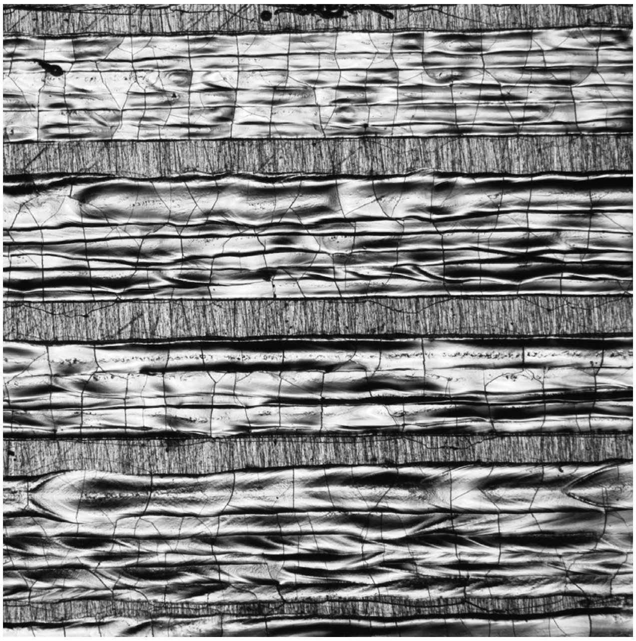

**Weld Track Cracks** from Lucy Farquhar. Image of a weld track study done on CoCrFeNiTi. The alloy contains a NiTi-based brittle intermetallic which causes solid state cracking under all processing parameters.

Sahin, A., Ray, P., Panoutsos, G., (2022), Self-tuning multi-model statistical process control for process monitoring in additive manufacturing, *2022 8th International Conference on Control, Decision and Information Technologies (CoDIT), 17-20 May 2022, Istanbul, Turkey*, 1049-1054, https://doi.org/10.1109/CoDIT55151.2022.9803964

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## 2023 (THEME: P2.1)

Mehrabi, M., Gardy, J., Talebi, F., Farschi, A., Hassanpour, A., Bayly, A.E., (2023), An investigation of the effect of powder flowability on the powder spreading in additive manufacturing, *Powder Technology*, **413**, 117997, https://doi.org/10.1016/j.powtec.2022.117997

## 2023 (THEME: P2.2)

Graham, S., Patel, A., Silva, B.F., Stott, W., Baxter, G.J., Roscher, M., Jackson, M., (2023), Solid-state processing of surplus aluminium alloy powders through a combination of field assisted sintering technology and hot rolling, *Powder Metallurgy*, 1-8, http://doi.org/10.1080/00325899.2023.2171582

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Zhou, S., Cai, Q., Tirichenko, I., Vinchez, V., Gavalda-Diaz, O., Bouville, F., Siaz, E., (2023), Additive Manufacturing of Al2O3 with Engineered Interphases and High Toughness Through Multi-Material Co-Extrusion, *Acta Materialia*, **246**, 118704, https://doi.org/10.1016/j.actamat.2023.118704

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Notley, S.V., Chen, Y., Thacker, N.A., Lee, P.D., Panoutsos, G., (2023), Synchrotron Imaging Derived Relationship between Process Parameters and Build Quality for Directed Energy Deposition Additively Manufactured IN718, *Additive Manufacturing Letters*, 100137, https://doi.org/10.1016/j.addlet.2023.100137

# EVENTS
# 2022–2023

MAPP has continued to host hybrid, in-person and online events throughout 2022 and into 2023. MAPP colleagues have been involved across a wide range of over 17 conferences and 30 public engagement events, both online and in person. This included 45 presentations, 10 invited / keynote lectures and coverage in the national press.

A number of MAPP Lectures were held in-person at Sheffield, the second MAPP/CAM² partnership workshop was hosted at the Leopold Hotel, Sheffield in October and MAPP's Quarterly Meetings were held as hybrid and online events as necessary.

The events attended included:

**TMS 2022**
[27/02/2022 - 03/03/2022]
The Materials Structure & Manufacturing group held in Anaheim, California. Attendees from MAPP presented 13 talks and a number of posters. MAPP speakers included Prof Peter Lee, Seb Marussi, Dr Chu Lun Alex Leung, David Rees, Xianqiang Fan, Dr Yunhui Chen, M. Fitzpatrick, C. Iantaffi, Dr Y Huang and Dr S Bhagavath.

**FAST/SPS Expert Group Meeting**
[16/05/2022 - 17/05/2022]
Dr Simon Graham and Dr Oliver Levano Blanch presented at the 10th anniversary of the FAST/SPS expert group in Germany which was attended by 30 people from across Europe in May 2022.

**SWANSEA UNIVERSITY WORKSHOP**
[22/06/2022 - 24/06/2022]
Attendees from across MAPP joined an MMSC led Workshop and site visit to the Faculties of Science and Engineering and Swansea Materials Research & Testing (SMART) laboratories at the Bay Campus, Swansea University.

**ADDITIVE INTERNATIONAL**
[13/07/22 - 14/07/22]
MAPP was represented by a number of attendees at the Additive International Conference, held in the Albert Hall, Nottingham. The two-day event brought together academic and industry experts to share their knowledge and ideas on all avenues of additive research.

**AFRC VISIT**
[03/08/2022]
Researchers in MAPP joined the technical team at the Henry Royce Institute for a site visit to the Advanced Forming Research Centre in Glasgow. Potential collaborative programmes were discussed which would use the complimentary equipment and facilities at the AFRC and Sheffield.

**AAMS, GERMANY**
[12/09/2022 - 14/09/2022]
Dr Samy Hocine was invited to give a talk in the conference on 'Operando monitoring of laser powder bed fusion process using synchrotron X-rays and other correlative techniques'. David Rees also gave a talk on 'Capturing the effect of powder oxidation on hot cracking in LAM of CM247LC using in situ synchrotron X-ray imaging'.

**MATERIAL FOR HUMANITY**
[19/09/2022 - 21/09/2022]
Ming Li delivered a talk on "Robust Underwater Oil-repellent Biomimetic Ceramic Surfaces: Combining the Stability and Reproducibility of Functional Structures" at the International Conference on Materials for Humanity 2022 at the National University of Singapore.

**MAPP/CAM² WORKSHOP**
[05 - 06/10/22]
This successful MAPP-hosted event was attended by 80 participants - see pages 24 & 25.

**WORLD PM 2022**
[09/10/2022 - 13/10/2022]
Dr Simon Graham delivered a keynote at the World PM 2022 Conference titled "Solid-State Processing of Surplus Aluminum Alloy Powders through a Combination of Field Assisted Sintering Technology and Hot Rolling.

**PRIMARY ENGINEER**
[19/10/2022]
MAPP Investigator Dr Chu Lun Alex Leung took part in a national online interview for Primary Engineer on 19th October 2022. Alex encouraged the 196 pupils who joined to develop their listening, literacy and observational skills, develop creative problem-solving approaches, illustration with annotation, and letter writing for a purpose.

**FAST/SPS EXPERT GROUP MEETING**
[29/11/2022]
Dr Simon Graham and Sam Lister (MAPP-aligned PhD student) attended the 21st meeting of the FAST/SPS expert group at the Research Institute Saint Louis, France.

## MAPP LECTURE SERIES

The MAPP Lecture Series continues to promote a wide range of thought-provoking topics since its launch in 2017.

A total of around 500 people have attended MAPP lectures with a number of the speakers forming new collaborative partnerships with MAPP colleagues to further investigate their specific research interests. Our one hour lectures held this year were:

Dr Peter Green, University of Liverpool, gave the online talk in February 2022; "AI Approaches for Automatic Defect Detection in Laser Powder Bed Fusion Builds."

In March 2022 Dr Matteo Seita, Nanyang Technological University, Singapore, gave the in-person lecture; "Microstructure heterogeneity in metal additive manufacturing: A double-edged sword?"

Dr Carolyn Atkins, STFC UK Astronomy Technology Centre, gave the lecture; "Additive manufacture & astronomical instrumentation: down the rabbit hole online in May 2022."

In September 2022 Dr Sophie Cox, Associate Professor in Healthcare Technologies, University of Birmingham gave the in-person lecture; "An Overview of the Centre for Custom Medical Devices."

The in-person lectures were held at the University of Sheffield and followed by lunch and the opportunity to meet and discuss research with the speakers.

## MAPP'S SECOND IMAGE COMPETITION

The competition, which was open to the wide network of MAPP researchers at all levels, showcased some of the fantastic photographs captured during the powder and processing studies taking place across partner sites. Researchers from across the MAPP programme submitted more than 20 entries ranging from microscopic images, heat maps and artefacts to equipment shots and structures.

The prize winners were as follows:

**First prize:** Simon Graham for Titanium Queen featured on Page 6

**Runner up:** Max Emmanuel for Steps to Nowhere featured on Page 10

**Third prize:** Felicity Freeman and Ben Thomas for Melt Pool Pacman featured on Page 33

**Fourth Prize:** Alex Goodall for Electric Machine Stator featured on Page 35

# SPOTLIGHT ON

# RESEARCH IN CAMBRIDGE FOR MAPP AND MMSC (MATERIALS MADE SMARTER CENTRE)

**Dr Phillip Stanley-Marbell leads the research team at the Physical Computation Laboratory, University of Cambridge**

## THE CAMBRIDGE MINIATURE SENSE-AND-COMPUTE PLATFORM

With integrated sensing capability was originally funded by a MAPP feasibility study and now serves as one of the research platforms for the Materials Passport effort in MMSC (Materials Made Smarter Centre). We have evolved the in-powder compute platform (Figure 1) to incorporate the ability for wireless data readout via NFC. This enables, for the first time, an ability for us to read the results of analyses performed within the miniature compute platform with integrated sensing which might have been used to monitor properties, e.g., of history of humidity in the raw powder used for additive manufacture. We have made the hardware platform designs open for adaptation by other research groups.

## THE IN-POWDER MINIATURE SENSE-AND-COMPUTE PLATFORM IS COMPLEMENTARY TO IN-PROCESS METROLOGY AND CONTROL

Within MAPP, our second goal has been to use an understanding of the physics of signals that we can measure during the additive manufacture (AM) process, to improve the efficiency or stability of the AM control and of the quality of the components manufactured by that system. To enable this, we have further instrumented our existing AM nylon selective laser sintering platform (Figure 2) to measure all the control signals (laser power, galvanometer state, chamber temperature, and more) to allow us to replace the AM system's control system with one which exploits information both about the uncertainty in control signals as well as in the physical constraints on those systems.

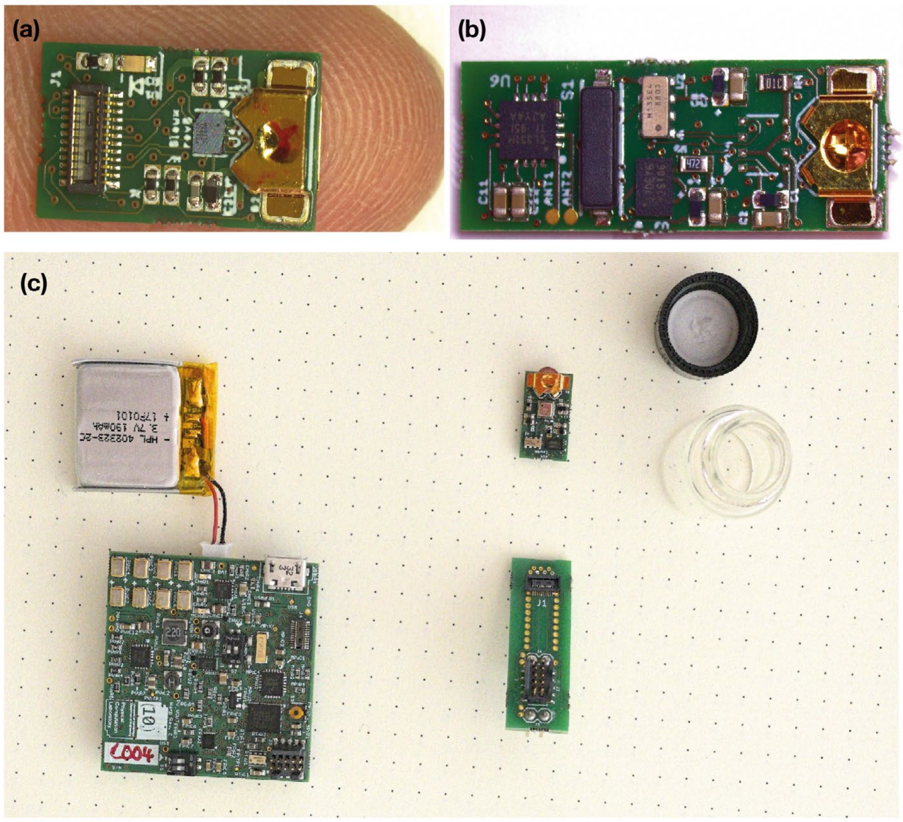



Figure 1. The evolution of the miniature integrated sense-and-compute system which is now also being used in the MMSC project. (a) Original version of miniature compute platform with integrated sensing. (b) Improved version of miniature compute platform with integrated sensing with NFC readout capability. (c) The research fits within an ecosystem of related integrated sense-and-compute platforms developed by the Cambridge Physical Computation.

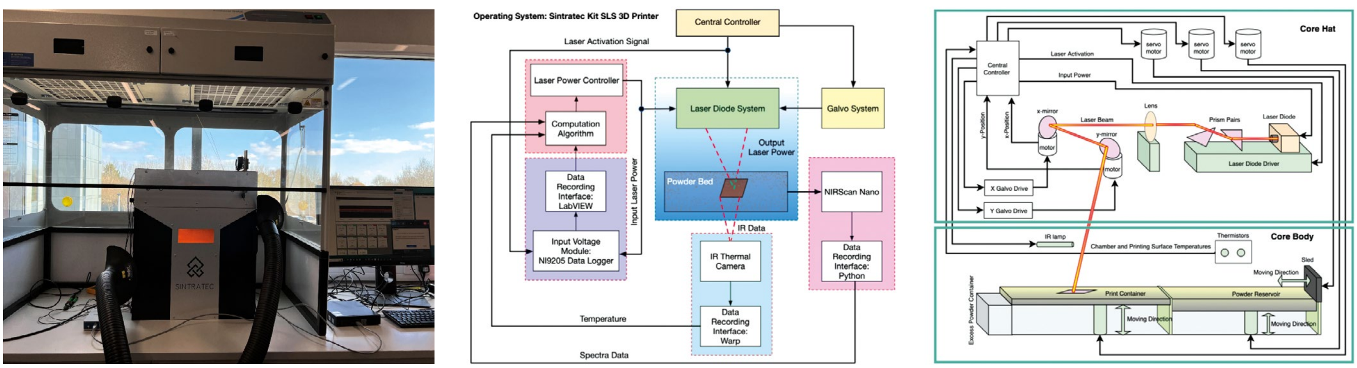



Figure 2. Instrumented nylon SLS system to allow us to replace control system with one which uses information about measurement uncertainty and physical constraints on system's signals to improve the quality of build object.

# MAPP

# EXECUTIVE TEAM

**Professor Iain Todd**, MAPP Director, Theme Co-Lead for P2.1a Laser Powder Bed Fusion and Theme Lead for P2.1b Directed Energy Deposition

Iain Todd is a Professor of Metallurgy at the University of Sheffield, and the Director of the MAPP EPSRC Future Manufacturing Hub.

His research is focused on both the development of new alloys and the development of new processes to enable engineering structures to be manufactured from them. Iain's manufacturing research is conducted on the near-industrial scale and actively supported by industry.

Iain is a Fellow of the IOM3 and Director of the Materials Made Smarter Research Centre.

**Professor John Francis**, Theme Co-Lead for P2.2a FAST/ SPS/HIP

John is Professor of Materials Welding & Joining, University of Manchester. John is accredited as an International Welding Engineer (IWE) under the International Institute of Welding (IIW) qualification scheme.

He obtained his academic qualifications from The University of Adelaide, and began his career in Australia with CSIRO, working as a postdoctoral research fellow and subsequently as a Research Scientist in welding process technology.

His research interests focus on understanding how welding processes and procedures impact the long-term performance of high integrity thick section welds. His research interests span from microstructural evolution in welds and weld overlays, to residual stress development in welds and overlays, including the influence of solid-state phase transformations on the development of residual stresses and they also include the creep performance of welds.

**Associate Professor Ali Hassanpour**

Ali is an associate professor at the school of chemical and process engineering, University of Leeds.

His research is mainly focused on the characterisation of single-particle properties and analysis of particles' collective properties and behaviours using multi-scale modelling approaches such as Discrete Element Modelling (DEM).

His research is supported by Innovate UK, EU, EPSRC and industry. Ali has more than 100 journal publications.

**Professor Visakan Kadirkamanathan**, Theme Co-Lead for X3 Modelling, Optimisation and Control

Visakan, University of Sheffield, is Director of Rolls-Royce University Technology Centre (UTC) in Control and Monitoring Systems Engineering.

His primary research field is signal and information processing, dynamic and spatio-temporal modelling, intelligent health monitoring and fault detection with applications in aerospace and biomedicine.

His multi-disciplinary research is funded by the UK research councils, EU, Innovate UK and Industry with more than £25M in grants.

He has published more than 200 papers and was awarded the PNAS Cozzarelli Prize (2012).

His research in manufacturing focuses on data analytics and informatics for process design, monitoring and prediction for additive and subtractive manufacturing processes.

He advances model-based signal processing and machine learning algorithms for in-process monitoring from spatial and temporal sensor data such as thermal imaging and acoustic emissions data.

**Professor Peter Lee**, Theme Lead for X1 *In-situ* Process Monitoring

Peter is Professor of Materials Science at University College London and holds the Royal Academy of Engineering Chair in the Emerging Technology of Additive Manufacturing.

He is an expert in characterising microstructural evolution during manufacturing using *in-situ* synchrotron imaging.

He uses these results to inform Integrated Computational Materials Engineering (ICME) models to predict processing-structure-property relationships, based on more than 30 years experience at Alcan, Imperial, Harwell, and now University College London.

He has published more than 300 journal papers and is a Fellow of the Royal Academy of Engineering, Institute of Materials, Minerals and Mining (IOM3) and the Institute of Cast Metals Engineers. IOM3 awarded him the John Hunt Medal in 2021.

**Dr Enzo Liotti**, Theme Co-Lead for P2.2b Fundamentals of Solid State Processing

Enzo is a Departmental Lecturer in the Processing of Advanced Materials at the Department of Materials, University of Oxford.

His research focus is on using and developing X-ray synchrotron techniques for the investigation of fundamental dynamic phenomena in metal processing and material science, with a particular interest in solidification of metal alloys.

He obtained his BSc (2004) and MSc (2006) in Material Engineering from Politecnico di Milano.

He gained a PhD in Materials science from the University of Loughborough (2011), working on the characterisation of a nano-quasicrystalline containing Al alloy with high-temperature mechanical properties.

From 2011 to 2019 he was a PDRA at the department of Materials, University of Oxford, working on *in-situ* imaging of solidification within Prof. Patrick Grant's Processing of Advanced Materials Group.

**Professor Eduardo Saiz**, Theme Lead for P2.3c Ceramics

Eduardo directs the Centre for Advanced Structural Ceramics (CASC) at Imperial College London.

His research interests include the development of new processing techniques for the fabrication of ceramic-based composites, in particular, hierarchical composites with bioinspired architectures.

He has published more than 120 papers, including high impact journals such as Science and Nature Materials and holds several US patents.

His work on the 3D printing of ceramics and graphene inks has been highlighted internationally from New York Times to Wired.

In 2021 the Institute of Materials, Minerals and Mining awarded him the Verulam Medal and Prize which is presented in recognition of distinguished contributions to ceramics.

# INDUSTRIAL ADVISORY BOARD (IAB)

**Dr Lee Aucott**, United Kingdom Atomic Energy Authority (UKAEA), Manufacturing Lead for the STEP programme

Lee received his undergraduate and doctorate degrees in the fields of mechanical and materials engineering from the University of Leicester.

He has significant experience working in the UK nuclear sector in a variety of roles focussed on the development of emerging manufacturing technologies.

In his current role, Lee is responsible for the manufacture and inspection of the UKAEA's Spherical Tokamak for Energy Production (STEP) reactor.

Powder metallurgy processes will be essential to realise the materials and component geometries required for STEP.

**Marko Bosman**, Chief Technologist Additive Manufacturing, GKN Aerospace

Director of the Materials Innovation Institute M2i in the Netherlands

Marko Bosman has an MSc degree in Materials Science and Engineering from the Technical University of Delft and has extensive experience in the field of aerospace materials and manufacturing technology.

Since 1999 he worked in different roles at Fokker, where he started exploring the potential of additive manufacturing in 2011, resulting in several product implementations.

In his current role as Chief Technologist, he coordinates the global additive manufacturing developments of GKN Aerospace.

**Dr Gael Guetard**, Rapid Alloy Research Centre Director, Alloyed

Gael graduated in 2016 with a PhD from the University of Cambridge where he investigated the use of powder metallurgy for rolling bearings.

He then joined Aubert & Duval, one of Europe's main producers of high-performance alloys. There, he worked on improving the quality of metal powders as well as the efficiency of the production process.

In 2018, he moved back to the UK to join Alloyed, a company specialised in the computational development of alloys and additive manufacturing technologies. There, he leads the Rapid Alloy Research Centre, a laboratory focused on accelerating Alloyed's technologies by providing experimental validation and proof-of-concept.

**Dr Hugh Hamilton**, Scientific Consultant, Johnson Matthey

Hugh has been with the Johnson Matthey Technology Centre since 1988, during which time he has worked in a variety of technical areas including catalysts for automotive applications, modified atmosphere packaging, PEM fuel cell membrane electrode assembly design and manufacture, hydrogen storage alloys and separation membranes, electrochemical processing and PM processing of titanium and other alloy powders.

**Professor Neil Hopkinson**,
VP AM technology,
Stratasys

Neil spent 20 years in academia conducting research in the field of additive manufacturing. His academic research has generated a strong Intellectual Property/Patent portfolio which has been licensed globally from small start-ups to global multinationals.

His research and IP portfolio has had a transformational impact on the additive manufacturing/industrial 3D printing industry with thousands of machines sold and over $1Bn revenues from businesses selling licensed products.

In 2016 Neil left academia to join Cambridge based inkjet printhead manufacturer Xaar and is now with global leading 3D Printing company Stratasys.

**Nick Jones**,
Technology Development Manager,
Renishaw's Additive Manufacturing Group

Based at the company head office in Gloucestershire, UK, Nick leads a team of engineers and scientists undertaking research and design. He has worked in or around laser powder bed fusion for fifteen years.

He has been with the company for more than twenty-five years, working in a number of product divisions as well as in process development and manufacturing roles. He holds bachelors and masters degrees in Mechatronic Engineering.

**Ian Laidler**,
Chief Technology Officer,
Wayland Additive

Ian is a physicist and engineer with 30 years of experience directing complex technical developments of high value capital equipment for the semiconductor and medical industries.

Following a career that has included working on a superconducting electron synchrotron for IBM's X-ray Lithography program, superconducting proton cyclotrons for PET scanners, X-ray beamlines for the world's third generation synchrotrons and electron beam lithography systems for the semiconductor and nanotechnology industries, Ian has cofounded Wayland Additive.

Wayland Additive is a Yorkshire based start-up developing and manufacturing a new capability in electron beam additive manufacturing systems, drawing on the experience of a highly skilled team of electron and ion beam system engineers coupled with the strong additive manufacturing expertise present in Yorkshire.

**Dr Ian Mitchell**,
Chief of Technology – Repair & Services,
Rolls-Royce

Ian has been with Rolls-Royce plc since 2009 following an undergraduate degree and engineering doctorate at the University of Birmingham in the fields of engineering and materials science.

Since joining Rolls-Royce plc he has worked in various roles in technology development, mechanical testing and validation, project management, and led the highly innovative blisk additive repair R&D project.

In his current role, Ian leads the global repair and services research portfolio and is responsible for defining the strategy for the development of innovative technologies to support Rolls-Royce products in service.

This diverse portfolio includes both *in-situ* repair (utilising advanced robotics and miniaturisation of technologies, i.e. 'key-hole surgery for jet engines'), as well as the next generation of component repair and inspection technologies for use in overhaul facilities.

**Dr Sozon Tsopanos**,
Head of Additive Manufacturing,
The Weir Group

Sozon's specialities are rapid prototyping and manufacturing, Selective Laser Melting, laser welding, additive manufacturing and STL file manipulation.

He is currently Head of Additive Manufacturing (AM) at Weir and was AM Technology Lead at Weir Minerals. Before joining Weir he was Principal Project Leader at TWI.

**Professor Ken Young**,
Chief Technology Officer,
Manufacturing Technology Centre (MTC)

Ken did both his BSc in Mechanical Engineering and his PhD in the Mechanical Engineering Department at the University of Nottingham, before spending six years in industry writing CAD based programming systems for industrial systems including robots, machine tools and CMMs.

He then spent 20 years at Warwick Manufacturing Group during which time he led their IMRC and the Manufacturing Technologies research group.

In his current role, he oversees research in fields as diverse as additive manufacturing, electronics, informatics, simulation, friction welding, advanced fixturing and intelligent automation.

The MTC specialises in maturing manufacturing processes from laboratory proof of concept through to being proven at low volume.

Since he joined the MTC in 2011 it has grown from two people to more than 800 and has become a £100M turnover business.

# THE SCIENTIFIC
# ADVISORY BOARD (SAB)

**Professor Tresa Pollock,**
SAB Chair, Alcoa Professor of Materials at the University of California, Santa Barbara

Tresa graduated with a B.S. from Purdue University in 1984, and a PhD from MIT in 1989.

She was employed at General Electric Aircraft Engines from 1989 to 1991, where she conducted research and development on high-temperature alloys for aircraft turbine engines.

She was a professor in the Department of Materials Science and Engineering at Carnegie Mellon University from 1991 to 1999 and the University of Michigan from 2000 - 2010.

Her current research focuses on the processing and properties of structural materials and coatings and on the use of ultrafast lasers for micro-fabrication and materials diagnostics.

Prof. Pollock was elected to the U.S. National Academy of Engineering in 2005, the German Academy of Sciences Leopoldina in 2016, is a Fellow of TMS and ASM International, Editor in Chief of Metallurgical and Materials Transactions and was the 2005-2006 President of The Minerals, Metals and Materials Society.

**Professor Carolin Körner,**
Friedrich-Alexander-University (FAU)

Carolin is the head of the Institute of Science and Technology for Metals (WTM) in the Materials Science Department, a member of the Collegial Board and head of the E-Beam Additive Manufacturing group of the Central Institute of Advanced Materials and Processes (ZMP) and the head of the Additive Manufacturing group of Neue Materialien Fürth GmbH (research company of the Bavarian state).

She studied theoretical physics at the FAU. She earned her PhD with distinction at the Materials Science Department of the FAU Faculty of Engineering in 1997 with a thesis on "Theoretical Investigations on the Interaction of Ultra-short Laser Radiation with Metals" under the supervision of Prof. H.W. Bergmann. Habilitation and venia legendi in Materials Science followed at FAU in the group of Prof. R.F. Singer in 2008 for "Integral Foam Molding of Light Metals: Technology, Foam Physics and Foam Simulation" (Springer Textbook). In 2011 she took up her current position at FAU. At present, she is advising some 25 PhD students and postdocs in the fields of additive manufacturing, casting technology, alloy development and process simulation.

**Professor Javier Llorca,**
Polytechnic University of Madrid & IMDEA Materials Institute

Javier is the scientific director and founder of the IMDEA Materials Institute and head of the research group on Advanced Structural Materials and Nanomaterials at the Polytechnic University of Madrid.

He has held visiting appointments at Brown University, Shanghai Jiao Tong University, Indian Institute of Science and Central South University.

Prof. Llorca, a Fulbright scholar, is a Fellow of the European Mechanics Society and of the Materials Research Society and a member of the Academia Europaea and has received the Research Award from the Spanish Royal Academy of Sciences and the Career Award for the Spanish Society of Materials.

His research activities have been focused on the systematic application of computational tools and multiscale modelling strategies to establish the link between processing, microstructure and properties of structural materials.

A key feature of his contributions is the use of novel experimental techniques to determine the properties of the phases and interfaces in the material at the nm and μm scale.

So, simulations are fed with experimental values independently obtained and free of "adjusting" parameters.

Some of these developments have become the foundation of the modern techniques of virtual testing of composites, which are starting to be used by the aerospace industry to minimise the number of costly mechanical tests to characterise and certify composite structures.

His current research interests – within the framework of Integrated Computational Materials Engineering – are aimed at the design of advanced materials for engineering applications in transport, health care (implants) as well as energy (catalysis), so new materials can be designed, tested and optimized *in silico* before they are actually manufactured in the laboratory.

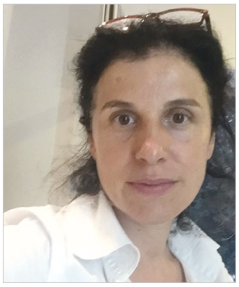
**Professor Jin Ooi,**
University of Edinburgh

Jin received a B.Eng.(Hons.) degree from The University of Auckland, a PhD degree from The University of Sydney and is currently the Professor of Particulate Solid Mechanics.

His principal research interests lie in the mechanics of particulate solids, from soils and rocks to many industrial powders and solids.

He co-founded EDEM (DEM Solutions Ltd) and Particle Analytics Ltd, bringing the impact of his research to many industrial and scientific problems.

He collaborates actively with academic and industrial partners, providing leadership as Coordinator for the TUSAIL EU ITN Consortium on upscaling of particulate manufacturing processes (www.tusail.eu) and previously for the T-MAPPP ITN on multiscale analysis of particulate processes, and the PARDEM ITN on DEM calibration and validation.



**Professor Barbara Previtali,**
Politecnico di Milano

Barbara is Full Professor in the Department of Mechanical Engineering of Politecnico di Milano.

She is the director of SITEC— Laboratory for Laser Applications at Politecnico di Milano and leads PromozioneL@ser within AITeM association, which connects Italian laser users in industry and academia.

Her research interests lie in the area of advanced manufacturing processes, specifically laser processes and additive manufacturing.

Her current focus is on monitoring and close-loop control of laser cutting, development of innovative SLM solutions, such as single point exposure pulsed SLM or dynamic and adaptive beam shaping techniques in SLM, and robotic laser and arc metal deposition of large components in aluminium and titanium alloys.

**Dr Fabrice Rossignol,**
Institute of Research for Ceramics (IRCER)

Fabrice received his PhD in 1995 at the University of Limoges in the field of Ceramic Processes and Surface Treatments.

He was a post-doc fellow in the Agency of Industrial Science and Technology in Japan from 1996 to 1998.

Then he joined industry as a technical manager for the Bosch Company from 1999 to 2001. In 2002 he returned to the academic field at the French National Research Council (CNRS) working in the Institute of Research for Ceramics (IRCER-200 members) in Limoges, France.

From 2007 to 2017, he was the Team Leader of the Ceramic Processes Team at IRCER. He is now Deputy Director of IRCER.

He conducts integrated research ranging from powder synthesis to the fabrication of prototype objects with improved or new properties using various shaping and consolidation techniques.

He aims to control preparation steps to obtain micro(nano)structures and macroscopic architectures adapted to specific functionalities of technical ceramics.

Dr Rossignol's personal research interests are more in the shaping of nanostructured ceramics (top-down and bottom-up approaches) and in the development of additive manufacturing technologies (inkjet printing).

One key application field of his research is energy, for example supported catalysts for H2 production.

# MAPP
# INVESTIGATORS

**Professor Andrew Bayly,** University of Leeds, P2.1a Laser Powder Bed Fusion Theme Co-Lead. Andrew is a chemical engineer with more than 20 years of experience in the development of particulate products and processes. He had significant experience in industry before moving to academia in 2013, including the position of Principal Scientist at Proctor and Gamble. His research focuses on the link between process, particle structure and process/product performance and application to optimisation and scale-up. His research is supported by ATI, AMSCI, EPSRC, EU and industry.

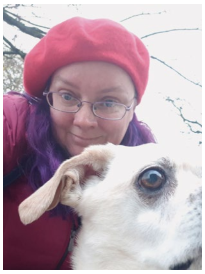
**Dr Finn Giuliani,** Imperial College London. Finn's research interests are in ceramic materials, particularly powder manipulation, characterisation and small scale testing, especially of interfaces. He has published more than 50 papers and holds more than £3M in active grants. He has collaborated with companies including SECO Tools, Shell and Element 6.

**Professor Patrick Grant** is Vesuvius Professor in the Department of Materials and Pro-Vice-Chancellor (Research) at Oxford University. He researches at the interface between manufacturing and novel materials, described in > 260 research papers and 8 patents. He commercialised his research work on spray formed 3D shapes in collaboration with Ford Motor Co., with licensed patents used in the production of components in Europe and the USA. Patrick is principal investigator of the £12.5M Faraday Institution (FI) grant *Next Generation Electrodes*, and work package leader for cell manufacture in FI project *Solid State Metal Batteries*. He is Co-I of EPSRC *Future Manufacturing Hub in Manufacture using Advanced Powder Processes*. Patrick served on the UK Fusion Advisory Board (2007-12), authored evidence paper New and Novel Materials for HMGs Foresight Future of Manufacturing report (2013). He is a member of Constellium's Scientific Council, a non-executive director of Oxford University Innovation, and was elected to the Royal Academy of Engineering in 2010.

**Dr Kristian Groom,** University of Sheffield. Kristian's research focuses on semiconductor optoelectronic component design and manufacture, with an interest in photonic integration and in the application of near- and mid-IR semiconductor lasers, superluminescent diodes, amplifiers, detectors and passive optical elements for application in high-value manufacturing. He is working on projects to develop capability for the heterogeneous integration of III-V semiconductor components and circuits upon a range of substrates to enable new sensor technologies, both through the EPSRC Heteroprint project and the EPSRC Future Photonics Hub. He is also pursuing research into the application of laser diode arrays for efficient high-speed additive manufacturing of both metallic and polymer parts.

**Professor Martin Jackson,** University of Sheffield, Theme Co-Lead for P2.2a FAST/SPS/HIP and P2.2b Fundamentals of Solid State Processing. Martin's research centres on the effect of solid state processes from upstream extraction technologies through to downstream finishing processes on microstructural evolution and mechanical properties in light alloys. A major research interest is to provide a step-change in the economics of titanium based alloys through the development of non-melt consolidation routes including FAST-*forge* and continuous rotary extrusion. Martin works closely with industry partners including VW, Rolls-Royce, Messier-Bugatti-Dowty, TiMET and DSTL. He has more than 80 publications, was awarded a RAEng/EPSRC Fellowship in 2005 and the IOM3 Ti Prize in 2003.

**Dr Chu Lun Alex Leung,** University College London, lecturer in Imaging of Advanced Materials and Manufacturing in the Department of Mechanical Engineering, UCL. He specialises in the application of synchrotron and laboratory X-ray imaging techniques to study AM processes and product performance. His research focuses on the development of intelligent advanced manufacturing using cutting-edge sensing technologies. In MAPP, he develops and applies multi-modal imaging and diffraction techniques for studying rapid solidification phenomena during AM, provides key insights into the fundamentals of AM, and generates data for validating existing and developing new process simulation models. He is the Chair of the MAPP training committee and advocates for developing a professional mentorship scheme for MAPP.



**Dr Candice Majewski,** University of Sheffield. P2.3b Future Manufacturing Platforms – High Speed Sintering & Polymer AM Theme Lead. Candice is a senior lecturer with over 20 years of experience in the field of AM. She manages the University's Advanced Polymer Sintering Laboratory and has built up a large network of academic and industrial collaborators, focusing much of her research towards improving powdered polymer AM materials and processes to increase their potential for widespread industrial usage. In 2011 she received the International Outstanding Young Researcher in Freeform and Additive Manufacturing Award. In 2022 she was shortlisted as one of five finalists in the 2022 TCT Women in 3D Printing Innovator Award, and placed within the 100 Highly Commended Finalists of the Top 50 Women in Engineering (WE50) 2022: Inventors and Innovators. She is an advocate for Equality, Diversity, Inclusion and Accessibility (EDIA), and has recently taken on a role as Departmental Director of One University, where her remit includes EDIA, well-being, workplace culture and sustainability.

**Professor Andrew Mullis,** University of Leeds. Andrew's career has been dedicated to research into advanced materials, particularly the solidification processing of metals far from equilibrium (rapid solidification). This research has been pursued through both experimental studies and numerical simulation. His research has been supported by a range of sponsors including EPSRC, European Space Agency, Wolfson Foundation and The Royal Society. Andrew has authored about 170 scientific publications and delivered more than 100 conference presentations. He is a co-investigator on the EPSRC Future Manufacturing Hub in Liquid Metal Engineering and a Fellow of the Institute of Materials, Minerals and Mining.

**Dr Kamran Mumtaz,** University of Sheffield. P2.3a Diode Area Melting Theme Lead. Kamran's research focuses on developing additive manufacturing methods and materials for metallic net shape component fabrication, specifically targeting the development of refined materials and new processes (i.e multi-laser Diode Area Melting) to deliver distinct capability advantages over conventional manufacturing techniques.

**Professor George Panoutsos,** University of Sheffield, X3 Theme Co-Lead. George's research is focused on the optimisation of manufacturing processes, systems design using computational intelligence and machine learning, as well as autonomous systems for manufacturing. A particular interest is metals design and processing with applications focusing on 'through-process modelling and optimisation' as well as 'prediction of mechanical properties' and 'real-time process monitoring' using data-driven methodologies.

**Professor Philip Prangnell,** University of Manchester. A leading expert on light metals and advanced manufacturing processes. His research activities are focused on studying advanced thermomechanical processing and joining techniques for light alloys (mainly aluminium and titanium). He works with major aerospace companies and their supply chain partners and has published extensively with more than 200 papers. He was co-director of the EPSRC LATEST2 programme grant in 'Light Alloys for Environmentally Sustainable Transport'. He is co-director of the Centre for Doctoral Training (CDT) in Metallic Materials with the University of Sheffield.

**Professor Mark Rainforth,** University of Sheffield. Mark's research interests are the high resolution characterisation of microstructures, in particular interfaces and surfaces. His research programmes are broadly based, covering metals, ceramics and coatings. He is a winner of the IOM3 Rosenhain and Verulam Medals and is a Fellow of the Royal Academy of Engineering. Mark has published more than 380 papers and is involved in >£40m of current grants. He co-directed the Mercury Centre with Prof. Iain Todd.

**Associate Professor Phillip Stanley-Marbell,** University of Cambridge. Phillip is a University Lecturer in the Department of Engineering and leads the Physical Computation Lab. His research focus is on exploiting an understanding of properties of the physical world to make computing systems more efficient. Prior to joining the University of Cambridge, he was a researcher at MIT, from 2014 to 2017. He received his PhD from CMU in 2007, was a postdoc at TU Eindhoven until 2008, and then a permanent Research Staff Member at IBM Research—Zurich. In 2012 he joined Apple where he led the development of a new system component now used across all iOS, watchOS, and macOS platforms.

**Professor Luc Vandeperre,** Imperial College London, Deputy Director of the Centre for Advanced Structural Ceramics (CASC) at Imperial College London. Luc's work encompassed near net-shaping and processing of ceramics, their structural performance and modelling of their thermo-mechanical response. He published more than 120 papers and works with industrial partners in the USA, Germany, France and the UK. Luc was a Fellow of the European Ceramics Society and of the Institute of Materials, Minerals and Mining (IOM3). He received the IOM3 Verulam Medal & Prize in 2019.

**Dr Jon Willmott,** University of Sheffield. Jon's Sensor Systems Research Group is part of the University's Advanced Detector Centre. He received his masters and PhD degrees in physics from the University of Southampton. After two years as a Post-Doctoral Research Associate in Liquid Crystal research at the University of Cambridge, he moved to the company Land Instruments International (now part of AMETEK Inc.) In industry, he designed thermal imaging cameras, radiation thermometers and other 'non-contact' scientific instruments. Following more than a decade in industry, he moved to the University of Sheffield in 2015 with an EPSRC Established Career Fellowship. He currently holds a Royal Society Industry Fellowship.

**Professor Philip Withers,** University of Manchester, Theme Lead for X2 Advanced Characterisation. Philip is the Regius Professor of Materials at Manchester and a major international figure in advanced characterisation. He is Chief Scientist at the Henry Royce Institute and a Director of the National Research Facility for Lab. X-ray CT. He has more than 500 publications in the field. Philip is a Fellow of the Royal Society and a Fellow of the Royal Academy of Engineering and the Chinese Academy of Engineering.

**MAPP PDRAs:**

Dr Daliya Aflyatunova
Dr Ryan Brown
Dr Yun Deng
Dr Iuliia Elizarova
Dr Felicity Freeman
Dr Simon Graham
Dr Emad M. Grais
Dr Oliver Hatt
Dr Samy Hocine
Dr Wei Li
Dr Rohit Malik
Dr Mozhdeh Mehrabi
Dr Scott Notley
Dr Rob Snell
Dr Ben Thomas
Dr Rahul Unnikrishnan
Dr Siyang Wang
Dr Kai Zhang
Dr Xun Zhang
Dr Zihan Song

**MAPP-aligned PDRAs**

Dr Shishira Bhagavath
Dr Chizhou Fang
Dr Anqi Liang
Dr Oliver Levano Blanch
Dr Janith Petangoda
Dr Minh Phan
Dr Chatura Samarakoon
Dr Hamid Toshani
Dr Vasileios Tsoutsouras
Dr Nicholas Weston
Dr Zhuoqun Zhang

**MAPP PhDs**

Mohamed Atwya
Hugh Banes
Cameron Barrie
Alex Goodall
Guy Harding
Oliver Leete
Joseph Samuel
Henry Saunders
Alex Sloane

**MAPP-aligned PhDs**

Hussam Abunar
Muhammad Aftab
Saad Syed Iqbal Ahmed
Talal M Al-Ghamdi
Abdullah Alharbi
Mohammed Alsaddah
Zaher Alsheri
Alkim Aydin
Josh Berry
Aisha Bhatt
Louise Chan
Harry Chapman
Lova Chechik
Max Chester Jude Emmanuel
Imogen Cowley
Xianqiang Fan
Lucy Farquhar
Cameron Favell Gallifant
Maureen Fitzpatrick
Matthew Gelmetti
Kubra Genc
Anna Getley
Adam Gothorp
Joe Hopkinson
Yinglun Hong
Caterina Iantaffi
Tianhui Jiang
Orestis Kaparounakis
Kwan Kim
Ruben Lambert-Garcia
Ming Li
Sam Lister
Elaine Livera
Francis Livera
George Maddison
Anran Mao
David McArthur
Karol Murgrabia
Kieran Nar
Ollie Osborn
Joe Palmer
James Pepper
Edward Rawson
David Rees
Nour Edinne Riahi
Tom Robb
Beatriz Fernandez Silva
Elena Ruckh
Sarath Veetil
Kai Wu
Zhen Xi
Jiaqi Xu
Yunqi Zhang
Miguel Zavala-Arredondo
Shitong Zhou

# MAPP

# OPERATIONS TEAM

**Eleona Chao,** Project Manager and Communications Officer. Eleona has a Masters Degree in Advanced Engineering and Management from Sheffield Hallam University. She joined MAPP at the end of 2022 with over six years of industrial project management experience and acts as the central contact point for the academic partners in MAPP.

**Dr Gavin Baxter,** Senior Business Development Manager, Gavin joined MAPP in April 2021. He supports the development of large strategic research bids and research partnerships with a wide range of stakeholders including industry and sponsors. He has more than 24 years of industrial experience in advanced materials joining and powder-based processing research at Rolls-Royce plc with wide involvement and collaboration across both academic and industrial research teams, manufacturing processes and test facilities. Through pioneering research in a series of major industry-led collaborative partnerships, he has supervised more than 60 PhD students, five PDRAs and co-authored more than 50 academic papers on Advanced Materials Processes.

**Clare Faulkner,** Project Administrator, Clare joined MAPP in April 2019 and works alongside Jess Bamonte. As well as providing executive support to Prof. Iain Todd and Dr Gavin Baxter she leads on project plans and reporting.

**Danielle Harvey,** Marketing and Communications Officer, Danielle joined MAPP in April 2017, bringing with her a wealth of experience across press and public affairs management in some of the region's biggest organisations. She is responsible for internal and external communications for MAPP. Her responsibilities include marketing, social media, digital media and public relations. Danielle is a strong advocate of continuous professional development and has recently completed her CIM Diploma in Professional Marketing. Danielle left MAPP in November 2022 and is now a Marketing and Recruitment Officer at the University of Sheffield.

**Sally Evans,** Project Administrator. Sally joined MAPP in July 2022 and works alongside Clare Faulkner. As well as providing executive support to Prof. Iain Todd and Dr Gavin Baxter, she leads on events and Researchfish.

# MAPP / MAPP-ALIGNED

# PHD RESEARCH ARTICLES

**PHD (OR ENGD) TITLE**

Additive Manufacturing of Novel High Entropy Alloys for an Extreme Environment Heat Exchanger

**RESEARCHER (& YEAR)**

Lucy Farquhar (4th year)

**SUPERVISOR(S)**

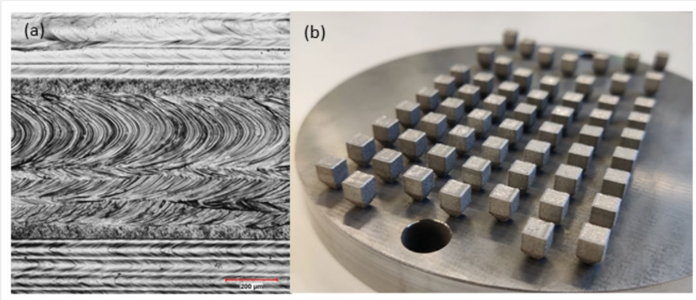
Prof Russell Goodall and Prof Iain Todd

**DEPARTMENT AND UNIVERSITY**

Department of Materials Science and Engineering at The University of Sheffield

**BACKGROUND**

This project focusses primarily on the design and evaluation of novel high entropy alloys (HEA) to be manufactured by laser powder bed fusion (LBPF). Initially, multiple HEAs were theoretically designed to have solid solution phases. Their AM processability was tested using weld tracks on arc melted samples. One of the resulting weldable alloys was then manufactured using LBPF.




(a) Example of weld tracks on a weldable HEA

(b) LPBF of novel TiVNbMo HEA

Data from the weld track study was then used to validate a completely theoretical processing map which predicts alloy cracking mechanisms and therefore it's AM processability prior to having to manufacture expensive powder.

**KEY RESULTS TO-DATE**

- Assessed Effectiveness of in-situ alloying (see paper)
- Two novel weldable HEAs found
- Successful LBPF of a novel TiVNbMo-based HEA
- Processing maps for AM processability of new alloys created.

**FUTURE WORK**

- Testing of thermal and mechanical properties of the TiVNbMo-based alloy made by LPBF
- LPBF of thin walls and heat exchanger of TiVNbMo-based alloy.

**PAPERS PUBLISHED TO-DATE**

Farquhar, L., Maddison, G., Hardwick, L., Livera, F., Todd, I., Goodall, R. In-Situ Alloying of CoCrFeNiX High Entropy Alloys by Selective Laser Melting. Metals 2022, **12**, 456. https://doi.org/10.3390/met12030456

**PHD (OR ENGD) TITLE**

FAST-*forge* of AM Titanium-Titanium Composites

**RESEARCHER (& YEAR)**

Cameron Barrie (4th year)

**SUPERVISOR(S)**

Prof. Martin Jackson, Prof. Iain Todd

**DEPARTMENT AND UNIVERSITY**

Department of Materials Science and Engineering, University of Sheffield

**BACKGROUND**

This project has investigated a method for creating complex, tailorable microstructure through combined process methods. Powder used in FAST sintering was combined with an additively-manufactured structure in the mould, creating one densified part. The different grain morphologies of each region then combined to create a complex microstructure, the fine powder grains contrasting to the large, columnar grains of the AM structure.

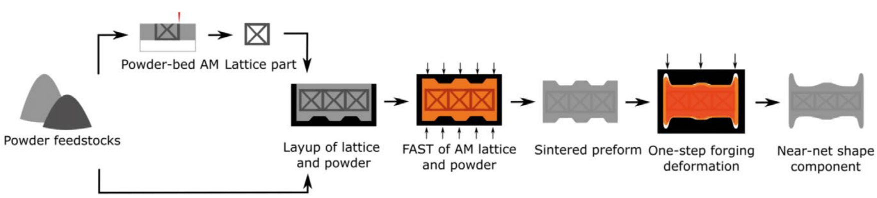
**KEY RESULTS TO-DATE**

The investigation has demonstrated that we can produce these parts to a high level of quality and microstructural precision. The arrangement of grains can be controlled by the design of the AM addition, allowing for fine and complex structures with a well-defined interface. Grain orientation also follows this microstructure, creating to a complex texture throughout the part defined by these regions.

Compression testing showed that the regions' interface remains well-bonded under significant deformation. Porosity measurement indicated that the sintering stage also reduces defects remaining in the original AM structure. Initial tests have confirmed this method's ability to combine multiple alloy chemistries into one item, and process parameter investigation revealed significant practical factors and guidance for industrial application and processing in the future.

**PAPERS PUBLISHED TO-DATE**

Barrie, C., Fernandez-Silva, B., Snell, R., Todd, I., Jackson, M., (2023), *Add*fast: A Hybrid Technique for Tailoring Microstructures in Titanium-Titanium Composites, *Journal of Materials Processing Technology*, **315**, 117920. https://doi.org/10.1016/j.jmatprotec.2023.117920




Schematic illustrating the stages of the *Add*FAST process.

## PHD (OR ENGD) TITLE
Towards HIPping of difficult to cast Ti alloys through time lapse 3D X-ray CT

**RESEARCHER (& YEAR)**
Jiaqi Xu (4th year)

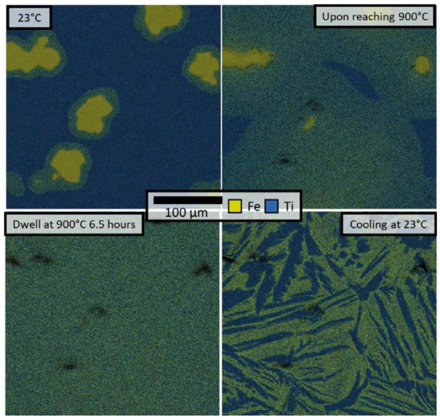
**SUPERVISOR(S)**
Prof. Philip Withers and Prof. Michael Preuss

**DEPARTMENT AND UNIVERSITY**
Department of Materials Science and Engineering at The University of Manchester

**METHOD / BACKGROUND**
This project aims to create new Ti-Fe binary alloys by elemental powder mixing and Hot Isostatic Pressing processing (HIPping). The aim is to gain a fundamental understanding of low-cost near-net shape manufacturing of Ti-alloys by elemental diffusion in solid state to avoid the chemical segregation observed during traditional casting. The phase transformation, microstructure evolution and internal porosity change during consolidation and homogenization has been characterised in both 2D and 3D by SEM/EDS/EBSD, X-ray diffraction and tomography.

**KEY RESULTS TO-DATE**
- Successful HIPping of the Ti-Fe alloys with fine lamellar α+β-Ti microstructure without beta fleck or intermetallic forming. Hardness of alloy has been doubled.
- The phase, porosity and microstructure development during heat treatment at 900°C has been captured by in-situ high temp EDS/EBSD mapping.
- Kirkendall pores observed at the location of Fe particles in heat treatment were found to be healed by HIP.

**FUTURE WORK**
- Testing of mechanical properties of Ti-Fe alloys with different compositions made from HIP.
- Investigate the influence of microstructures on mechanical properties.



In-situ EDS mapping of Ti and Fe in the semi-HIPped Ti-5wt%Fe sample upon being heated up to 900°C and held for 6.5 hours.

## PHD (OR ENGD) TITLE
In-Situ and Post Operando Investigations of Additively Manufactured Pure Lunar Regolith Simulants Parts

**RESEARCHER (& YEAR)**
Caterina Iantaffi (4th year)

**SUPERVISOR(S)**
Peter D. Lee (UCL), T. Rohr (ESA)

**DEPARTMENT AND UNIVERSITY**
Department of Mechanical Engineering at UCL

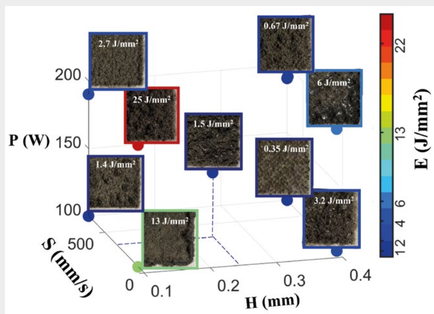
**BACKGROUND AND RESULTS TO-DATE**
Let's imagine an atypical working day: on an extraterrestrial lab, with your special strong suit doing experiments on your 3D printing machine. How different your workday would be? This is one of the key questions that drives researchers to delineate the concepts for the first permanent human settlement on the moon.

Additive Manufacturing (AM) using *in-situ* resource utilisation (ISRU i.e. local resources) has been identified as a key technology for on-demand component fabrication on the moon. Laser powder bed fusion (LPBF) has received increasing attention to produce components made of fine lunar grey soil - regolith.

On earth, LPBF is a key AM technology; however, obtaining the optimal parameters to AM rich oxidised metals such as regoliths requires extensive characterisation and understanding of the key manufacturing mechanisms. Severe vaporisation and balling phenomena dominate the process, requiring novel printing strategies to improve densification.

Here at UCL, by *in-situ* and *ex-situ* techniques, we aim to understand and enhance the printability of moon dust.

After a comprehensive characterisation of two simulants, and a systematic experimental campaign at the Henry Royce Institute at Sheffield, we defined the processability window and we are now ready to perform fast synchrotron X-ray experiments. With an improved experimental set up, we can reveal laser interaction and melt flow dynamics for the first time.



LPBF regolith simulant process map. The process window for sintered regolith proves to be very narrow. In the middle the optimum parameters at 1.5 J/mm$^2$; the fluctuation in laser power (P), scan speed (S) or hatch spacing (H) causes process instabilities *e.g.* balling and vaporisation.

# IN MEMORY OF

# LUC VANDEPERRE

**With great sadness, we received the news of the death of Professor Luc Vandeperre, our dear colleague.**

**He made an outstanding contribution to MAPP and will be painfully missed by many.**

Luc was Deputy Director of the Centre for Advanced Structural Ceramics (CASC) at Imperial College London. His work encompassed near net-shaping and processing of ceramics, their structural performance and modelling of their thermo-mechanical response.

He published more than 120 papers and worked with industrial partners in the USA, Germany, France and the UK. Luc was a Professor of Structural Ceramics at Imperial College London and a Fellow of the Institute of Materials, Minerals and Mining.

**In memoriam: Professor Luc Vandeperre**

**ForeverMissed**

Luc at Industry Briefing in 2019

# ALIGNED PROJECTS

We are involved in a wide range of user-defined projects funded by industry, Innovate UK and agencies such as the Aerospace Technology Institute, which are focused on the translation and commercial application of advanced powder processes. In addition to these user-defined projects, we are also involved with a range of fundamental projects funded by research councils covering areas from new materials discovery to new manufacturing process development. Our aligned projects increase the breadth and reach of our research. These pages feature a selection of our aligned projects.

## LIVE PROJECTS

**AIRLIFT** (Additive Industrialisation for Future Technology)

**Funder:** Innovate UK

**Funded Value:** £6,138,691

**Funding period:**
December 2018 - November 2023

**Organisations:** GKN Aerospace Services Limited, Siemens Industrial Software, University of Sheffield, Cfms Services Limited.

**DAM** (Developing Design for Additive Manufacturing)

**Funder:** Innovate UK

**Funded Value:** £7,212,148

**Funding period:**
December 2018 - November 2022

**Organisations:** GKN Aerospace Services Limited, University of Sheffield, Autodesk Limited.

**DATA-DRIVEN, RELIABLE, AND EFFECTIVE ADDITIVE MANUFACTURING USING MULTI-BEAM TECHNOLOGIES (DREAM BEAM)**

**Funder:** EPSRC

**Funded Value:** £399,163

**Funding period:**
November 2022 - October 2025

**Organisations:** University College London, Renishaw Plc, European Space Agency (ESA), European Synchrotron Radiation Facility (ESRF), STFC Laboratories.

**DIGITAL QUALIFICATION PLATFORM FOR ADVANCED ALLOY COMPONENTS**

**Funder:** ATI

**Funded Value:** £13,992,261

**Funding period:**
January 2023 - December 2026

**Organisations:** University of Sheffield, University of Manchester, Alloyed, Renishaw Plc, TWI, Boeing, CCFE/UKAEA.

**DIODE AREA MELTING** (A novel reconfigurable multi-laser approach for efficient additive manufacturing with enhanced thermal process control)

**Funder:** EPSRC

**Funded Value:** £629,879

**Funding period:**
August 2022 - February 2025

**Organisations:** University of Sheffield, Carpenter Additive, Thinklaser, Renishaw Plc, Diamond Centre Wales.

**DOING MORE WITH LESS: A DIGITAL TWIN OF STATE-OF-THE-ART AND EMERGING HIGH VALUE MANUFACTURING ROUTES FOR HIGH INTEGRITY TITANIUM ALLOY COMPONENTS**

**Funder:** EPSRC

**Funded value:** £2,608,542

**Funding period:**
November 2020 - October 2024

**Organisations:** Aubert and Duval, Henry Royce Institute, High Value Manufacturing (HVM) Catapult, Rolls-Royce Plc, Timet UK Ltd, W. H. Tildesley Ltd, Wilde Analysis Ltd.

## LIVE PROJECTS

### MANUFACTURING BY DESIGN

**Funder:** EPSRC

**Funded Value:** : £1,612,580

**Funding period:**
March 2022 - March 2027

**Organisations:** University of Manchester, Jaguar Cars Ltd, The European Space Research and Tech Centre, TISICS Ltd, National Physical Laboratory NPL, University of Bristol, Renishaw Plc, National Composites Centre, Fraunhofer, Manufacturing Technology Centre, Britishvolt, Johnson Matthey Plc, Rolls-Royce plc,University of Sheffield, European Synch Radiation Facility – ESRF, EURATOM/CCFE.

### MATERIALS MADE SMARTER

**Funder:** EPSRC

**Funded Value:** £4,049,023

**Funding period:**
September 2021 - February 2025

**Organisations:** University of Sheffield, Constellium UK Ltd, Sheffield City Region, Knowledge Transfer Network KTN, National Composites Centre, Celsa Steel UK, Seco Tools, Manufacturing Technology Centre, ESI UK Ltd, STFC – Laboratories, Alloyed Limited, The Alan Turing Institute, Ferroday Ltd, Bikrkenhead, Advanced Manufacturing Research Centre, Tata Steel UK, Diamond Light Source, Rolls-Royce plc,Pro Steel Engineering, Materials Processing Institute (MPI), Thyssenkrupp Tallent Ltd.

### NATIONAL RESEARCH FACILITY FOR LAB X-RAY CT

**Funder:** EPSRC

**Funded Value:** £10,097,652

**Funding period:**
November 2020 - October 2025

**Organisations:** University of Manchester, Nordson (UK) Ltd.

### **TAMMI** (Transforming Additive Manufacturing via Multiscale *in-situ* Imaging)

**Funder:** Royal Academy of Engineering (Chair in Emerging Technology)

**Value of award to the consortium:**
£2,687,000

**Funding period:**
April 2019 - March 2029

**Organisations:** University College London.

### The Effect Of Fibre Interface Chemistry And Thickness On CMC Mechanical And Environmental Performance

**Funder:** Rolls-Royce

**Funded value:** £100,000

**Funding period:**
July 2021 - December 2022

**Organisations:** CASC Imperial.

## COMPLETED PROJECTS

### **AMITIE** (Additive Manufacturing Initiative for Transnational Innovation in Europe)

**Funder:** European Commission - Horizon 2020

**Value of award to the consortium:**
£774,147

**Funding period:**
March 2017 - 2021

**Organisations:** Imperial College London, University of Limoges, via the SPCTS laboratory, National Institute of Applied Sciences of Lyon, University of Valenciennes Haut Cambresis, University of Erlangen, Federal Institute for Material Research and Testing, University of Padova, Polytechnical Institute of Torino, Polytechnical University of Catalunia, Belgium Ceramic Research Center, Mohammadia Engineering College of Rabat in Morocco, 3DCeram, Saint-Gobain, Noraker, Anthogyr, Bosch, HC Starck, Desamanera.

### **COMBILASER** (COMbination of non-contact, high speed monitoring and non-destructive techniques applicable to LASER Based Manufacturing through a self-learning system)

**Funder:** European Union's Horizon 2020 research and innovation programme

**Project costs:** EUR 3 439 420

**Funded value:** EUR 3 439 420

**Funding period:**
January 2015 - December 2017

**Organisations:** HIDRIA AET, IK4 Lortek (LORTEK), Laser Zentrum Hannover (LZH), The Research Centre for Non Destructive Testing (RECENDT), The University of Sheffield, Laserline, Orkli S. Coop (ORKLI), Talleres Mecánicos Comas (TMCOMAS), Mondragon Assembly, 4D Ingenieurgesellschaft für Technische Dienstleistungen (4D), Cavitar Ltd. (CAVITAR) and SiEVA Development Centre (SIEVA).

### **DARE** (Designing Alloys for Resource Efficiency)

**Funder:** EPSRC

**Project costs:** £4,033,113

**Funded value:** £3,226,490

**Funding period:**
September 2014 – September 2019

**Organisations:** University of Sheffield, King's College London, University of Cambridge, Imperial College London, Magnesium Elektron Ltd, Siemens, Tata Steel, Firth Rixon, ArcelorMittal, Timet Ltd, Rolls-Royce PLC, Safran, Sheffield Forgemasters Engineering Ltd.

### **Development of MgWOxB Ceramic Neutron Shielding Material**

**Funder:** UKAEA
(UK Atomic Energy Authority)

**Funded value:** £20,000

**Funding period:**
July 2021 - March 2022

**Organisations:** CASC Imperial.

### **FACTUM**

**Funder:** Innovate UK

**Project costs:** £1,427,215

**Funded value:** £725,001

**Funding period:**
November 2013 - October 2016

**Organisations:** University of Sheffield, Farapack Polymers, Xaar, Unilever, Cobham, BAE Systems, Sebastian Conran Associates and Loughborough University.

### **FAST-STEP3** (Swarf Titanium to Engine Parts in 3 Steps)

**Funder:** Innovate UK

**Funded value:** £507,551

**Funding period:**
March 2018 - 2021

**Organisations:** Participants include Force Technology Limited, Northern Automotive Alliance Limited, Transition International Limited, University of Sheffield and Victoria Drop Forgings Co. Limited.

### **Horizon** (AM)

**Funder:** Aerospace Technology Institute and Innovate UK

**Project costs:** £13,304,769

**Funded value:** £7,042,370

**Funding period:**
March 2015 – November 2017

**Organisations:** GKN Aerospace Services Ltd, Delcam Ltd, Renishaw PLC, University of Sheffield, University of Warwick.

### **INTEGRADDE** (Intelligent data-driven pipeline for the manufacturing of certified metal parts through Direct Energy Deposition)

**Funder:** Horizon 2020

**Funded value:** £672,915

**Funding period:**
January 2019 - December 2022

**Organisations:** Limitstate Limited, University of Sheffield, ESI Software Germany GmbH, Atos Spain, Commissariat à l'énergie atomique et aux énergies alternatives, L'Institut de recherche technologique Jules Verne, MX3D, Loiretech Mauves, Fundingbox Accelerator SP Zoo, Imperial College of Science Technology and Medicine, Bureau Veritas Services, Indust Recherch Procedes Applicat Lase, Högskolan Väst, New Infrared Technologies S.L, GKN Aerospace Sweden, DIN - Deutsches Institut für Normung e.V., Arcelormittal Innovacion Investigacion E Inversion SL, Universidade de Coimbra, Datapixel SL, Corda - Orodjarna Proizvodnja Trgovina In Storitve Doo, Dgh Robotica Automatizacion Y Mantenimiento Industrial Sa, Panepistimio Patron, Brunel University London, Prima Industrie S.p.A., ESI Group.

## COMPLETED PROJECTS

**JewelPrint** (Innovative Jewellery Manufacturing Process using 3D Printing)

**Funder:** Innovate UK

**Funded value:** £401,528

**Funding period:**
June 2019 - May 2020

**Organisations:** Diamond Centre Wales Ltd, University of Sheffield.

**Large Volume, Multi-material High Speed Sintering Machine**

**Funder:** EPSRC

**Project costs:** £1,115,283

**Funded value:** £892,226

**Funding period:**
April 2015 – September 2017

**Organisations:** University of Sheffield.

**LATEST2** (Light Alloys Towards Environmentally Sustainable Transport)

**Funder:** EPSRC

**Project costs:** £7,202,651

**Funded value:** £5,762,121

**Funding period:**
July 2010 - July 2016

**Organisations:** University of Manchester, Airbus Group Limited, Alcan, Alcoa, Bridgnorth Aluminium Ltd, Centre for Materials & Coastal Research, CSIRO, FEI Company, Innoval Technology Ltd, Jaguar Land Rover, Keronite International Ltd, Magnesium Elektron Ltd, Meridian, Business Development, NAMTEC, Norton Aluminium Ltd, Novelis, Rolls-Royce Plc, TWI Ltd.

**LIVING MATERIALS**

**Funder:** ONRG

**Value of award to the consortium:**
£400,000

**Funding period:**
July 2018 - January 2022

**Organisations:** Cidetec, Imperial College London.

**MIAMI** (Improving the productivity of industrial additive manufacturing)

**Funder:** University of Sheffield (Impact, Innovation and Knowledge Exchange funding)

**Project costs:** £552,732

**Funded value:** £200,000

**Funding period:**
July 2017 – March 2020

**Organisations:** MAPP, Future Metrology Hub at the University of Huddersfield.

**MIRIAM** (Machine Intelligence for Radically Improved Additive Manufacturing)

**Funder:** Innovate UK

**Funded value:** £666,383

**Funding period:**
October 2017 - March 2019

**Organisations:** Reliance Precision Ltd, University of Sheffield.

**OPTICON** (Optical Infrared Coordination Network for Astronomy)

**Funder:** European Union's Horizon 2020 research and innovation programme

**Funded value:** £166,605

**Funding period:**
January 2017 - June 2021

**Organisations:** The Chancellor, Masters and Scholars of The University of Cambridge, Centre National de la Recherche Scientifique (CNRS),Istituto Nazionale di Astrofisica, Max-Planck-Gesellschaft zur Forderung der Wissenschaften EV, Science and Technology Facilities Council, European Southern Observatory - ESO European Organisation for Astronomical Research in the Southern Hemisphere, Agencia Estatal Consejo Superior Deinvestigaciones Cientificas, Universiteit Leiden, First Light Imaging SAS, Office National D'etudes et de Recherches Aerospatialess, Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek TNO, Instituto de Astrofisica de Canarias, Magyar Tudomanyos Akademia Csillagaszati es Foldtudomanyi Kutatokozpont (KONKOLY), Uniwersytet Warszawski, National Observatory of Athens, National University of Ireland, Galway, Kobenhavns Universitet, Universite de Liege, Universidade do Porto, Leibniz-Institut fur Astrophysik Potsdam (AIP), Politecnico di Milano, Nordic Optical Telescope Scientific Association, Department of Industry (AAO) Australia, Heriot-Watt University, The University Court of The University of St Andrews, Liverpool John Moores University, University of Durham, The University of Exeter, University of Bath, The Chancellor, Masters and Scholars of The University of Oxford, The University of Sheffield, Institut D'optique Theorique et Appliquee IOTA - Supoptique.

**REMASTER** (Repair Methods for Aerospace Structures using Novel Processes)

**Funder:** Aerospace Technology Institute and Innovate UK

**Project costs:** £3,484,901

**Funded value:** £1,742,390

**Funding Period:**
January 2016 – December 2018

**Organisations:** Rolls-Royce PLC, 3TRPD Ltd, University of Sheffield.

**SHAPE** (Self Healing Alloys for Precision Engineering)

**Funder:** Aerospace Technology Institute and Innovate UK

**Project costs:** £2,127,805

**Funded value:** £1,071,094

**Funding period:**
September 2015 – August 2018

**Organisations:** Ilika Technologies Ltd, Reliance Precision Ltd, University of Sheffield.

**TACDAM** (Tailorable and Adaptive Connected Digital Additive Manufacturing)

**Project funder:** Innovate UK and EPSRC

**Project costs:** £1,482,626

**Funded value:** £1,071,094

**Funding period:**
January 2017 - December 2018

**Organisations:** Hieta Technologies Ltd, Insphere Ltd, Metalysis Ltd, Renishaw PLC, McClaren Automotive Ltd, LSN Diffusion Ltd, University of Sheffield, University of Leicester, University of Exeter.

**TiPOW** (Titanium Powder for Net-shape Component Manufacture)

**Funder:** Aerospace Technology Institute and Innovate UK

**Project costs:** £3,129,835

**Funding period:**
March 2015 – February 2020

**Organisations:** GKN Aerospace Services Ltd, Metalysis Ltd, Phoenix Scientific Industries (PSI) Ltd, University of Leeds.

**VULCAN**

**Funder:** Innovate UK

**Funded value:** £267,650

**Funding period:**
January 2020 - December 2021

**Organisations:** The University of Sheffield, Wayland Additive.

**When the drugs don't work...** Manufacturing our pathogen defenses

**Project funder:** EPSRC

**Funded value:** £149,031

**Funding period:**
March 2018- March 2019

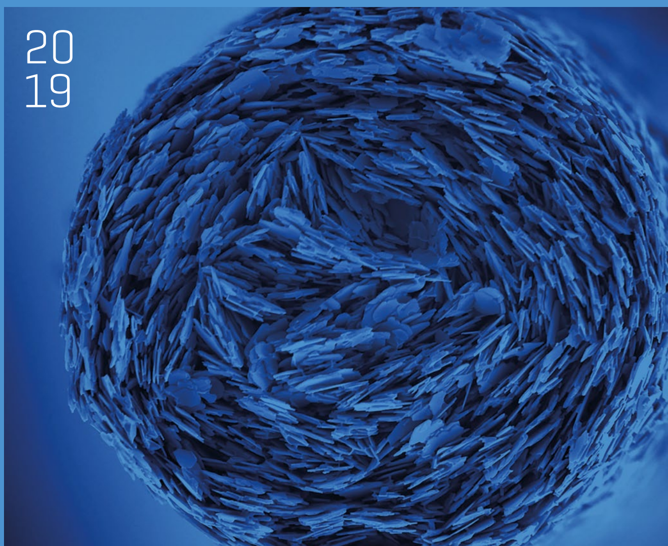
**Organisations:** University of Sheffield.

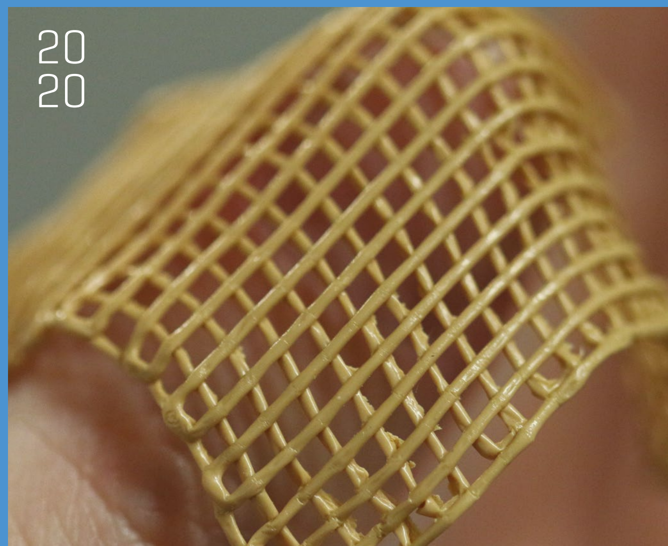
MAPP
Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

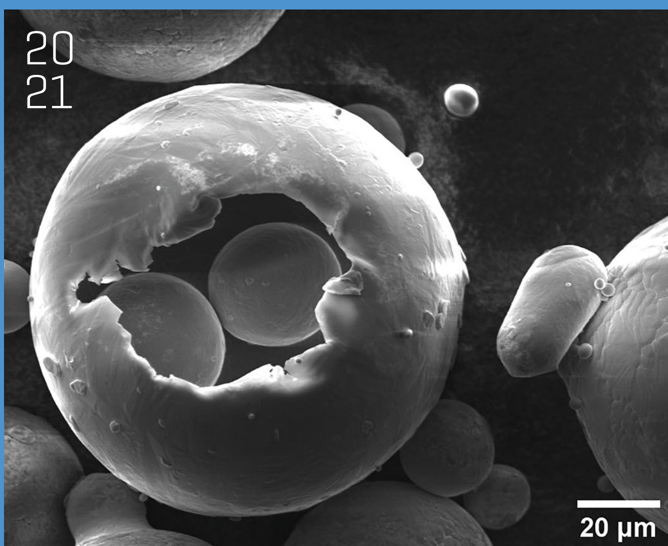
**MAPP**
University of Sheffield
Sir Robert Hadfield Building
Mappin Street
Sheffield, South Yorkshire
S1 3JD
United Kingdom

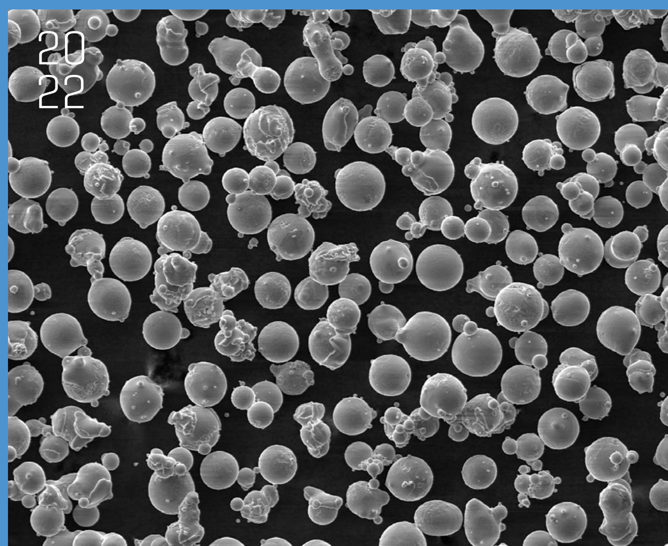
mapp@sheffield.ac.uk
www.mapp.ac.uk

UKRI Engineering and Physical Sciences Research Council




**2019:** Feilden *et al.*, (2016). Progress in Novel and Unexpected Areas. *Materials Today.* **19** (9), 544-545.

**2020:** $Al_2O_3$ net similar to those discussed in Elizarova, *et al.*, (2020). Conformable green bodies: Plastic forming of robocasted advanced ceramics. *Journal of the European Ceramic Society.* **40** (2), 552-557.

**2021:** Scanning Electron Microscope image of a Ti-6Al-2Sn-4Zr-2Mo gas atomised powder particle taken by Lorna Sinclair (UCL). Although particles are usually solid, this particle is hollow and holds two smaller powder particles inside.

**2022:** SEM image by Xianqiang Fan (UCL) showing the morphologies and size of AlCu powder used in LPBF.

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