



MAPP

Manufacture using Advanced
Powder Processes
EPSRC Future Manufacturing Hub

Annual Report | 20 20



Engineering and
Physical Sciences
Research Council



The
University
Of
Sheffield.

Imperial College
London



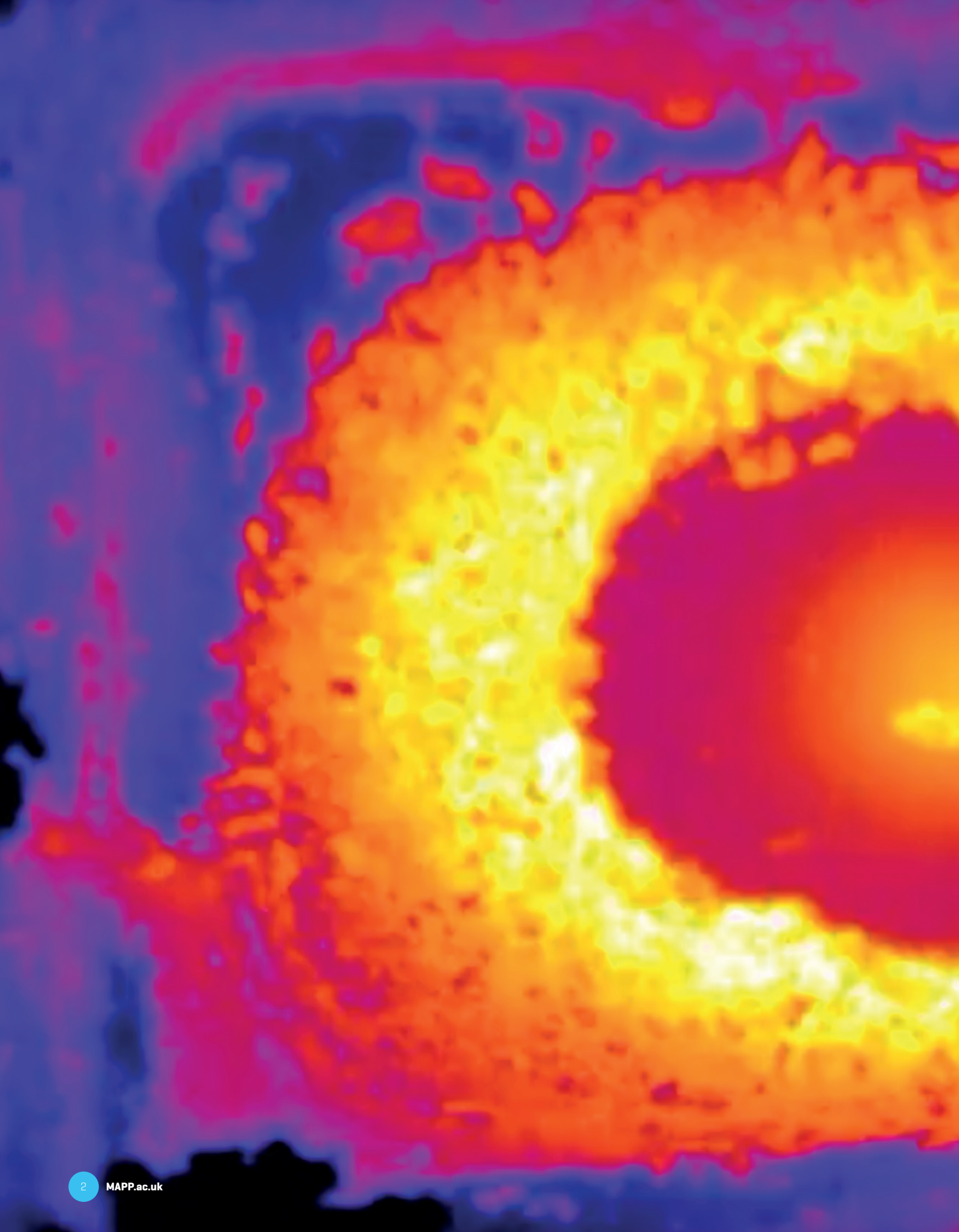
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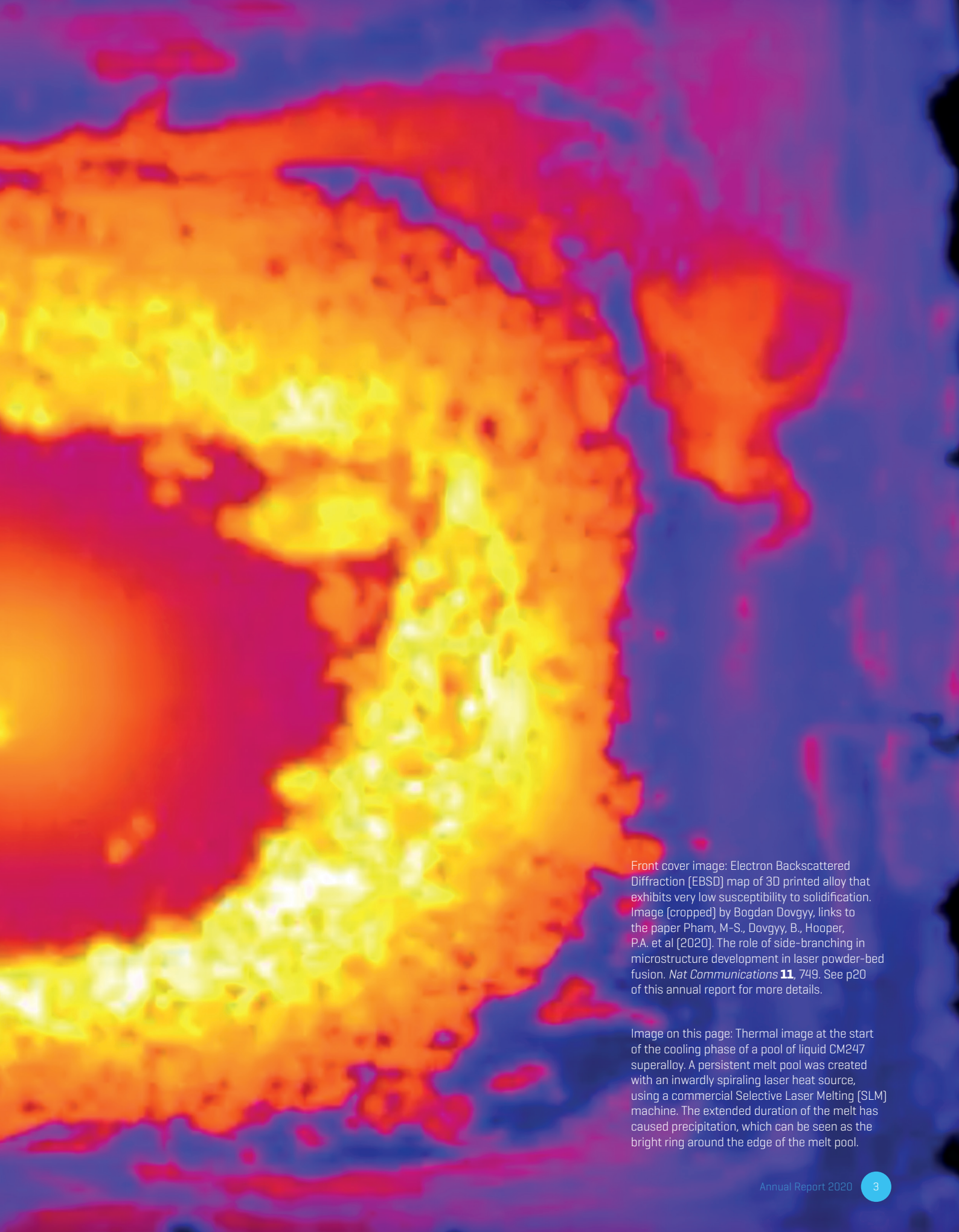
MANCHESTER
1824
The University of Manchester



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Front cover image: Electron Backscattered Diffraction (EBSD) map of 3D printed alloy that exhibits very low susceptibility to solidification. Image (cropped) by Bogdan Dovgvy, links to the paper Pham, M-S., Dovgvy, B., Hooper, P.A. et al [2020]. The role of side-branching in microstructure development in laser powder-bed fusion. *Nat Communications* **11**, 749. See p20 of this annual report for more details.

Image on this page: Thermal image at the start of the cooling phase of a pool of liquid CM247 superalloy. A persistent melt pool was created with an inwardly spiraling laser heat source, using a commercial Selective Laser Melting (SLM) machine. The extended duration of the melt has caused precipitation, which can be seen as the bright ring around the edge of the melt pool.

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WELCOME

Welcome to the third MAPP Annual Report. This year marks our midway point, so as we look back on some of the highlights and successes of last year – we are also looking forward to refreshing some of our core research to ensure we continue to deliver world class knowledge and understanding against our Grand Challenge themes.

Over the course of the last year members of MAPP have been taking part in a variety of engagement activities, ranging from meeting school children at a large STEM event and taking to the stage in a London theatre, through to presenting at key advanced manufacturing conferences around the globe. We of course continue to publish MAPP research in leading journals and feature some of the fantastic outcomes of our research programme in this report.

In September 2019, MAPP announced its second round of feasibility funding to UK academics eligible for EPSRC funding. As with our first call in 2018, we received many excellent applications from across the UK academic community and our Scientific Advisory Board were once again part of the selection process. Brief summaries of outcomes from the first round are given in this report and we are looking forward to seeing how these as well as our new awardees continue to grow their research areas. We are delighted that our second round of funding will extend our network of university and industry partners even further.

We have also welcomed more visiting speakers to our series of talks which have taken place either at Sheffield as featured events or at partner sites as a part of quarterly research

meetings. As always these have generated a good deal of interest from the MAPP research community we have built and indeed some have led to the creation of new collaborative projects.

Our focus, going forwards, will be on ensuring that research done in the first half of the programme can be taken forward with industry and help to deliver real economic impacts. As we do so we will continue to work closely with all of our industrial partners to make sure that we are still addressing the most relevant research questions.

At this pivotal point in the programme it is an exciting time for us here – I hope you enjoy reading about some of our highlights of 2019 and we look forward to continuing to work with you in the future.



Professor Iain Todd
MAPP Director

HEADLINE ACHIEVEMENTS

Across the MAPP programme, we have seen many successes over the past three years.

Our research programme has defined the scientific and engineering challenges that were set in conjunction with all partners at the outset.

A number of key outputs have been achieved including:

- **Characterising a library of powders at the individual and bulk level**
- **Developing ceramic inks based on robocasting**
- **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**
- **Development of a new additive manufacturing (AM) technology – Diode Area Melting (DAM)**
- **New understanding in process models through the development of a laser powder bed AM replicator**
- **Machine learning used to develop data driven approaches to predict printability in AM.**

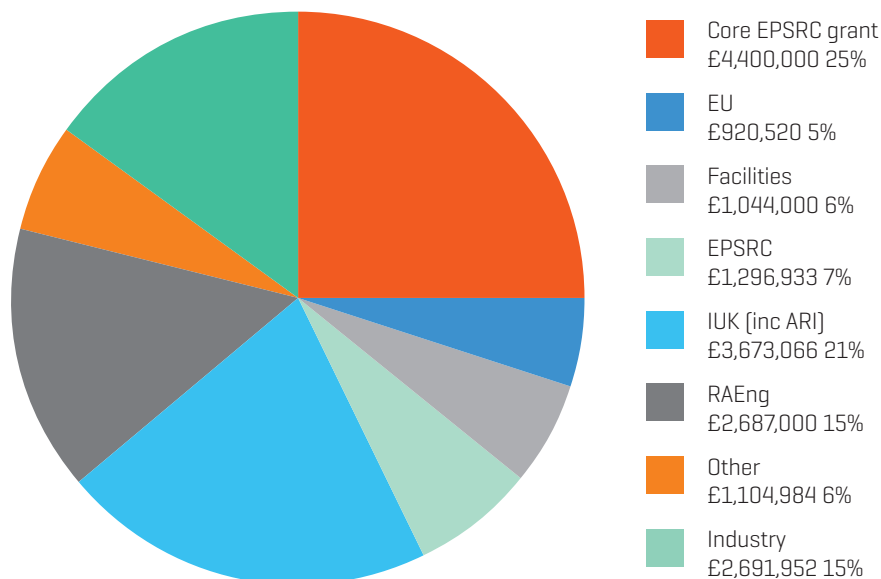
Some of our research has progressed more quickly thanks to additional linkages with our aligned projects (you can find out more about these on pages 42-47) and we have successfully leveraged funding to enable us to build a wider team and retain key skills.



Dr Kamran Mumtaz, DAM

The graph below shows how the Hub's funding portfolio has developed.

MAPP HUB FUNDING PORTFOLIO



Correspondingly, our connections with external partners have also increased and we are developing a number of international partnerships, as well as engaging with academia via routes including feasibility studies, of which four are now complete and four more are due to start in 2020.

Other key performance indicators are shown opposite.

Our researchers have been hard at work, supporting our events as well as delivering at grassroots level on our research programme.

They have also benefitted from various training opportunities such as project management and writing for publications and we are delighted that several MAPP researchers have moved on to more senior posts and are now attracting funding of their own.



Dr Chu Lun Alex Leung, who joined MAPP as a Postdoctoral Research Associate (PDRA) and is now a MAPP Investigator and a lecturer in Imaging of Advanced Materials and Manufacturing at University College London.



Former MAPP PDRA Dr Samuel Tammas-Williams is now a senior lecturer at Liverpool John Moores University.

8

Funded feasibility studies

53

Publications

>700

Delegates at MAPP events

9

MAPP Lectures

93

Presentations at conferences including 58 keynote/invited lectures

52

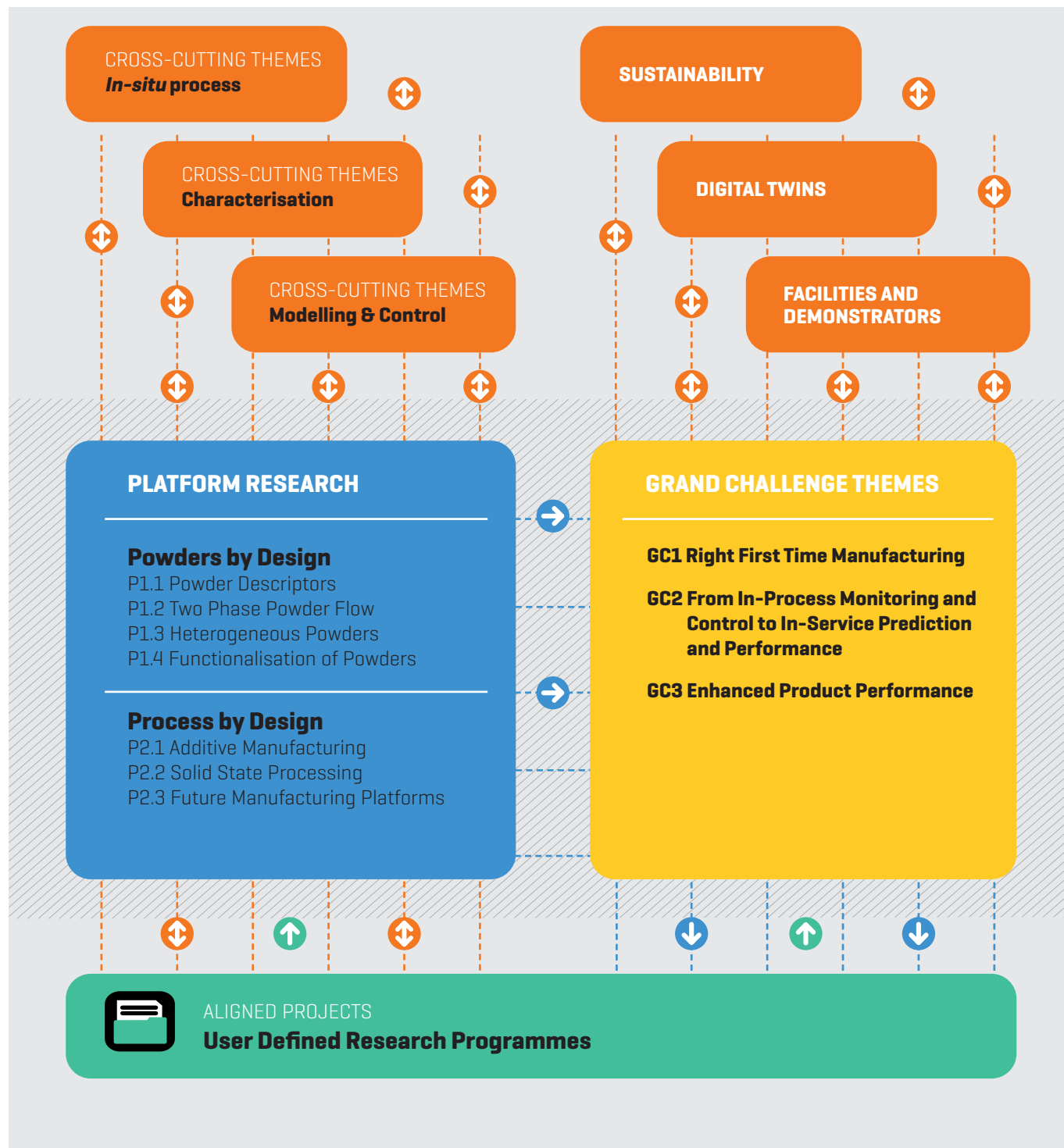
Aligned projects

26

Additional companies working on aligned projects

The figures and information on this page relate to the time period of January 2017 to March 2020.

RESEARCH PROGRAMME OVERVIEW



CORE RESEARCH THEMES

PLATFORM RESEARCH THEME 1 (P1) – POWDERS BY DESIGN

This theme enables us to understand the complexity in powder systems and develop a systems level approach to deepen understanding of their morphology and interaction.

- **P1.1: Powder Descriptors.** To develop an understanding of the link between fundamental powder properties and their behaviour in process. Can we identify a minimum and critical set of powder descriptors for a given material and process combination?
- **P1.2: Two Phase Powder Flow.** To understand and control the rheology of particle loaded flows for applications in printing. To develop extruded, freeze cast and printed parts with engineered [heterogeneous and/or anisotropic] microstructures. *Note, this theme is being incorporated into P2.3 Future Manufacturing Platforms – Ceramics.*
- **P1.3: Heterogeneous Powders.** To monitor, understand and control the size distribution of particles in the gas atomisation process. Can we design and produce particles with new structures?
- **P1.4: Functionalisation of Powders.** To design coatings which realise benefit during subsequent processing, e.g. coatings which protect metal powders for processing via Hot Isostatic Pressing.

PLATFORM RESEARCH THEME 2 (P2) – PROCESS BY DESIGN

This theme encompasses various powder processing systems, developed through advanced processing, control and monitoring to ensure consistent performance and enhanced manufacturing rates.

- **P2.1: Additive Manufacturing.** To identify the critical parameters which provide isotropic properties, defect free components, and allow real time process control.
- **P2.2: Solid State Processing (FAST/SPS).** To better understand and measure critical parameters which impact densification. To better control the process outcome.
- **P2.3: Future Manufacturing Platforms.** To develop new and emerging advanced powder processes including Diode Area Melting (DAM), High Speed Sintering (HSS) and printing of ceramics.

CROSS CUTTING RESEARCH THEMES

These X themes underpin our core research themes, with elements of each X theme running through all P1 and P2 themes.

- **X1: In-Situ Process Monitoring.** Development of process replicators for *in-situ* time resolved synchrotron and neutron observation of structure, chemistry and phase evolution. This new understanding informs process modelling and the development of in-process monitoring approaches.
- **X2: Advanced Characterisation.** Developing a full understanding of our starting materials and the changes they experience at critical stages of processing. This is key to developing a deeper understanding of the underpinning material-process interaction phenomena.
- **X3: Modelling, Optimisation and Control.** To turn the data and information from advanced processing and monitoring technologies into process understanding and control, via computational intelligence modelling and machine learning, and taking a systems engineering approach.

GRAND CHALLENGE THEMES

During a recent review of the MAPP core research programme we have identified the three grand challenges and some of the technical aims within these grand challenges are summarised below.

- **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.

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.

P1.1 Powder Descriptors

Investigators – Prof. Andrew Bayly and Dr Ali Hassanpour, Leeds

Collaborators – Sheffield [P2.1/X2/X3], Manchester, Imperial, UCL [X1]

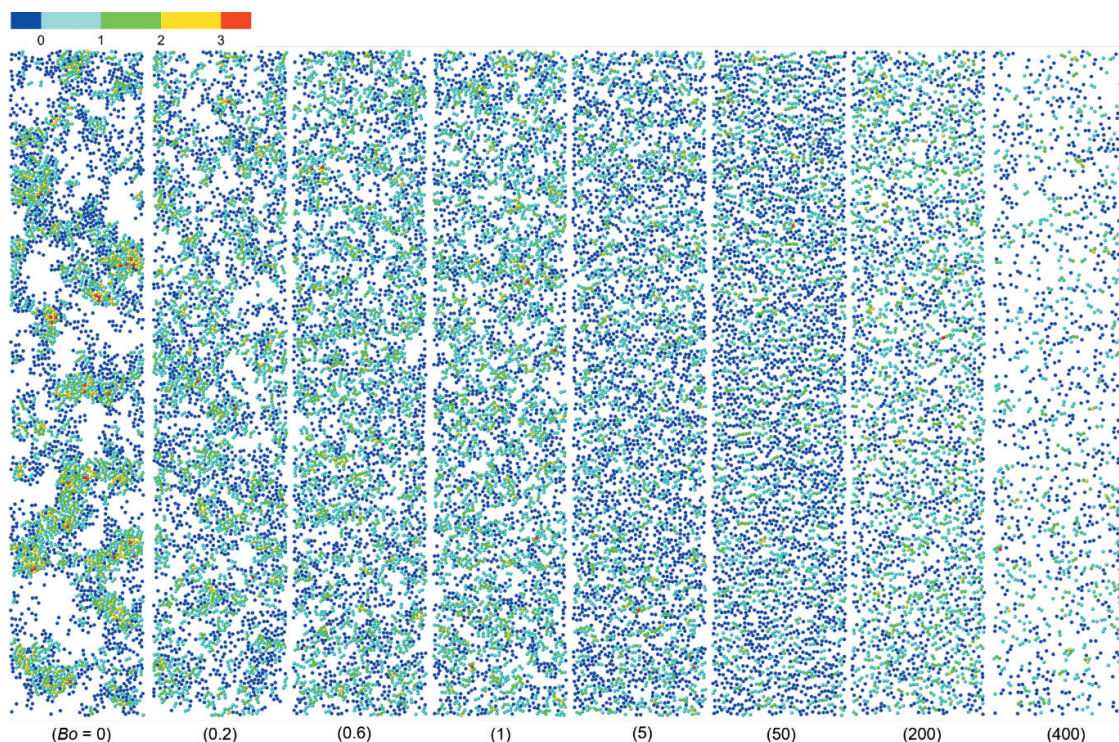
Powders produced for additive manufacturing (AM) processes typically have a wide particle size and morphology distribution with potential batch to batch variation in their surface properties which could adversely affect their processability. The studies in this theme aim to establish a powder descriptor set that defines powder performance and to build a fundamental understanding of the role of distributed properties of these materials.

Our focus has predominantly been on metal powders used in Electron Beam Melting (EBM) and Selective Laser Melting (SLM) processes. The focus has been to understand firstly, how the homogeneity of powder layer in EBM and SLM spreading process is influenced by morphology [particle size and shape], particle surface properties [satellite and surface roughness], bulk chemistry of the powders, environmental conditions [purging gases, temperature and humidity] and spreading method [geometry and blade speed]; secondly, to establish links between individual particle properties, bulk properties and process performance; and thirdly, to provide a safe environment for the AM powder handling and processing during spreading by identifying the risk of spark, fire and explosion hazards for

the powders. A key part of this work has been the development of a test rig, and methodologies, to assess both quantitative and qualitative flowability and characterisation data for a library of powders.

MAPP researchers have also extended the capability of an in-house GPU-based DEM [Discrete Element Method] code to handle variations in both size and shape for fine particles. The developed model is being calibrated and applied to the study of particle behaviour during powder spreading in additive manufacturing. To enable the efficient analysis of cohesive powder systems [which includes many of the metal powders under consideration within MAPP] it has been necessary to develop new methodologies which have wide application across many sectors.

Cohesion effect on the spread powder layer, in which particles are coloured by coordination number. The cohesion is quantified by a dimensionless Bond number, Bo , which is defined as the ratio of the maximum adhesive force to particle gravity.



P1.2 Two Phase Powder Flow (until August 2020)

P2.3 Future Manufacturing Platforms - Ceramics (from August 2020)

Investigators – Prof. Eduardo Saiz, Dr Finn Giuliani and Prof. Luc Vandeperre, Imperial

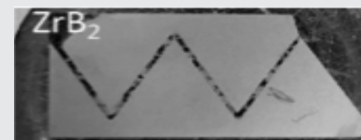
Collaborators – Oxford, Manchester [X2], Leeds, UCL [X1] and Sheffield [P2.2, X3]

As the development of inks and pastes for use in 3D printing relies on controlling the rheological behaviour, the MAPP team at Imperial College London has been manipulating ceramic pastes to show how robocasting can be used to build composite parts with a range of geometries. The team has developed ceramic inks for robocasting based on thermally reversible hydrogels, graphene

oxide or phenolic resins. The latter are used to print conformable structures that enable post-printing shaping and machining. These inks have been applied to print a wide range of materials and applications, from structural ceramics [such as Al_2O_3 or SiC], ultrahigh temperature ceramics, thermoelectrics [collaboration with Queen Mary College], graphene or metals.

One of the current challenges in ceramics additive manufacturing is the fabrication of composites and devices combining different materials with the degree of structural control required to optimise structural and functional performance. In order to understand the underlying physicochemical phenomena and to develop a comprehensive approach that encompasses shaping and sintering we work in coordination with Manchester [*in-situ* analysis of defect formation and drying using XCT] and Oxford and Sheffield [on SPS/FAST] and

industry. The techniques developed include flow control during extrusion of anisotropic particles, embedded printing inside self-healing ceramic gels and a core-shell extrusion-based technology to print composites with continuous fibres or micro-channels inside ceramic matrices.



Phenolic resin-based inks can be used to print conformable objects with technical ceramics. A conformable ceramic grid can be used to prepare a high-temperature ZrB_2 joint between non-planar surfaces.

P1.3 Heterogeneous Powders

Investigator – Prof. Andrew Mullis, Leeds

Collaborators – Sheffield (the Henry Royce Institute, Sheffield), Industry

MAPP researchers at Leeds are aiming to optimise gas atomisation by reducing the instabilities observed in the melt flow as it interacts with the high pressure gas. Precise control of the atomisation process is highly desirable in order to constrain the particle size distribution, thereby maximising the usable fraction of powder. In the atomisation process, the size and size distribution of the powder produced is influenced by many factors, most notable by the way that the film of molten metal interacts with the jet stream. The breakup of the molten material into droplets is heavily influenced by gas and particle velocities – which makes studying the velocities within the gas atomisation plume a key focus of this theme.

The team have developed image analysis routines to process data captured by high speed filming of the melt atomisation process. By analysing images through MATLAB distinctive features within the melt plume are identified and tracked between images to characterise their motion. The data is then processed to create heat maps of estimated velocity within the atomisation plume.

The resulting heat maps illustrate where in the melt plume the slowest and fastest moving material is located. High shear is restricted to the margins of the plume with much of the melt being shielded from the gas, leading to low efficiency within the process. The work has identified the mechanism leading to melt pulsation, a low frequency instability giving rise to extreme variability in the gas-to-metal ratio in the atomiser and hence in the powder product. Future work will look at modifying atomiser nozzle designs to improve process variability and efficiency.

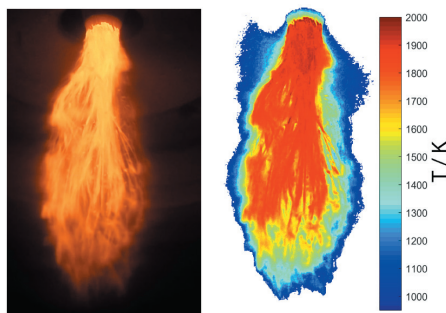


Image of gas atomisation plume and corresponding temperature map.

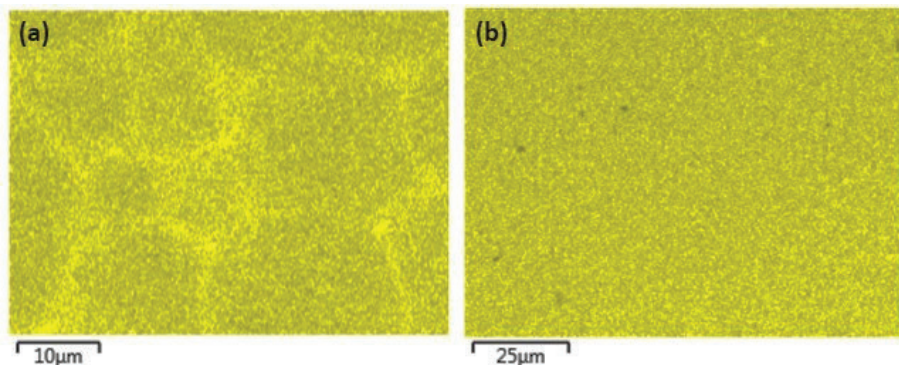
P1.4 Functionalisation of Powders

Investigator – Prof. Michael Preuss, Manchester

Collaborators – Leeds (P1.1) and Sheffield (P2.2)

The focus in the theme has been on developing coatings to protect powders from oxygen pickup and mix different powders to create new types of alloy systems. The first application is on low alloy steel powders and Hot Isostatic Pressing (HIP), although the method, once successfully developed, can be applied to any powder manufacturing technique. It is also being explored as a way to either adjust/change alloy chemistries of a powder batch. Different powder mixing is currently being explored to develop metal/metal composite materials or potentially develop alloys that would be impossible to cast.

SEM EDS map of Cr [K α 1] distribution in [a] Partially HIPped and [b] Fully HIPped Cr coated 316L powder. Cr is found to be homogeneously diffused in the fully HIPped component]



P2.1 Process Definition and Control in Powder Bed Fusion (PBF) (until August 2020)

P2.1 Additive Manufacturing (from August 2020)

Investigator – Prof. Iain Todd, Sheffield

Collaborators – Sheffield (X2, X3), Manchester (X2), UCL (X1)

As a net-shape, material processing technology, PBF has really begun to gain credibility in industrial applications. However, there are still some issues related to the control and minimisation of processing defects and this aspect of the research programme in MAPP aims to address those issues.

In order to establish an in-depth understanding of specific defects that occur during powder processing, the team have investigated the changes in mechanical properties using different AM technologies, materials and powder sizes. To understand the causes of the defects they have altered processing parameters and have been able to track defects through the build process. *In-situ* thermal imaging has been combined and correlated with microscopy and X-Ray Computed Tomography (XCT) to identify and classify defect populations and these are used to inform the development of process models in X3. In addition, the incorporation of thermal and optical imaging into the process replicators developed by the UCL team based at Harwell has allowed us to gain a unique insight into the root cause of defect formation in PBF.

The team has now developed deep learning control for laser PBF. Working with researchers on X3 they have implemented such an approach on an “open” L-PBF platform (Aconity 3D). Using relatively low spatial [but high temporal] resolution pyrometry and applying a deep learning algorithm most commonly used in robotics – SLAM (Simultaneous Localisation And Mapping) – they have been able to process successfully and without human intervention, several commercially important metallic materials (nickel-based superalloys e.g. CM247, 713LC, as well as steels) in simple 3D geometries. This is presently being extended to enable these materials to be manufactured in more complex geometries and to further develop the sensors and deep learning algorithms used, including moving to higher spatial resolution thermal imaging and developing a robust system for deployment on a commercial system.

P2.2 Solid State Processing (FAST/SPS)

Investigators – Prof. Martin Jackson, Sheffield, Dr Enzo Liotti, Oxford, Prof. Patrick Grant, Oxford

Collaborators – Oxford, UCL [X1], Manchester [X2], Sheffield [X2, X3]

The development of Field Assisted Sintering Technology (FAST, a.k.a. Spark Plasma Sintering) is being used for producing fully dense parts from high strength titanium and nickel based super alloys and as an approach for joining dissimilar materials for application in the Energy sector.

They have developed the process to diffusion bond dissimilar metal systems together with the final part having excellent mechanical properties compared with conventional joining techniques. This new process, known as FAST-DB (Diffusion Bonding) allows Sheffield to produce a range of functionally graded parts.

The MAPP team at Oxford have successfully fabricated millimeter thick tungsten coating

on textured steel substrate in spite of the significant difference in thermal expansion coefficient and melting point of the two materials. The team is working with the Culham Centre for Fusion Energy to evaluate the durability of these manufactured coatings for fusion reactor components.

Finite element modelling of the FAST process is being used to predict localised heating rates and densities during processing of shaped FAST parts. Once validated, the live monitoring system being tested on the FAST machine in Sheffield will feedback into these models to predict the required temperature inputs to get the desired temperature and density field in the real part.

The next stages are to further expand the monitoring capabilities of the FAST machine to probe the mechanisms during electrical current assisted sintering. The teams at Manchester and UCL are also developing an experimental rig for *in-situ* FAST measurements in an X-ray synchrotron beamline.

P2.3b Future Manufacturing Platforms – High Speed Sintering

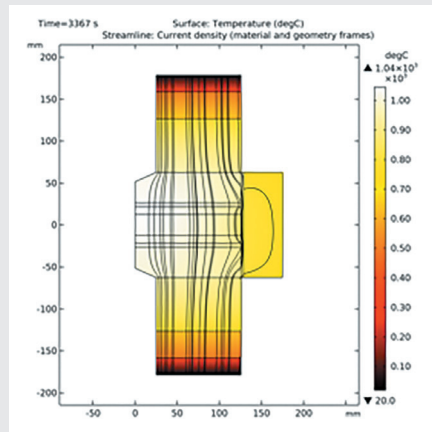
Investigator – Dr Candice Majewski, Sheffield

Collaborators – Sheffield [X3], Manchester [X2]

This project is developing our understanding of the processes, materials, and interaction between the two, with an overall aim of developing an optimised manufacturing process for powdered-polymer AM.

There is a growing need for increased repeatability of polymer AM parts as we move towards higher numbers of end-use applications, often in highly-demanding sectors. A crucial part of achieving this is to obtain a better understanding of the effects of processing parameters and material characteristics on part performance. As part of our efforts in this area we have been using micro-CT techniques to examine porosity of our parts (and its relationship with processing parameters and final part performance), providing previously unseen information into the ways in which we can minimise and control porosity.

Investigations are underway into the use of Positron Annihilation Lifetime Spectroscopy (PALS) for non-destructive characterisation of polymer AM parts, with an expectation of applying these findings to further powder-based techniques. Current work is investigating the potential to identify changes in parts at a material level (crystallinity and molecular weight) and a performance level (tensile properties). In this way we aim to develop a much deeper understanding of the underlying science behind changes in part performance, which we can then apply to modelling and predicting the performance of our parts in real-life situations.



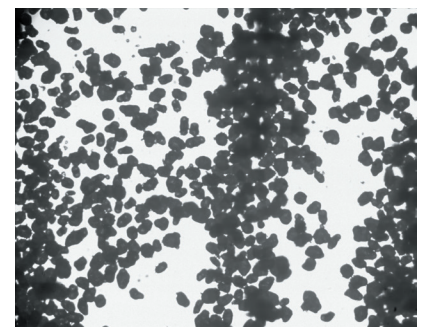
Example of modelling the Joule heating effect in large FAST tooling arrangements.

P2.3a Future Manufacturing Platforms – Diode Area Melting

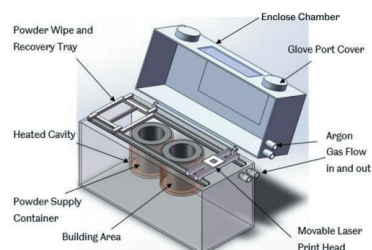
Investigators – Dr Kamran Mumtaz and Dr Kristian Groom, Sheffield

MAPP researchers are developing Diode Area Melting (DAM), a novel and highly scalable approach for high speed processing of powders to create net shape 3D components. DAM uses low power diode laser sources which can be used

to melt powder directly or act to pre-heat areas of the powder. Diode lasers can be selected with a wider range of wavelengths than conventional AM systems enabling more efficient coupling of laser energy into powdered materials of interest and the ability to work with challenging highly reflective materials such as copper and precious metals. We have developed a DAM prototype system and successfully processed a variety of powdered alloys (steel, titanium and nickel based) using low laser powers ~4W.



Nylon-12 particles at elevated temperature. Each particle is roughly 0.05mm.



DAM processing chamber and early stage Ti64 sample.

CROSS-CUTTING X THEMES

Cross-cutting themes underpin our core research themes. These three X themes focus on developing novel *in-situ* observation, advanced characterisation, and modelling optimisation and

control. Elements of each theme run through the platform research activities to enable a deeper understanding that allows MAPP to deliver on outcomes.

X1. In-Situ Process Monitoring

Investigator – Prof. Peter Lee, UCL

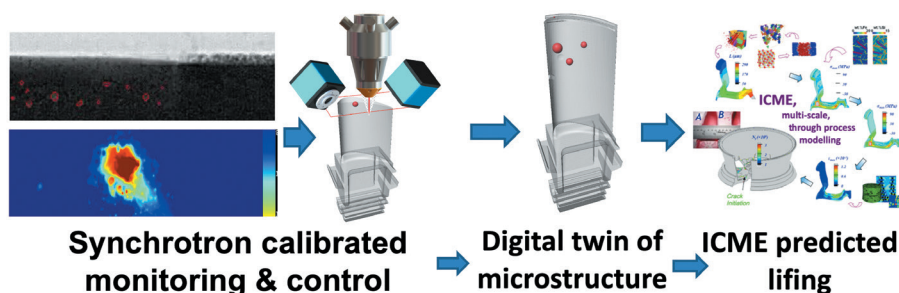
Collaborators – Manchester, Sheffield, Leeds, Imperial, Oxford

A series of world unique *in-situ* and operando process replicators [ISOPRs] have been designed, built and commissioned to replicate laser powder bed AM and blown powder processes, adding unique insights into the other themes. These ISOPRs have performed thousands of experiments during a dozen beamtimes with a focus on solving key scientific, technological and industrial challenges.

The X1 team has been aiming to visualise, understand and elucidate complex molten pool and defect dynamics in a multi-layer AM build using a combination of multi-modal ultra-fast imaging techniques, including X-ray,

Infra-red and optical imaging, all at ca. 50 kHz. Additionally, the project aims to use diffraction to capture the phase transformation [Solid->Liquid->Solid, new precipitates, etc.], and the development of residual stresses during Laser Additive Manufacturing [LAM]. The overall goal is to enable the accelerated development of new alloys, processes and control systems, which will be scaled up to full processes with academic/ industrial collaborators.

Recent work has focused on using the ultra-fast synchrotron imaging [DLS, ESRF, APS] results as the ground truth to calibrate Machine Learning monitoring and control strategies for low cost optical and Infrared [IR] imaging for both blown and laser powder bed processes. The results are laying the foundation for a transformational use of synchrotron calibrated digital twins that would enable a per component certification.



Synchrotron Digital Twin

X2. Advanced Characterisation

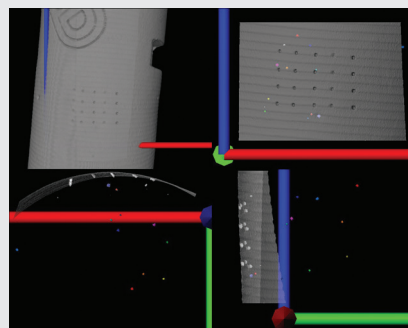
Investigators – Prof. Philip Withers, Manchester, and Prof. Mark Rainforth, Sheffield

Collaborators – Manchester, Leeds, Sheffield, Imperial

Researchers have been developing and employing advanced characterisation techniques. In particular combining high resolution X-ray CT to target areas for detailed 3D imaging by electron microscopy. For example to better understand the detailed structure of pores within additively manufactured titanium after HIPing using X-ray tomography and focused ion beam-SEM. Following the development of successful methodology for pore characterisation they are now looking at single particle, surface and bulk powder characterisation.

In-situ time-lapse X-ray tomography is being used to investigate microstructural evolution during manufacturing and in service, for

example the effects of porosity on mechanical behaviour in nylon samples manufactured by High Speed Sintering (HSS). Researchers are performing *in-situ* tensile tests, correlating crack formation with particular porosity distributions and regions of high strain.



A composite figure of the 3D X-ray tomography representation of a sample

X3. Modelling, Optimisation & Control

Investigators – Prof. Visakan Kadirkamanathan and Prof. George Panoutsos, Sheffield

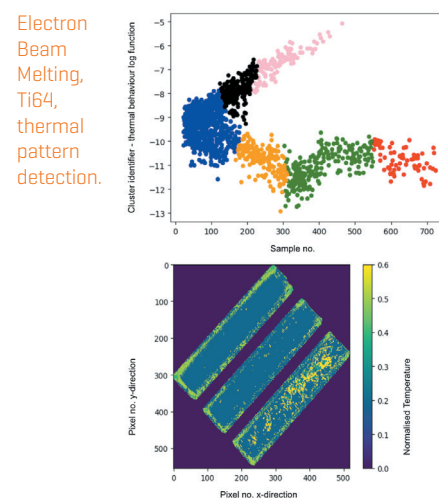
Collaborators – Sheffield, UCL, Imperial

In the X3 cross-cutting theme we are looking to turn the information and data from advanced processing and monitoring technologies into process understanding and process optimisation and control. The fast track development of emerging powder-based process technologies is being enabled through merging knowledge capture from intelligent experimental design and the novel approaches developed in X1 and X2 with computational intelligence [CI] modelling and machine learning [ML].

The team's work on process modelling and simulation has focused on laser PBF, demonstrating how data driven modelling [Machine Learning] can be used to capture complex process-part relationships. A predictive model has been constructed which is capable of estimating the printability of a given artefact before it is additively manufactured.

Research on process monitoring has focused on thermal imaging in electron beam Powder Bed Fusion [PBF]. A new unsupervised learning method, achieving very efficient data use suitable for real-time monitoring, has been developed. Thermal monitoring data was used, to demonstrate how we can capture and classify thermal behaviours during EBM. The thermal patterns were mapped onto 2D, layer by layer, to reveal relevant regions of interest in parts. This has the potential to link process conditions to specific microstructure and/or defects in areas of the part.

Work on process optimisation and control has focused on optimising experimental trials for AM processes, developing algorithms for process-part optimisation, and layer-by-layer control in laser PBF. A Bayesian optimisation algorithm is being developed for intelligent design of experiments for AM, significantly reducing the time to develop process parameters in new materials and geometries. Deep reinforcement learning has been used to achieve layer by layer control of temperature in laser PBF process, demonstrating a first in closed-loop control of AM processes.



PATHWAYS TO IMPACT

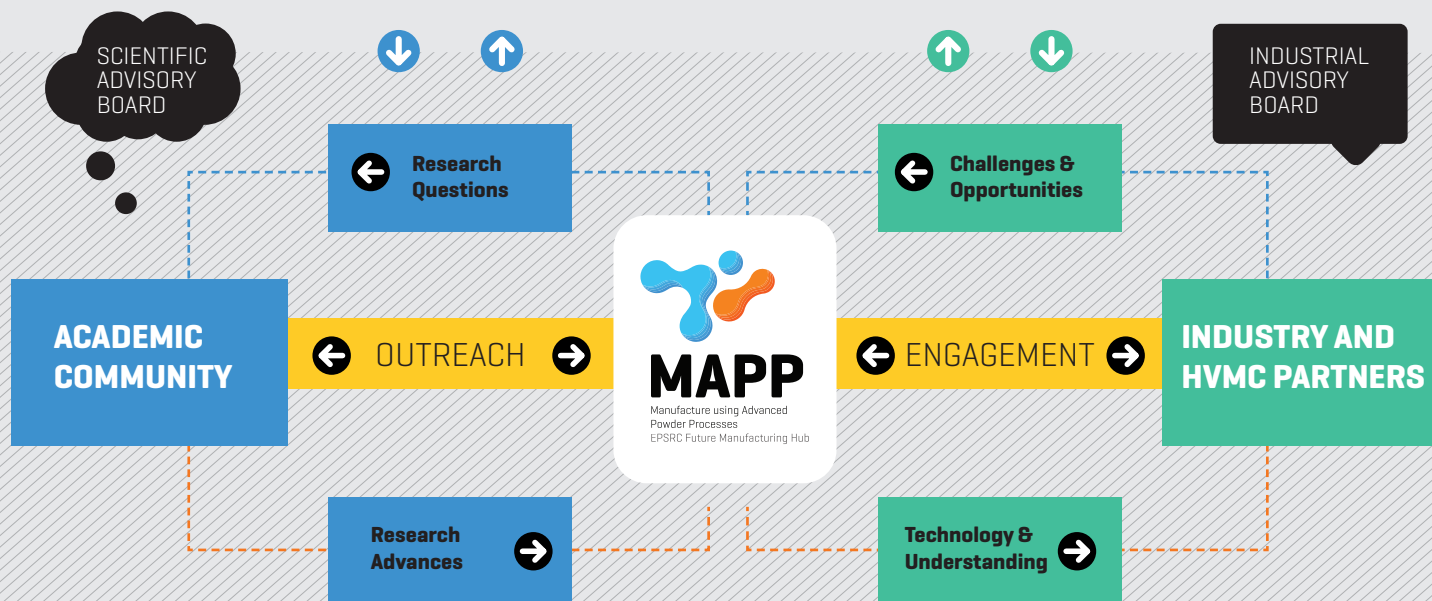
To ensure maximum impact on academia, technology, and the UK economy, MAPP has established a range of pathways to impact.

Working with our partners and gaining insight from our advisory boards we will deliver 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



MAPP INDUSTRY PARTNER EVENTS



MAPP INDUSTRY PARTNER BRIEFING

MAPP's Industry Partner Briefing event was hailed a resounding success by its academic, High Value Manufacturing Catapult and industry partners.

Almost 100 people, including MAPP's academic investigators and senior representatives from MAPP's industry and High Value Manufacturing Catapult partners, attended the event, at the end of April 2019, at Sheffield City Hall.

Industry sectors from across the advanced powder process supply chain were represented including end users from aerospace and energy, equipment manufacturers and advanced materials companies.

The event featured presentations, posters and a number of discussions, ensuring partners had the opportunity to network and learn more about the different interests involved across the consortium.

MAPP Director Professor Iain Todd gave a presentation that focused on the importance of



collaboration and engagement between the Hub and all partners.

Academic investigators shared their plans across MAPP's core research programme and members of MAPP's scientific advisory board shared the benefit of their experience with MAPP researchers by explaining key developments in their specialist fields.

Professor Todd said: "The event brought our industry partners together to look at MAPP's work since our launch in 2017, giving us a chance to re-engage with this community and have conversations about where we should be taking our ideas.

"MAPP is an open research Hub with an ambitious pre-competitive research programme looking to unlock some of the common challenges which are limiting the uptake of powder-based manufacturing processes. Collaboration is at the heart of what we do and this event was about deepening the engagement with partners on our current plans as well as looking to the future."

INDUSTRY PARTNER WORKSHOP - HELPING TO SHAPE MAPP'S FUTURE RESEARCH PROGRAMME

By Dr Richard France, MAPP Senior Business Development Manager

Our investigators came together with industry and High Value Manufacturing (HVM) Catapult partners again in November 2019 to shape MAPP's research programme over the next few years. We've worked closely with our industry partners throughout MAPP's development.

Our partners have articulated a number of challenges which required a programme of fundamental manufacturing research to solve: the variability of input material and process outcomes, the lack of explicit process understanding, the absence of suitable real-time modelling, no direct link from processing to in-service performance, and the skills gap.

The first years of MAPP have been focused on establishing the tools and technologies to answer these challenges and developing the interdisciplinary teams across the six academic institutions. As we move towards MAPP's midterm point we are starting to realise early indicators of MAPP's vision.

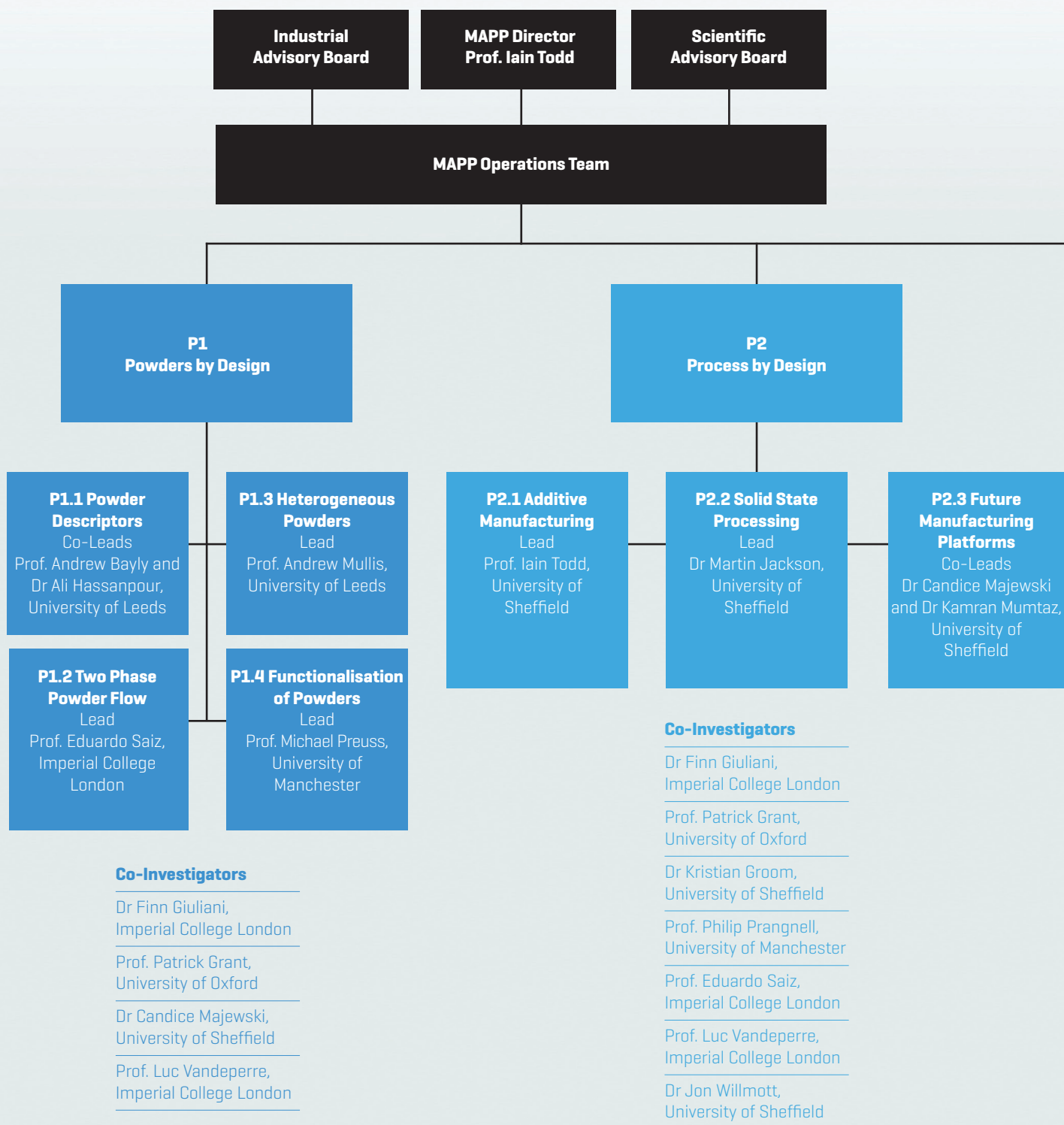
As we move towards demonstrating 'right first time' manufacturing, we are extending the tools and technologies we have developed - e.g. advanced metrology and machine learning approaches - and applying these to new challenges such as the prediction of in-service performance for components manufactured by advanced powder processes.

In parallel, we are working with industry partners to apply tools and technologies to their specific manufacturing challenges via aligned projects such as MIRIAM, AIRLIFT and DAM.

At the November workshop, we gave industry partners an overview of what we have achieved and our plans for the next two years of the programme. Industry partners gave us valuable feedback on these plans which we are now incorporating into a new research strategy which we will share in 2020.

MAPP PROJECT

ORGANISATION CHART



X1 In-situ Process Monitoring

Lead Prof. Peter Lee,
University College London

Co-Investigators

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. Michael Preuss,
University of Manchester

Prof. Iain Todd,
University of Sheffield

X2 Advanced Characterisation

Lead Prof. Philip Withers,
University of Manchester

Co-Investigators

Prof. Andrew Bayly,
University of Leeds

Dr Finn Giuliani,
Imperial College London

Dr Candice Majewski,
University of Sheffield

Prof. Michael Preuss,
University of Manchester

Prof. Luc Vandeperre,
Imperial College London

Prof. Mark Rainforth,
University of Sheffield

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

Dr Ali Hassanpour,
University of Leeds

Prof. Andrew Mullis,
University of Leeds

Prof. Philip Prangnell,
University of Manchester

FOCUS ON EQUIPMENT AND FACILITIES

As a multi-disciplinary hub, MAPP benefits from a wide range of specialist equipment.

Across the sites, MAPP researchers can benefit from access to world-leading resources.

This includes the facilities at Diamond Light Source, the UK's national synchrotron science facility. MAPP has been successful in securing several experimental runs utilising the high energy electron beam to produce valuable research data on powder structures.



The ultrasonic agitation rig for SLM at the University of Sheffield.

The team, led by Prof. Peter Lee, MAPP Executive and lead for the X1 research theme in MAPP, has developed the world's first blown powder additive manufacturing replicator in collaboration with an industrial partner which has allowed us to understand the formation and means of avoidance of gas porosity which is critical for the repair of critical aerospace components.

The team also created a novel laser additive manufacturing [LAM] process replicator, the LAMPR, which allows them to image and quantify the formation of the melt track as the layers are printed during AM.

The LAMPR was designed to fit on the beamline and mimics a commercial LAM system, with windows that are transparent to X-rays, allowing scientists to see right into the heart of the LAM process as it takes place.

By enabling varying process conditions to be studied, the LAMPR allowed the team to create

a process map which illustrates how to tune the LAM process to produce a quality product with minimal trial and error. Unlike a traditional process map, synchrotron imaging produces a mechanism map, which reveals the fundamental physics limiting the process window. This enables the alloy, conditions or even process to be altered to overcome the restrictions and obtain a more efficient processing environment.

This methodology sheds new light on the mechanisms of pore formation, including the migration, dissolution, dispersion, and bursting of pores during LAM, and future investigations in these areas will deepen our fundamental understanding of the nature of the laser-matter interaction.^[1]

At the University of Leeds, MAPP benefits from a wide variety of equipment including:

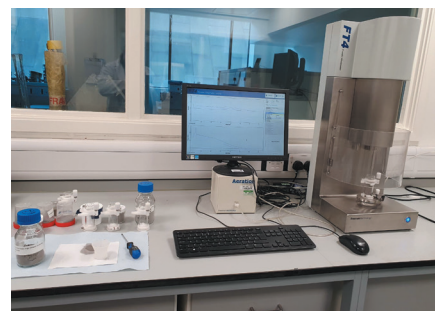
Instron 5566 Universal Testing Machine which allows a wide range of mechanical properties testing. Simple changes of setup allow for measurement of tensile, flexural and compressive properties, as well as coefficient of friction, creep-relaxation and other properties of interest.

Freeman Technology [FT4] Powder Rheometer - a universal powder flow tester for measuring powder flow properties and powder behaviour. It differs from other powder testers in many ways but when assessing industrial value, three features are critical:

- 1- The ability to simulate powder processing conditions, by testing samples in consolidated, moderately stressed, aerated or fluidised state
- 2- The application of multi-faceted powder characterisation to assess dynamic powder flow, bulk and shear properties to construct the most comprehensive understanding of how a powder behaves
- 3- Unparalleled sensitivity, enabling the differentiation of powders that other testers classify as identical

The FT4 has application in all powder processing industries, including metals, ceramics, polymers and additive manufacturing.

The Morphologi G3 provides an advanced yet easy to use particle characterisation tool for the measurement of particle size and particle shape from 0.5 microns to several millimeters. The technique is often used in conjunction with laser diffraction particle sizing, to gain a deeper understanding of product or process behavior.

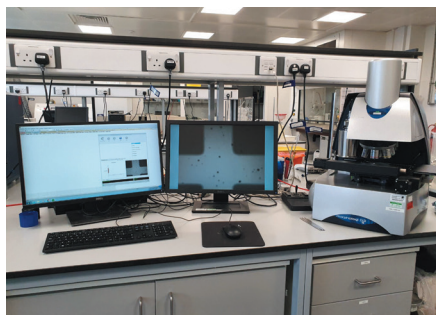


FT4 at the University of Leeds

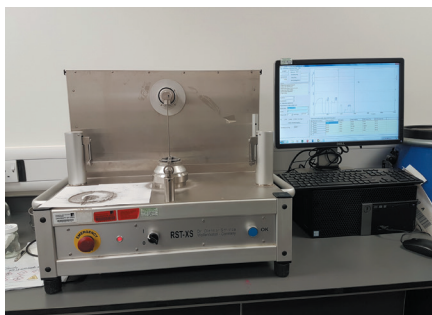
The Ring Shear Tester RST-XS provides computer-controlled measurement of the flow properties of powders and other bulk solid materials, under conditions which duplicate handling situations. Such properties are useful for many applications.



Instron 5566 Universal Testing Machine at the University of Leeds



Morphologi G3 at the University of Leeds



Shear cell tester at the University of Leeds



Dr Rahul Unnikrishnan, the University of Manchester.

At the University of Manchester, the Multidisciplinary Characterisation Facility (MCF), including the Manchester X-ray Imaging Facility (MXIF), represents one of the most extensive characterisation facilities in the UK and is able to provide:

- Multiscale imaging
- Correlative imaging
- Multidimensional imaging

The facilities at MXIF enable 2D, 3D and 3D over time (so-called 4D) imaging of materials. They also have the capability to recreate service conditions, via *in-situ* stages and rigs, enabling the materials to be imaged under stress.

The MCF enables MXIF capabilities to be combined with elemental, atomic and isotropic characterisation techniques allowing complete characterisation of materials from macro to nano scale.

The MCF is part of the University of Manchester's commitment to the Henry Royce Institute and represents a world-leading capability for materials characterisation and imaging.

The Henry Royce Institute, Sheffield is leading the advanced metals processing theme to accelerate the development and adoption of new materials systems to meet global challenges.

This includes various additive manufacturing and advanced metallurgy equipment, currently situated either on the University of Sheffield campus or at the purpose-built Royce Translational Centre based at the University of Sheffield Innovation District.

Examples include:

- Q20plus Electron Beam Melting - Arcam
- Q10plus Electron Beam Melting - Arcam
- BeAM Magic 2.0
- Gas Atomisation-Arcast ATM DM 50

MAPP works closely with colleagues involved with the Henry Royce Institute for Advanced Materials, which is the UK's national institute for advanced materials research and innovation.

The £235 million Institute is a critical component of the Government's Northern Powerhouse initiative and part of the strategy to boost economic growth in the North of England and balance the UK economy.

The Royce brings together world-leading academics from across the UK and works closely with industry to ensure commercialisation of fundamental research.

The Royce hub is at The University of Manchester, with spokes at the founding partners, comprising the Universities of Sheffield, Leeds, Liverpool, Cambridge, Oxford and Imperial College London, as well as the Culham Centre for Fusion Energy and the National Nuclear Laboratory.

The Royce's initial focus is on nine key areas of materials research, Materials Systems for Demanding Environments (MS4DE), Biomedical Systems and Devices, 2D Materials, Nuclear Materials, Materials for Energy Efficient ICT, Atoms to Devices (A2D), Energy Storage, Advanced Metals Processing and Chemical Materials Discovery.

Many of the MAPP investigators are involved with the hub and spoke model that is operated by the Henry Royce Institute, and which offers access to > £150m worth of specialist equipment.

[1] Leung, C.L.A., Marussi, S., Atwood, R.C., Towrie, M., Withers, P.J., Lee, P.D., [2018]. *In-situ* X-ray imaging of defect and molten pool dynamics in laser additive manufacturing. *Nature Communications*. **9**, 1355.

FEASIBILITY FUNDING

The successful applications from MAPP's first round of feasibility funding have led to exciting results.

In 2018 MAPP opened its first round of feasibility funding in order to initiate collaborative projects that support the development of new research directions and draw in complementary expertise.

There was a large amount of interest in the call, which attracted a wide range of advanced powder and process development research. MAPP's external Scientific Advisory Board formed part of the three-stage evaluation process.

The four successful applications (alphabetically) were:

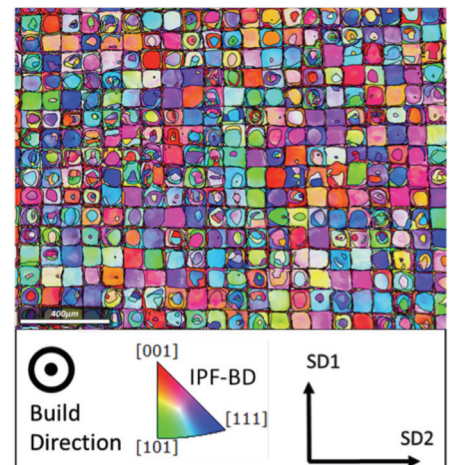
- **Prof. Jawaad Darr – University College London ‘Cold press sintering of solid-state electrolyte powders.’**
- **Dr Minh-Son Pham – Imperial College London ‘Assessing the printability of alloys for fusion-based additive manufacturing by coupling thermodynamics phase diagrams and machine learning.’**
- **Dr Cornelia Rodenburg – The University of Sheffield ‘Feasibility of polymer powder based SMART parts.’**
- **Dr Phillip Stanley-Marbell – The University of Cambridge ‘Programmable in-powder sensors (PIPS) for real-time metrology and data-analysis in powder processes.’**

Read on for a closer look at three of the projects, each written by the team working on the project being discussed.

Assessing the printability of alloys for fusion-based additive manufacturing by coupling thermodynamics phase diagrams and machine learning

This feasibility study project contributes to MAPP's vision by providing the additive manufacturing (AM) community with an effective and powerful tool in selecting materials and predicting the process defects, helping to reduce capital costs based on science-underpinned knowledge. In particular, the project develops a comprehensive design methodology incorporating key thermodynamic features (freezing range, solidification gradient, crystal phase, thermal expansion and chemical segregation) to assess the susceptibility of alloys to the porosity and crack formation. A design platform incorporating machine learning and thermodynamics calculation of phase diagrams was successfully developed to accelerate the design of the printable alloys. In this project, the susceptibility to solidification cracking and porosity of Ni, Fe and high entropy alloys were extensively assessed. A highlight of this feasibility project includes the design of a Fe-based alloy with exceptionally low susceptibility to solidification. The alloy was fabricated and tested to validate the design methodology. Thorough processing optimisation and characterisation are being carried out to better understand the process-microstructure relationship of this alloy to improve the current design methodology, in particular against ductility loss cracking. Another highlight of the project is a fundamental study (Pham, M-S., Dovgvy, B., Hooper, P.A. et al [2020]. The role of side-branching in microstructure development in laser powder-bed fusion. *Nature Communications* **11**, 749) that reveals the influential role of side-branching

in microstructure development in AM, helping to increase the confidence in microstructure control in AM. Last but not least, a network of academic and industrial experts in artificial intelligence, microstructure modelling and AM processing was established to collectively work in the direction of alloy design for AM, helping to build up a critical mass in solving materials-related issues in AM.



Electron Backscattered Diffraction (EBSD) map of 3D printed alloy that exhibits very low susceptibility to solidification. Inverse pole figure orientation triangle is coloured along the Build Direction (BD). Scanning directions are marked as SD1 and SD2, indication a 90° rotation between layers. Image by Bogdan Dovgvy.

Programmable in-powder sensors (PIPS) for real-time metrology and data-analysis in powder processes

Powder bed temperature profiles, in-powder and build chamber gases, and compressive forces within powder, all affect properties of objects manufactured by Selective Laser Sintering/Melting (SLS/SLM)^[1, 2, 8].

Modern SLS and SLM processes can monitor properties such as powder surface temperature^[1].

Several efforts are underway to perform other kinds of *in-situ* process monitoring^[3, 4, 5, 6, 7], including our own efforts to use low-cost photospectrometers to monitor the powder surface^[9].

In this project, our objective was to go beyond monitoring properties at the powder bed surface,

to monitor properties throughout the volume of the powder bed, in selective laser sintering of nylon powder.

Our research hypothesis was that using miniaturised sensor integrated circuits together with custom circuit design and new research to improve sensor energy efficiency, we would be able to create miniature sense-and-compute systems to monitor temperature, humidity, and pressure at a fine scale within the volume of the powder bed and to perform signal processing of the sensor data *in-situ*.

Our goal was to use this novel sensing system to study the properties within the nylon powder

reservoir as the build chamber warms up in the pre-print heating phase.

Our final system is 14.6×8.9×4 mm [520mm³] when powered by two batteries. We achieved our goal of in-powder placement and in-powder metrology and our results demonstrate how we can use temperature and humidity sensors to investigate the adsorption of humidity to nylon powder in a nylon Selective Laser Sintering [SLS] process.

The final miniature programable in-powder sensor system contains a state-of-the-art integrated multi-modal sensor for temperature, humidity, pressure, carbon monoxide [CO] and volatile organic compounds [VOCs] including Ethane/Isoprene/2-methyl-1,3 Butadiene/ Ethanol/Acetone. The heart of the system is a 32-bit ARM Cortex-M0 microcontroller in a chip-scale package for *in-situ* signal processing, paired with a temperature-compensated real-time clock for accurate timekeeping in the

presence of in-powder temperature variations, 16 Mb of Flash memory for storage, a miniature connector for programming and data retrieval, and sockets for up to two miniature 8mAh Zn/AgO batteries which can power the system for between 20 and 200 hours, depending on the chosen sensor sampling rates.

One of the project's key outcomes is the low-power programable in-powder sensor [PIPS] hardware. We have made the platform available to research groups in the UK [University of Liverpool] and abroad [Max Planck Institute] and intend to make the designs and firmware open source, to support research in applications of sensors to in-powder metrology.

[1] P. Green, K. Black, and C. Sutcliffe, "Towards Additive Manufacturing Process Control using Semi-Supervised Learning". Connected Everything Feasibility Study, January 2017.

[2] P. Bidare, I. Bitharas, R.M. Ward, M.M. Attallah, A.J. Moore, Fluid and particle dynamics in laser powder bed fusion, *Acta Materialia*, Volume 142, 2018, Pages 107-120.

[3] Philipp Lott et al., Design of an Optical system for the In Situ

Process Monitoring of Selective Laser Melting [SLM], *Physics Procedia*, Volume 12, Part A, 2011, Pages 683-690.

[4] Sarah K. Everton et al. Review of *in-situ* process monitoring and *in-situ* metrology for metal additive manufacturing, *Materials & Design*, Volume 95, 2016, Pages 431-445.

[5] D. Cerniglia, M. Scafidi, A. Pantano, J. Rudlin, Inspection of additive-manufactured layered components, *Ultrasonics*, Volume 62, 2015, Pages 292-298.

[6] Richard J. Smith, Matthias Hirsch, Rikesh Patel, Wenqi Li, Adam T. Clare, Steve D. Sharples, Spatially resolved acoustic spectroscopy for selective laser melting, *Journal of Materials Processing Technology*, Volume 236, 2016, Pages 93-102.

[7] Matthias Hirsch, Rikesh Patel, Wenqi Li, Guangying Guan, Richard K. Leach, Steve D. Sharples, Adam T. Clare, Assessing the capability of *in-situ* nondestructive analysis during layer based additive measurements, *Additive Manufacturing*, Volume 13, 2017, Pages 135-142.

[8] P. Bidare, R.R.J. Maier, R.J. Beck, J.D. Shephard, A.J. Moore, An open-architecture metal powder bed fusion system for *in-situ* process measurements, *Additive Manufacturing*, Volume 16, 2017, Pages 177-185.

[9] P. Stanley-Marbell, R. Hewson, N. Dulake, and D. Petrelli, Continuous In Situ Microstructure and Composition Analysis within 3D-Printed Structures Using In-Chamber Sensors, *ConnectedEverything Feasibility Study*, 2018.

Feasibility of polymer powder based SMART parts

The aim of this project was to establish the feasibility of powder-based SMART parts with integrated printed CMOS [complementary metal-oxide-semiconductor].

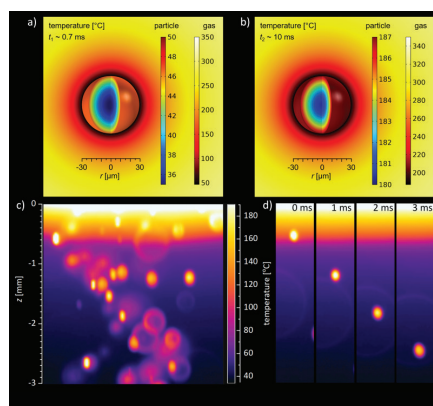
To integrate electronics in parts manufactured from polymer powders requires, semiconductor, metal and insulator materials that can well cover rough polymer surfaces. In addition, it needs an additive manufacturing tool that allows powder deposition without prolonged heat exposure.

We introduced an innovative plasma source for well controlled simultaneous polymer powder Functionalisation and deposition and evaluated the deposition process terms of suitability for additive manufacturing using powders commonly used for Laser Sintering. Print profile, microstructure [optical microscopy, advanced SEM [x-section and plan view], chemistry [EDX and FTIR] evaluation together with high speed imaging and modelling of the deposition process gave fundamental insights on the key mechanisms and allowed prediction of how they can be controlled to obtain printed parts with well controlled microstructure/ chemistry at the lowest possible heat exposure of the substrate.

This new deposition method was successfully used to sandwich aerosol jet printed transistor structures in parts produced from PA12 powder.

Lead – Dr Cornelia Rodenburg, University of Sheffield

Cols – Dr Kate Black, University of Liverpool; Dr Jon Willmott, University of Sheffield; Dr Jan Schäfer, Leibniz Institute for Plasma Science and Technology Greifswald, Germany



Temperature dynamics of particles. Particle and gas temperature obtained from heat-transfer simulations after $t_1 = 6.6 \times 10^{-4}$ s [a] and $t_2 = 9.3 \times 10^{-3}$ s [b], both for a background temperature of 350 °C; high-speed IR [infrared] thermography of particles in the effluent at 2 kfps: [c], tracked single-particle movement [d]. Note that in [c] and [d] different sizes of particles are caused by IR imaging optics being focused to the axis of the jet. Particles out of focus appear with different size and with incorrect temperatures. Reproduced from Schäfer, J et al, *HelixJet: An innovative plasma source for next-generation additive manufacturing [3D printing]*. *Plasma Process Polym.* 2019:e1900099 <https://doi.org/10.1002/ppap.201900099> under CC-BY 4.0.

Second Round of Feasibility Funding

MAPP's second round of feasibility funding also attracted a range of applications from around the UK.

Karen Wood, MAPP Project Manager, said: "Once again we had a great range of applications. It was especially encouraging to receive applications from earlier stage academic researchers, and we are looking forward to working with them over the coming year. All of them will be invited to a quarterly meeting where they can begin to grow their collaborations with MAPP researchers."

The second competitive funding round closed in November 2019. Projects have been awarded a maximum of £50,000 (80% FEC) and will run for a maximum of six months.

The successful applications [alphabetically] are:

- **Prof. Michael Bradley, University of Greenwich - Powder layer surface quality monitoring including a novel method in development**
- **Dr Simon Hogg, University of Loughborough - Enhanced Understanding of Field Assisted Sintering Mechanisms Through Novel In-situ Characterisation**
- **Dr James Murray, University of Nottingham - Toward perfect powders: four easy pieces**
- **Dr Kit Windows-Yule, University of Birmingham - CoExSiST: Coupled Experimental-Simulation Study Technique**

PROJECT PARTNERS

MAPP is led by the University of Sheffield and brings together leading research teams from the Universities of Leeds, Manchester and Oxford, Imperial College London and University College London, together with a founding group of 17 industry partners and the UK's High Value Manufacturing Catapult. In the past 12 months, MAPP has welcomed three new industry partners.

HIGH VALUE MANUFACTURING CATAPULT CENTRES



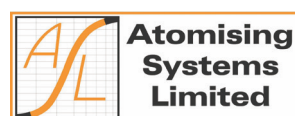
NUCLEAR AMRC



INDUSTRY PARTNERS



NEW INDUSTRY PARTNERS



A WORLD LEADER IN ADDITIVE MANUFACTURING

MAPP executive member Professor Peter Lee



In April 2019, the Royal Academy of Engineering announced ten years of support for Professor Peter Lee, UCL Mechanical Engineering, as a world leader in applying synchrotron imaging to help develop more efficient, environmentally friendly and cost effective additive manufacturing (AM) technologies.

Prof. Lee is one of nine Chairs receiving part of £20m in funding plus ten years of support from the Academy.

Each Chair focuses on developing technologies with the potential to bring significant economic and societal benefits to the UK. The ten-year support provided aims to enable the progress of disruptive innovations from basic science through to full deployment and commercialisation.

Prof. Lee's work focuses on applying synchrotron imaging to help develop more efficient, environmentally friendly and cost effective additive manufacturing (AM) technologies, also known as 3D printing.

A synchrotron works like a giant microscope, using the power of electrons to enable scientists to study anything from fossils to viruses. The UK's synchrotron is Diamond Light Source, located on the Harwell Science and Innovation Campus in Oxfordshire.

On receiving the award, Prof. Lee said: "Additive manufacturing promises to be a truly enabling technology. It will allow us to make personalised products that are digitally designed and

electronically delivered. These designs can then be fabricated on the other side of the world to help tackle a range of challenges, from alleviating drought to solving medical emergencies.

"The new insights gained from our project will help to make metal AM a more reliable and affordable technology for the production of components, with applications in a wide variety of fields from aerospace to biomedicine. This will place the UK at the heart of this key underpinning technology, enabling manufacturing in a truly digital environment from concept to final component, as well as personalised production, while reducing resource consumption."

Prof. Nigel Titchener-Hooker, Dean of UCL Engineering, said: "We're thrilled that Peter's invaluable contributions to additive manufacturing and his future potential have been recognised by the Academy with this prestigious award. Peter is at the forefront of developing unique nanoprecision equipment that applies ultrafast synchrotron X-ray imaging to improve advanced materials and manufacturing techniques.

"The support from the Academy will enable Peter and his academic and industrial collaborators

"The funding from the RAEng Chair and UCL will support about one dozen PhD studentships aligned with MAPP studying aspects of additive manufacturing from modelling to nano-printing to machine learning based control algorithms, all informed by synchrotron imaging."

Prof. Lee

to develop this vital technology to help lead the way in design without bounds, revolutionising manufacturing so that it becomes a digital tool where future generations don't have to worry about how objects are produced and can focus solely on personalised design."

The awards were made through the Academy's Chairs in Emerging Technologies programme and the nine chairs are supported through the UK government's Investment in Research Talent initiative.

Prof. Dame Ann Dowling, President of the Royal Academy of Engineering (2014-19), said: "The new technological areas advanced by our Chairs in Emerging Technologies have the potential to transform our everyday lives, as well as positively impact the UK's economy and generate new sources of wealth. Engineering is critical to achieving the goals of the UK government's industrial strategy, and investment in emerging technologies means that we can secure our footing in important future markets.

"For these technologies to reach their full potential it is important to invest in the pioneering individuals who advocate for them, as without their vision and foresight it is difficult to identify the products and services of tomorrow."

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LECTURE SERIES



From metrology to quantum technologies the MAPP Lecture Series has gone from strength to strength with a wide range of thought-provoking topics.

The regular one-hour lectures have been well attended with each lecture attracting about 30 attendees from industry and academia.

They provide an opportunity to hear from experts in the field of advanced powder processes and are followed by lunch and a chance to speak with the lecturer.

Director of MAPP, Professor Iain Todd said: "The MAPP Lecture Series is interesting and informative. It has been fantastic to hear high-quality speakers give their insight into advanced powder processes and related subjects."

Richard Leach, Professor of Metrology at the University of Nottingham, gave the inaugural talk in the MAPP Lecture Series in November 2017. It was followed by four lectures in 2018.

There have been four MAPP Lectures in 2019 and the series will be continuing into 2020.

The sixth lecture in the series, in January 2019, was given by Dr Sarah Everton, a Metals Research Engineer at Added Scientific, a spin-out of the Centre for Additive Manufacturing at the University of Nottingham.

The talk gave an introduction to the burgeoning quantum sector and highlighted some of the market applications for quantum technologies.

The seventh lecture in the series was given in June, by Dr Ifty Ahmed, the University of Nottingham. It was titled 'Manufacturing Micro Spherical and Porous Particles from Glasses and Glass Ceramics.'

Dr Ifty Ahmed is part of the Advanced Materials Research Group. His areas of expertise include phosphate-based glass production and characterisation including phosphate glass-fibre (PGF) production.

Recent work has also focused on the manufacture of resorbable biocomposites using PGF as reinforcement to tailor mechanical properties and resorption characteristics, mainly for bone repair applications. Applications for these resorbable biocomposites span fracture fixation devices including, plates, screws and intramedullary nails.

He is currently working on the manufacture of microspheres (ranging from 60-350 microns diameter) from a range of materials to include glasses, glass ceramics and polymers. These microspheres have been produced in both bulk and porous forms, with a wide range of porosity levels.

The eighth lecture in the series was given in October, by Dr Simon Hogg, Senior Lecturer in Metallurgy in the Department of Materials at Loughborough University.

His research interests revolve around using advanced characterisation techniques to investigate microstructure during processing and in-service operation of industrial and novel metal alloy systems.

The talk 'Processing and Characterisation of High Entropy and Spray Formed Alloys' focused on the characterisation of Cr-Mn-Fe-Ni and Cr-Mn-Fe-Co-Cr high entropy alloys produced using powder routes.

The ninth lecture of the series was given in December 2019 by Dr Phillip Stanley-Marbell, lecturer in the Department of Engineering at the University of Cambridge where he leads the Physical Computation Lab. He led on one of the projects selected for MAPP's first round of feasibility funding [see page 20 for more details].

His research focus is on exploiting an understanding of the properties of the physical world to make computing systems more efficient.

'Augmenting Raw Materials with Sensing and Computation,' looked at how materials and manufacturing processes can be made to adapt to the way in which their end-products are used, by imbuing raw materials with sensing and computation elements. By making the algorithms that run on these computing elements aware of the physics of the objects in which they are embedded, computation-and-sensing augmented materials could change the way we think about the border between inanimate objects and computing systems.



MAPP Lectures in 2017 and 2018:

1. November 2017, Professor Richard Leach, the University of Nottingham
2. February 2018, Dr Hector Basoalto, the University of Birmingham (now at the University of Sheffield)
3. May 2018, Dr Kate Black, the University of Liverpool
4. September 2018, Dr Paul Hooper, Imperial College London
5. October 2018, Professor Andrew Moore, Heriot-Watt University

SETTING THE NATIONAL AGENDA

Manufacturing research engagement with the UK's Large Facilities

By Dr Richard France, Senior Business Development Manager



The UK's Large Facilities include a number of central research large scale facilities used by scientists and engineers worldwide. They include the Central Laser Facility, ISIS Neutron and Muon Source, and the Diamond Light Source.

MAPP makes extensive use of the Diamond Light Source within our X1 (*In-situ* Process Monitoring) research theme led by Professor Peter Lee at University College London. A number of other EPSRC Hubs such as CMAC (Continuous Manufacturing and Crystallisation) and the Catalysis Hub make use of the facilities as part of their research programmes. There is potential to develop these activities further, for example by establishing a manufacturing research focused station at Diamond.

MAPP researchers convened a Town Hall event at the Royal Society in London on 21st January 2020 to further stimulate the use of the facilities by the UK's manufacturing research community.

The objectives of the event were:

- 1. To start to set the national agenda for Hub and industry engagement with the UK's Large Facilities**
- 2. To obtain strategic industrial input on how to optimise translation from the Large Facilities**
- 3. To elucidate the key science drivers required by the Hubs, catapults and industry**
- 4. To determine the requirements of stakeholders and start to develop a roadmap with which to move developments forward.**

The event brought together more than 90 delegates from across a wide range of stakeholders: directors from all of the EPSRC Future Manufacturing Hubs, the EPSRC Catalysis Hub, senior delegates from industry and the High Value Manufacturing Catapult, directors from the UK's Large Facilities, and sponsors including EPSRC and STFC (Science and Technology Facilities Council).

The event involved a series of presentations and panel sessions: Directors of the Large Facilities outlined their capabilities and future plans, Hub Directors outlined existing activities and potential research opportunities, and industry representatives from the catalysis, pharmaceutical and aerospace sectors shared their experience of working with the facilities.

A facilitated workshop built on the panel sessions to share best practice and identify what might be required to further development in terms of facilities, people, equipment, software and training.

A number of options were identified to develop both the facilities and the research community and we will be taking these forward over the next year.



THE HENRY ROYCE INSTITUTE

New Core Area Champion at Sheffield - MAPP's Prof. Martin Jackson

The Henry Royce Institute has appointed Prof. Martin Jackson as the new Core Area Champion for the Advanced Metals Processing (AMP) research theme.

Martin, a MAPP Investigator, is Professor of Advanced Metals Processing at the University of Sheffield.

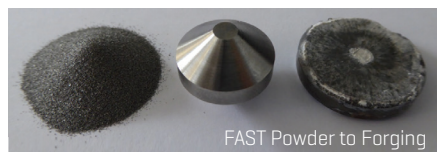
He has led the development of the emerging FAST-forge route. Previously at Imperial College London, Martin developed an innovative forging test methodology, for which he won the IOM3 Titanium Prize 2003. The methodology Martin developed is now a recognised forgeability test in the ASM Handbook and has been since employed by the aerospace and nuclear build industry.

In 2005 he won a RAEng/EP SRC Fellowship and in 2008 he moved from Imperial to Sheffield, providing a platform to develop research in both solid-state processing of titanium powder and titanium machining studies.

He has since supervised more than 25 PhD students and published more than 100 peer-reviewed journal and conference papers in processing of light alloys, including forging, machining and associated mechanical property development.

He has been a member of the IOM3 Light Metals Board for more than 16 years and is the UK representative for the World Titanium Committee.

Royce spoke with Martin to discuss his sustainable vision for AMP, bridging the gap between research and commercial innovations and why he first took up materials science.



As the newest member of the Core Area Champions, what benefits do you think the Royce can bring to Sheffield and the wider materials community?

Sheffield is an important national hub for advanced manufacturing, building on its historic importance in steelmaking and glassmaking. The Royce will capitalise on the local industry infrastructure and expertise to provide a world-leading centre for advanced metals manufacturing for the next few decades. For me [as a Yorkshireman and Sheffield graduate!]

this is an exciting opportunity and I would not dream of being anywhere else to work on the next generation of metals manufacturing challenges with the UK industry and academic community.

Your research background has spanned both academia and industry roles. Is there a need for a more joined-up approach to research and innovation across the UK?

Absolutely, having spent time working in industry and working closely with industry as an academic, it is important that we blur the boundaries between the two – Royce will facilitate and encourage this. I would like to see the interconnection of engineers, academics and industrialists in the Royce. We can also provide invaluable hands-on training for engineers in both industry and academia. The Royce will be a centre of constant learning and value-add to the manufacturing community. We may make some mistakes, as there will be some high-risk technical challenges, but with the right industry and academic teams, it's an exciting time to make a real step-change and ensure the UK is leading manufacturing innovation in metals.

What are your main priorities for the Advanced Metals Processing theme for the next 12 months?

I will be reaching out to universities and key industry sectors and encourage them to join us on the Royce journey. This is a national facility and the knowledge and impact that is created within Royce will be reliant on scientists and engineers from all over the UK getting involved. We are already putting together key projects with industry and translational centres such as the HVM Catapults Centres to demonstrate that the Royce community can accelerate impact for UK businesses.

The metals industry is one of many working to reduce its carbon footprint. Are there any innovations on the horizon that will help the UK meet its decarbonisation targets?

Within Sheffield, Royce will play a key part in some of the EPSRC manufacturing hubs – such as SUSTAIN – developing carbon-neutral steel and ironmaking and smart steel processing. Another important focus for Royce will be making sure that we “do more with less”: the digitalisation of processes, and development of reliable digital twins of advanced manufacturing processes will empower UK industry to have more confidence in materials and their properties, leading to less wasteful manufacturing processes. This will ultimately lead to increased productivity,

economic growth and job creation. If we can combine recycling with light-weighting of vehicle parts then this will have a massive impact on CO₂ emission reductions. The Royce is already working with the automotive sector to reuse aerospace waste machined turnings into next-generation parts for electric vehicles. We've only just begun this journey and what is really exciting is that the new Royce infrastructure and investment will enable us to develop new approaches for recycling, light-weighting and reducing the UK's carbon footprint.

A version of this article originally appeared on the Henry Royce Institute website and is republished here with permission.



The Henry Royce Institute is a partnership of nine leading institutions – the universities of Cambridge, Imperial College London, Liverpool, Leeds, Manchester, Oxford, Sheffield, the National Nuclear Laboratory, and UKAEA (United Kingdom Atomic Energy Authority).

The Royce coordinates more than 900 academics and more than £300 million of facilities, providing a joined-up framework that can deliver beyond the current capabilities of individual partners or research teams.

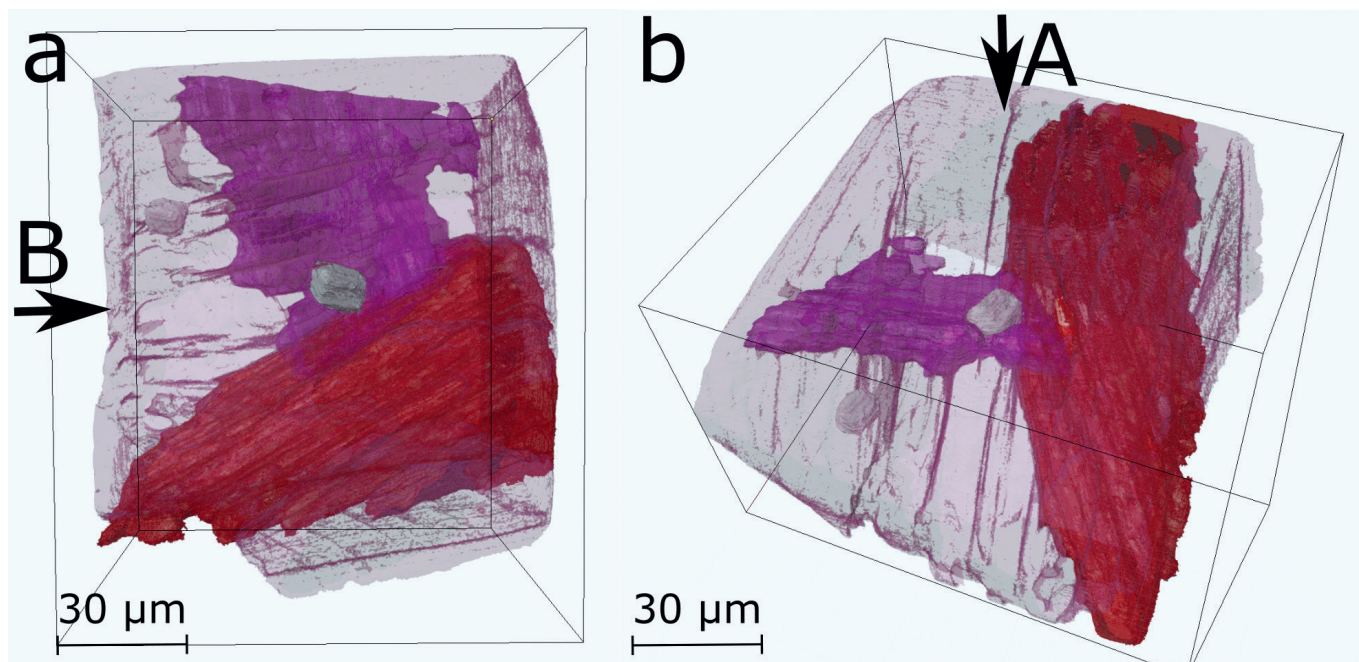
The Henry Royce Institute is funded by the Engineering & Physical Sciences Research Council, part of UK Research & Innovation.

SPOTLIGHT ON

X2 ADVANCED CHARACTERISATION

At The University of Manchester and the University of Sheffield

By Dr Jo Sharp, MAPP PDRA



X2: Characterisation of pores in heat treated electron-beam additive manufactured Ti using 3D serial sectioning and EBSD.

Collaborators - University of Manchester, University of Sheffield.

Pores are often seen as the nemesis of additive manufacturing for fatigue applications such as jet turbine parts, and can come from various sources, such as pores in the original powder or adsorbed gases on its surface. Fatigue crack surfaces can often be traced back to a pore at the initiation point. Hot Isostatic Pressing can be applied to close up pores, but when a metallurgical heat treatment is applied to achieve the microstructure needed for other properties, some of the pores (particularly noble-gas pores from the insides of powder particles) reopen.

In this project, Manchester and Sheffield have collaborated to section a pair of reopened pores and reconstruct their shapes and the phases and crystal orientations of the grains around them. Our goal was to find out whether they regrow spherical or faceted, what determines the facets, and whether something can be changed to make them less intense stress concentrators for fatigue applications.

We found that pores did indeed grow faceted and aligned with each other, and with the crystal structures of both the high-temperature Ti phase in the heat treatment process, and the low-temperature phase the metal transforms to as it cools. Their relation to the slip systems in the surrounding grains tells a complex history.

Their faceted shape makes their stress concentrating ability stronger, but their relation to the material around them opens the door to many possibilities to change pore behaviour and bring the goal of additive manufactured fatigue-critical components a step closer.

3D reconstruction of the two pores [grey] showing their relation to the grains and boundaries around them, and their faceted shape.

In [a], the arrow marked B is the point of view from which image [b] is taken, and in [b], arrow A is the point of view from which image [a] is taken.

PUBLICATIONS

Journal Paper: Elizarova, I.S., Vandeperre, L., Saiz, E., [2020]. Conformable green bodies: Plastic forming of robocasted advanced ceramics. *Journal of the European Ceramic Society*. **40** (2), 552-557.

Journal Paper: Fouda, Y.M., Bayly, A.E., [2020]. A DEM study of powder spreading in additive layer manufacturing. *Granular Matter*. **22**, 10.

Journal Paper: Turner, R.D., Wingham, J.R., Paterson, T.E., Shepherd, J., Majewski, C., [2019] Use of silver-based additives for the development of antibacterial functionality in Laser Sintered polyamide 12 parts. *Scientific Reports*. **10**, 892.

Journal Paper: Snell, R., Tammas-Williams, S., Chechik, L., Lyle, A., Hernández-Nava, E., Boig, C., Panoutsos, G., Todd, I., [2020]. Methods for Rapid Pore Classification in Metal Additive Manufacturing. *JOM [3D Materials Science]*. **72**, 101-109.

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Journal Paper: Velasco-Castro, M., Hernandez-Nava, E., Figueroa, I.A., Todd, I., Goodall, R., [2019]. The effect of oxygen pickup during selective laser melting on the microstructure and mechanical properties of Ti-6Al-4V lattices. *Heliyon*. **5** (12), e02813.

Journal Paper: Feilden, E., Glymond, D., Saiz, E., Vandeperre, L., [2019]. High temperature strength of an ultra high temperature ceramic produced by additive manufacturing. *Ceramics International*. **45** (15), 18210-18214.

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FAST-forge titanium particulate to final component in two steps

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Pham, M-S., et al, [2019] Damage-tolerant architected materials inspired by crystal microstructure. *Nature*. **565**, 305-311

Journal Paper: Hernández-Nava, E., Mahoney, P., Smith, C. J., Donoghue, J., Todd, I., Tammas-Williams, S., [2019]. Additive manufacturing titanium components with isotropic or graded properties by hybrid electron beam melting/hot isostatic pressing powder processing. *Scientific Reports*. **9**, 4070.

Journal Paper: Leung, C.L.A., Marussi, S., Towrie, M., Atwood, R.C., Withers, P.J., Lee, P.D., [2019]. The effect of powder oxidation on defect formation in laser additive manufacturing. *Acta Materialia*. **166**, 294-305.

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Journal Paper: Ali, H., Ghadbeigi, H., Mumtaz, K., [2018]. Processing Parameter Effects on Residual Stress and Mechanical Properties of Selective Laser Melted Ti6Al4V. *Journal of Materials Engineering and Performance*. **27** [8], 4059-4068.

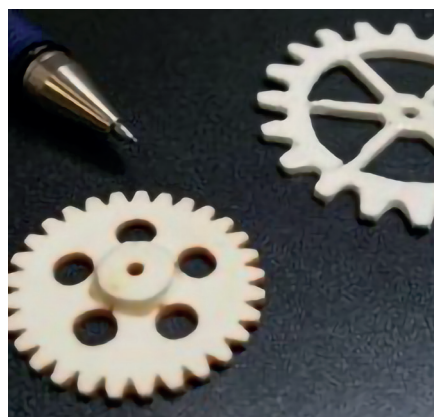
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Feilden, E., et al. [2017] 3D Printing Bioinspired Ceramic Composites. *Scientific Reports*. **7**, 13759.

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Comment: Todd I., [2018]. Metallurgy: Printing steels. *Nature*. **17**, 13-14.

Journal Paper: Ali, H., Ghadbeigi, H., Mumtaz, K., [2018]. Effect of scanning strategies on residual stress and mechanical properties of Selective Laser Melted Ti6Al4V. *Materials Science & Engineering A*. **712**, 175-187.

Journal Paper: Feilden, E., Ferraro, C., Zhang, Q., García-Tuñón, E., D'Elia, E., Giuliani, F., Vandeperre, L. & Saiz, E., [2017]. 3D Printing Bioinspired Ceramic Composites. *Scientific Reports*. **7**, 13759.

Comment: Todd I., [2017]. Metallurgy: No more tears for metal 3D printing. *Nature*. **549**, 342-343.

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Journal Paper: Tamas-Williams, S., Withers, P.J., Todd, I., Prangnell, P.B., [2017]. The Influence of Porosity on Fatigue Crack Initiation in Additively Manufactured Titanium Components. *Scientific Reports*. **7**, 7308.

Journal Paper: Mousavi, T., Hong, Z., Morrison, A., London, A., Grant, P.S., Grovenor, C., Speller, S.C., [2017]. A new approach to fabricate superconducting NbTi alloys. *Superconductor Science and Technology*. **30**, 9, 094001.

Journal Paper: Tamas-Williams, S. & Todd, I., [2017]. Design for additive manufacturing with site-specific properties in metals and alloys. *Scripta Materialia*. **135**, 105-110.

Journal Paper: Zavala-Arredondo, M., Boone, N., Willmott, J., Childs, D.T.D., Ivanov, P., Groom, K.M., Mumtaz, K., [2017] Laser diode area melting [DAM] for high speed additive manufacturing of metallic components. *Materials & Design*. **117**, 305-315.

Journal Paper: Feilden, E., Giovannini, T., Ni, N., Ferraro, C., Saiz, E., Vandeperre, L., Giuliani, F., [2017]. Micromechanical strength of individual Al2O3 platelets. *Scripta Materialia*. **131**, 55-58.

FEATURED PUBLICATIONS

PAPER:

Effect of pre-emptive *in-situ* parameter modification on residual stress distributions within selective laser-melted Ti6Al4V components.

PUBLICATION:

The International Journal of Advanced Manufacturing Technology

AUTHORS:

Ali, H., Ghadbeigi, H., Hosseinzadeh, F., Oliveira, J., Mumtaz, K.

This paper demonstrates the need for Selective Laser Melting (SLM) systems to develop processing parameters that can be adapted during builds.

Being able to react 'on the fly' would bring many benefits and help lead to right first time manufacturing.

The paper shows how temporarily switching to an increased layer thickness during the build, below highly stressed regions, redistributed stresses and reduced the overall stresses within the structure.

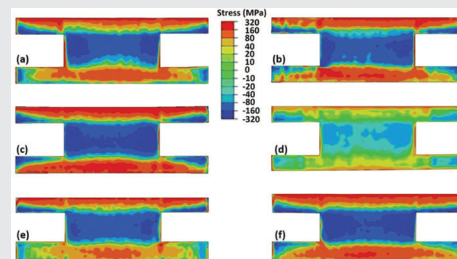
This temporary switching from standard build parameters to those known to assist in redistributing or reducing stresses would be a key step in developing a more intelligent process.

This intelligent process would reduce build and in-service part failures by anticipating stresses and allowing an action to be taken to remedy them.

The paper states: "The effect of thermally induced residual stresses is not dynamically considered during a Selective Laser Melting (SLM) build; instead, it processes using invariable parameters across the entire component's cross-section.

"This lack of pre-emptive *in-situ* parameter adjustment to reduce residual stresses during processing is a lost opportunity for the process with the potential to improve component mechanical properties.

"This work demonstrates the need for current SLM systems to focus on developing a more intelligent processing architecture with parameters that adapt on the fly during a build, in order to manage residual stresses within the built structure."



"Comparison of residual stress (MPa), contour maps for various test cases a IB-1 (standard parameters), b IB-2 (75- μ m layer thickness for region 2 and region 4), c IB-3 (150 W power and 133- μ s exposure for region 2 and region 4), d IB-4 (570 $^{\circ}$ C bed pre-heating on Renishaw SLM-125 machine), e IB-5 (75- μ m layer thickness for region 1 and region 3) and f IB-6 (150 W power and 133- μ s exposure for region 1 and region 3)"

Ali, H., *et al.* Effect of pre-emptive *in-situ* parameter modification on residual stress distributions within selective laser-melted Ti6Al4V components. *Int J Adv Manuf Technol* **103**, 4467–4479 (2019) doi:10.1007/s00170-019-03860-6 .

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PAPER:

Additive manufacturing titanium components with isotropic or graded properties by hybrid Electron Beam Melting/Hot Isostatic Pressing powder processing.

PUBLICATION:

Scientific Reports

AUTHORS:

Hernández-Nava, E., Mahoney, P., Smith, C. J., Donoghue, J., Todd, I., Tammas-Williams, S.

This paper presents a novel methodology of processing titanium powder [Ti-6Al-4V] using a combination of Electron Beam Melting (EBM) additive manufacture [AM] and Hot Isostatic Pressing [HIP] processes.

HIP is used to create components with fine homogeneous microstructures. HIP processing uses cans that are welded to create a preform skin, which is then filled with powder to densify components to be HIPed. Finally, the skin is machined off to reveal the component beneath.

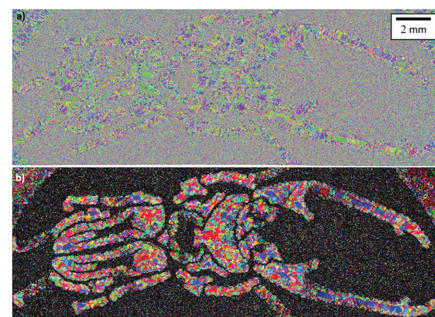
EBM is an AM process that creates near net shape components using metal powder that is fully melted by a concentrated beam of electrons.

The methodology discussed in the paper involves using EBM AM to generate a hollow preform filled with sintered powder, before HIPing to full density.

The authors report on the microstructure and mechanical properties of Ti-6Al-4V produced by this hybrid approach to manufacturing and contrast them with Ti-6Al-4V manufactured by standard EBM techniques.

The methodology has the following advantages:

- Improving production times by manufacturing skin and filling with powder simultaneously
- Improved yield and ultimate tensile strength when compared to standard EBM processed material
- An ability to generate material with site-specific properties and graded and/or homogeneous microstructures
- A decrease in build time - enhancing the commercial viability
- Avoids directional microstructures associated with variation of final properties of the product.



"Grain orientation data regarding the beetle capsule. (a) Room temperature α phase grain orientation information collected by EBSD from the beetle sample; (b) Initially solidified β microstructure reconstructed from, and at the same scale as, data in (a). Here, the build direction [z] is normal to the plane of the page."

Hernández-Nava, E., *et al.* Additive manufacturing titanium components with isotropic or graded properties by hybrid electron beam melting/hot isostatic pressing powder processing. *Sci Rep* **9**, 4070 (2019) doi:10.1038/s41598-019-40722-3.

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PAPER:

Single-operation, multi-phase additive manufacture of electro-chemical double layer capacitor devices.

PUBLICATION:

Additive Manufacturing

AUTHORS:

Fieber, L., Evans, J.D., Huang, C., Grant, P.S.

As the UK works towards its commitment to move to full electrification and zero-emissions vehicles this paper looks at additive manufacturing [AM] of energy storage devices.

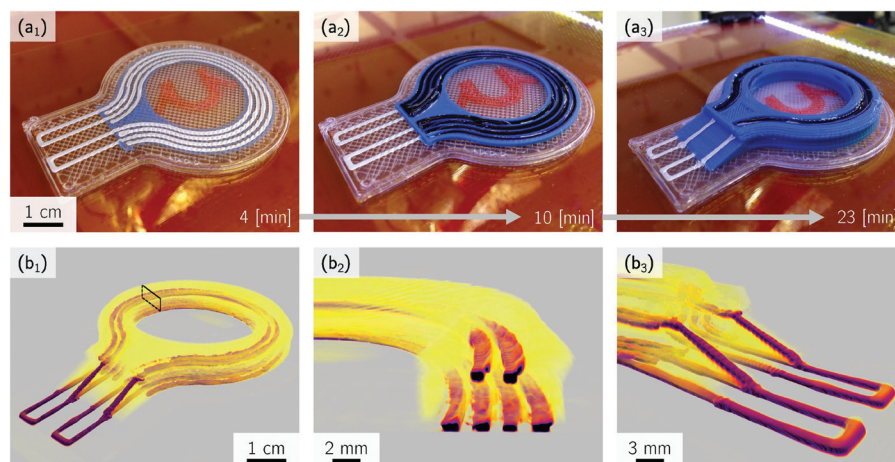
The benefits of AM in terms of energy storage devices such as batteries and supercapacitors have not been widely explored.

However, this paper shows AM of supercapacitors/EDLC's (electro-chemical double layer capacitors) is "feasible and attractive" in some areas.

The paper demonstrates a novel, single-operation manufacturing process to fabricate fully functioning supercapacitor/EDLC devices using a hybrid AM approach.

It describes the design of a hybrid-AM system, combining low-cost fused filament fabrication (FFF) and direct ink writing (DIW) techniques.

In FFF a thermoplastic filament is liquefied by heating in a print head, extruded through a nozzle and solidified upon deposition onto a temperature controlled building platform, eventually forming



the 3D part.

DIW is based on the micro-dispensing of materials as a viscous liquid ink through a small nozzle onto the building platform.

The paper states: "In the field of mass-market, ultra high area coated electrodes for conventional supercapacitor device fabrication it is unlikely that AM will be able to rival conventional manufacturing processes in terms of economic viability, throughput and efficiency."

It also points out that: "AM of energy storage devices may provide opportunities in new decentralized manufacturing solutions, with emphasis on material waste minimization and reduction in part specific tooling requirements."

"[a] Photographs of sequential manufacture and [b] XRT renders of 3D spatial arrangement of EDLC components. [a1] Housing base layer (FFF) and current collectors [DIW], [a2] electrodes [DIW] in cavities, [a3] stacking of printed EDLCs, [b1] complete device, [b2] cross section showing stacked EDLC cells and [b3] current collector bridge connecting stacked cells." Fieber, L., *et al* [2019]. Single-operation, multi-phase additive manufacture of electro-chemical double layer capacitor devices. *Additive Manufacturing* **28**, 344-353. <https://doi.org/10.1016/j.addma.2019.05.001> Attribution-NonCommercial-NoDerivatives 4.0 International [CC BY-NC-ND 4.0] (<https://creativecommons.org/licenses/by-nc-nd/4.0/legalcode>).

PAPER:

High temperature strength of an ultra high temperature ceramic produced by additive manufacturing.

PUBLICATION:

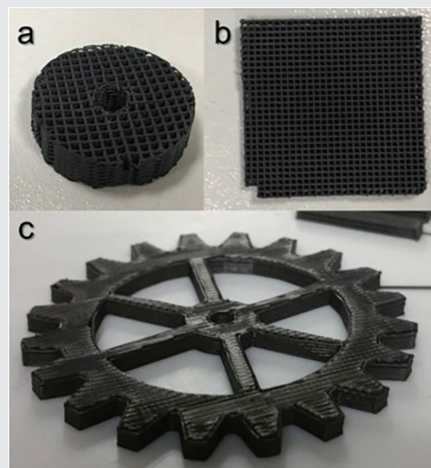
Ceramics International

AUTHORS:

Feilden, E., Glymond, D., Saiz, E., Van derperre, L.

This paper looks at the combination of ultra-high-temperature ceramics (UHTCs) and the additive manufacturing (AM) technique robocasting. UHTCs are a class of heat resistant ceramics that offer excellent stability at temperatures exceeding 2000°C.

They exhibit a combination of high thermal conductivity and high-temperature strength, making them candidates for thermal protective coatings for applications in space e.g. the leading edges of hypersonic and re-entry vehicles.



This research shows that hafnium diboride (HfB₂) with good mechanical strength and density can be produced via robocasting. Robocasting is a direct writing AM technique that deposits a continuous flow of paste material through a

"[a, b] Examples of parts with internal structure and [c] example of a complex shaped, dense part."

Reprinted from *Ceramics International*, **45** [15], Feilden, E., Glymond, D., Saiz, E., Van derperre, L., High temperature strength of an ultra high temperature ceramic produced by additive manufacturing, 18210-18214, Copyright (2019), with permission from Elsevier. <https://doi.org/10.1016/j.ceramint.2019.05.032>.

nozzle in three dimensions. Parts were printed with "complex shapes and internal structures not possible via conventional manufacturing techniques" and the properties – tested up to 1950°C – were in line with conventionally produced HfB₂.

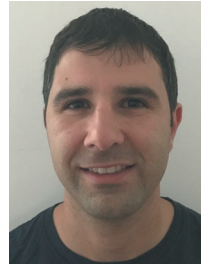
The paper's authors infer the results could be duplicated with many other UHTC materials, and discuss the advantages over traditional manufacturing methods for both prototyping and complex shape production. Advantages include allowing for complex shapes and internal structures, for example, cooling channels.

EXECUTIVE TEAM



**Professor
Iain Todd,
MAPP Director**

Iain holds a Royal Academy of Engineering GKN Aerospace Research Chair in Additive Manufacture and Advanced Structural Metallic Materials. 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 a number of industry partners including GKN, Rolls-Royce and Weir Group. Iain has led grants and research projects with a total value of £30M as PI. He is leading the activities to build powder manufacturing facilities within the Henry Royce Institute. He previously led the Mercury Centre at Sheffield, an ERDF supported activity which helped regional SMEs secure contracts worth >£7m and safeguarded/created 150 jobs. Iain is a Fellow of the Institute of Materials, Minerals and Mining. Iain leads the theme Additive Manufacturing [P2.1].



Dr Enzo Liotti

Enzo is a Departmental Lecturer in Processing of Advanced Materials at the Department of Materials, University of Oxford. His research focus on using and developing X-ray synchrotron techniques for the investigation of fundamental dynamic phenomena in metal processing and material science, with particular interest in solidification of metal alloys. He obtained his BSc [2004] and MSc [2006] in Material Engineering from the 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
Peter Lee**

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 Institute of Materials, Minerals and Mining and the Institute of Cast Metals Engineers. Peter leads the X1 research theme in MAPP – '*In-situ* Process Monitoring'.



**Dr Ali
Hassanpour**

Ali leads the Complex Systems and Processes research group at 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 publications. He is co-lead for the Powder Descriptors [P1.1] theme.



**Professor
Michael Preuss**

Michael's research focuses on microstructure, mechanical properties and residual stresses in high temperature materials – zirconium alloys, titanium alloys and nickel-base superalloys – for application in aerospace, oil and gas and nuclear sectors. Michael is Champion of the Materials for Demanding Environment Theme within The Royce Institute and deputy director of the Nuclear Rolls-Royce University Technology Centre (UTC) at Manchester. He has published almost 200 papers and is a Fellow of the Institute of Materials, Minerals and Mining. Michael leads the MAPP theme Functionalisation of Powders [P1.4].



**Professor
Eduardo Saiz**

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. Eduardo leads the theme Two Phase Powder Flow [P1.2].



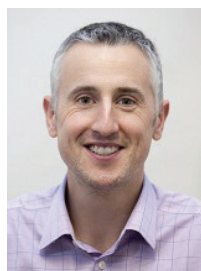
Professor Andrew Bayly, University of Leeds, is a chemical engineer with more than 20 years' experience in the development of particulate products and processes. He had significant experience in industry before moving to academia in 2013, including the position of Principal Scientist at Proctor and Gamble. 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. Andrew is co-lead for the Powder Descriptors [P1.1] theme.



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 Pro-Vice-Chancellor (Research) and Vesuvius Chair of Materials at Oxford University. His research takes place at the interface between advanced materials and manufacturing and concerns a wide range of structural and functional materials. His research uses variants of manufacturing techniques used in industry such as vacuum plasma spraying and field assisted sintering alongside in-house developed novel processes such as spray deposition of multi-suspensions and 3D printing of dielectric materials. Current applications include structured porous electrodes for supercapacitors and batteries, 3D printed materials with spatially varying electromagnetic properties for microwave devices, and advanced metallics for power generation. His research has been published in more than 200 research papers and eight patents. He is a Fellow of the Royal Academy of Engineering.



Dr Kristian Groom, University of Sheffield. Kristian graduated with an MPhys (1999) and a PhD (2003) both from the Dept. of Physics at The University of Sheffield. His 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 methodologies. He is currently 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 collaborative EPSRC Heteroprint project and via the EPSRC Future Photonics Hub. At the same time, he is 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, P2.2 Theme Lead. His 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, in particular, titanium 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 such as the FFC Process, FAST-*forge* and continuous rotary extrusion. Martin has more than 80 publications on manufacturing, was awarded a RAEng/EPSRC Fellowship in 2005 and the IOM3 Ti Prize in 2003. He works closely with industry partners such as VW, Rolls-Royce, Messier-Bugatti-Dowty, TIMET and DSTL.



Professor Visakan Kadirkamanathan, University of Sheffield, X3 Theme Co-Lead. Visakan is Director of Rolls-Royce University Technology Centre (UTC) in Control and Monitoring Systems Engineering. Visakan's primary area of research is in the field of signal and information processing, dynamic and spatio-temporal modelling, intelligent health monitoring and fault detection with applications in aerospace and biomedicine. He was awarded the PNAS Cozzarelli Prize (2012) and is the Editor-in-Chief of the International Journal of Systems Science. His research in manufacturing is focused on data analytics and informatics for process design, monitoring and prediction for additive and subtractive manufacturing processes.



Dr Chu Lun Alex Leung, University College London. He obtained his PhD in Material Science [University of Manchester, 2018] and MEng in Aerospace Materials [Imperial College London, 2010]. He specialises in the application of synchrotron and laboratory X-ray imaging techniques to study additive manufacturing (AM) processes. His role in the MAPP team is to develop and apply multi-modal imaging (e.g. optical, thermal and X-ray) and diffraction techniques for studying rapid solidification phenomena during AM. The aim of his research is to provide key insights into the fundamentals of AM and generate data for validating existing and developing new process simulation models.



Dr Candice Majewski, University of Sheffield. P2.3b Future Manufacturing Platforms – High Speed Sintering Theme Lead. Candice is a senior lecturer with almost 20 years' experience in the field of additive manufacturing [AM]. During her career to date, she has built up a large network of academic and industrial collaborators, focusing much of her research towards improving powdered polymer AM materials and processes in order to increase their potential for widespread industrial usage. As part of these activities, she manages the University's Advanced Polymer Sintering Laboratory. In 2011 she was awarded the International Outstanding Young Researcher in Freeform and Additive Manufacturing Award for her contributions in this field.



Professor Andrew Mullis, University of Leeds, P1.3 Theme Lead. His research focuses on advanced materials, particularly with regards to the solidification processing of metals far from equilibrium [rapid solidification]. He has published more than 130 papers on his theoretical and experimental research, studies of industrial process optimisation during powder production, the development of multi-scale models for the prediction of microstructure evolution in metals particularly during rapid quenching as would be experienced in metal atomisation processes. Andrew is a co-investigator on LiME, the EPSRC Future Manufacturing Hub in Liquid Metal Engineering. He is a Fellow of the Institute of Materials, Minerals and Mining.



Dr Kamran Mumtaz, University of Sheffield. P2.3a Future Manufacturing Platforms – 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, Faculty Director of Research and Innovation – Faculty of Engineering, X3 Theme Co-Lead. His 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. His 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 leading the development of the Sheffield wing of the Henry Royce Institute and is the principal investigator on the EPSRC DARE project [Designing Alloys for Resource Efficiency – a Manufacturing Approach]. He is a winner of the IOM3 Rosenhain Medal and is a Fellow of the Royal Academy of Engineering. Mark has published more than 300 papers and is involved in >£40m of current grants. He co-directed the Mercury Centre with Prof. Iain Todd.



Professor Luc Vandeperre, Imperial College London, is Deputy Director of the Centre for Advanced Structural Ceramics [CASC] at Imperial College London. His work encompasses near net-shaping and processing of ceramics, their structural performance and modelling of their thermo-mechanical response. He has published more than 120 papers and works with industrial partners in the USA, Germany, France and the UK. Luc is a Fellow of the Institute of Materials, Minerals and Mining.



Dr Jon Willmott, University of Sheffield. Jon's Sensor Systems Research Group is part of the University's Advanced Detector Centre. They are able to grow novel semiconductor detectors and use them as the sensing element for novel thermal imaging and other optoelectronic devices. 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. In addition to optical, mechanical and electronic design skills, he also developed a fundamental understanding of metrology. Following more than a decade in industry, he moved to the University of Sheffield in 2015 with an EPSRC Established Career Fellowship.



Professor Philip Withers, University of Manchester, 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 co-directs the Manchester X-ray Imaging Facility [MXIF]. 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. Philip is X2 Theme Lead.

MAPP PDRA's:

Dr Daliya Aflyatunova	Dr Samuel McDonald
Dr Timothy Bigg	Dr Scott Notley
Dr Yunhui Chen	Dr Alec Shackleford
Dr Sam Clark	Dr Jo Sharp
Dr Wen Cui	Dr Rob Snell
Dr Iuliia Elizarova	Dr Ben Thomas
Dr Jabbar Gardy	Dr Rahul Unnikrishnan
Dr Oliver Hatt	Dr Siyang Wang
Dr Yi He	Dr Rhys Williams
Dr Yuze Huang	Dr Zicheng Zhu
Dr Ashfaq Khan	

MAPP-aligned PDRA's

Dr Felicity Freeman	Dr Minh Phan
Dr Bo Luo	Dr Nicholas Weston

MAPP-aligned PhDs

Hussam Abunar	Addhithya Ashok
Abdullah Alharbi	Kumar
Mohammed Alsaddah	Oliver Levano Blanch
Miguel Zavala-Arredondo	Elaine Livera
Alisha Bhatt	Alistair Lyle
Nick Boone	George Maddison
Matthew Boreham	Guillame Matthews
Ryan Brown	Maha T Omran
Florian Buschek	Ollie Osborn
Louise Chan	Sourabh Paul
Lev Chechik	James Pepper
Max Chester Jude	Tom Robb
Emmanuel	David Rees
Ben Evans	Leigh Stanger
Xianqiang Fan	Emmanouil
Kubra Genc	Stavrouakis
Adam Gothorp	Pawel Stuglik
Simon Graham	James Wingham
Abdul Haque	Kylee Yingwei Wu
Caterina Iantaffi	Jiaqi Xu
	Zhouran Zhang

MAPP PhDs

Mohamed Atwya	Oliver Leete
Cameron Barrie	Mozhdeh Mehrabi
Alex Goodall	Joseph Samuel
Guy Harding	Lorna Sinclair

MAPP Operations Team:

Jess Bamonte
Project Administrator
Dr Richard France
Senior Business Development Manager
Danielle Harvey
Marketing and Communications Officer
Elinor Noble
Project Administrator
Karen Wood
Project Manager

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 and Indian Institute of Science. Prof. Llorca, a Fulbright scholar, is Fellow of the European Mechanics Society and member of the Academia Europaea and has received the Research Award from the Spanish Royal Academy of Sciences. 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 – supported by an Advanced Grant from the European Research Council – are focused in the development of multiscale modelling strategies to carry out virtual design, virtual processing and virtual testing of metallic materials, including the experimental validation at different length scales, so new alloys can be designed, tested and optimised *in silico* before they are actually manufactured in the laboratory.



The Scientific Advisory Board (SAB) brings together a group of international and independent researchers in fields closely related to MAPP's objectives.

The role of the SAB is to independently appraise and advise on the academic research programme and impact activities, within an international context, and help develop MAPP's international profile and links.



Professor Jin Ooi,
University of Edinburgh

Jin received B.Eng.[Hons.] degree from The University of Auckland and a PhD degree from The University of Sydney. He is currently the Professor of Particulate Solid Mechanics and the Director of Civil and Environmental Engineering at Edinburgh and holds a Qiushi Chair Professor position at Zhejiang University China. His principal research interests lie in the mechanics of particulate solids, from soils and rocks to many industrial powders and solids. He

has published extensively and is on the Editorial Board of the Canadian Geotechnical Journal and edited special issues in Powder Technology and Granular Matter. He co-founded 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 T-MAPPP European ITN Consortium on multiscale analysis of particulate processes, and the PARDEM ITN Project 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, where she received her M.S. degree in 1997 and her PhD degree in 2002, both in Industrial Engineering. 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 multi-material and high-preheating chambers and robotic laser metal deposition of large components in aluminium and titanium alloys.



Professor 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. Prof. 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 (ink jet printing). One key application field of his research is energy, for example, supported catalysts for H₂ production.

INDUSTRIAL

ADVISORY BOARD (IAB)



Dr Phil Carroll,
Chair IAB, Advisor

Phil founded LPW Technology Ltd (LPW), a market leader in the development, processing and supply of high-quality metal powders and innovative software solutions for the additive manufacturing (AM) industry, in 2007.

In 2018 Carpenter Technology Corporation acquired LPW. Carpenter Additive have facilities dedicated to AM across the world. From metal ingot, to atomisation, to final built parts- they

have facilities that support every stage of the AM journey, with data-driven solutions that optimise performance along the way.

Passionate about metal powders and their central importance throughout the AM process, Phil is an advocate of focusing on AM applications from the perspective of the powder.

His vision and ambition have led LPW to win numerous awards, including the Queen's Award for Export 2016 and the European Business Awards Ruban d'Honneur for Import/Export 2017.



Marko Bosman,
Chief Technologist Additive Manufacturing,
GKN Aerospace

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. He started in additive manufacturing in 2011 coordinating R&D and product implementations within Fokker. In his current role as Chief Technologist, he coordinates the global additive manufacturing developments of GKN Aerospace.



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,
Director of Technology, Xaar 3D

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 that has been licensed widely from small start-ups to global multinationals and is having a transformational impact on the additive manufacturing/industrial 3D printing industry.

In 2016 Neil left academia and became Director of 3D Printing at Cambridge based inkjet printhead manufacturer Xaar. He is now building a 3D printing equipment business – a joint venture called Xaar 3D owned by Xaar and Stratasys – based on one of his inventions, High Speed Sintering.



The Industrial Advisory Board (IAB) brings together senior figures from MAPP's industry and HVMC partners.

The board appraise and advise on the research programme to ensure the link to industry's longer-term challenges and advise on and help support the development and growth of MAPP,

including its leadership role within the national research and innovation landscape.

The IAB help MAPP to maximise the opportunities for knowledge exchange and ensure the Hub delivers impact for UK industry.



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 & 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 Tsoupanos,
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

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 an £80m turnover business.



Marc Saunders,
Director of AM Applications, Renishaw

Marc has more than 25 years' experience in high tech manufacturing. In previous positions at Renishaw, he played a key role in developing the company's award-winning RAMTIC automated machining platform and has also delivered turnkey metrology solutions to customers in the aerospace sector.

Marc's role is to accelerate adoption of metal AM by helping manufacturers to develop industrial AM processes. He leads Renishaw's global network of AM Solutions Centres, where customers can access innovative AM equipment and application engineering support. Marc is also responsible for process engineering, developing innovative processing techniques for new materials.

GET UP TO SPEED WITH STEM

MAPP researchers introduced schoolchildren to advanced powder processes at the Get Up To Speed with STEM event.

The annual event is held at Magna Science Adventure Centre, Rotherham, South Yorkshire, and is designed for young people to see some of the UK's most exciting science, technology and engineering inventions, and meet the people who design, build and operate them.

The MAPP stand gave attendees the opportunity to find out more about advanced powder processes, with hands-on activities, a quiz and an opportunity to win their school a special visit to the University of Sheffield.

Scores of pupils watched a 3D printer in action, tried out some 3D printing pens and spoke to PhD students and research associates about their work, how a 3D printer works and material properties.

Six months after the event the winning school visited the University of Sheffield for an Engineer Experience Day.

Year Ten Design and Technology pupils from Kirk Balk Academy, Barnsley, South Yorkshire, visited MAPP's Sheffield site in September.

Organised by MAPP Project Administrator Elinor Noble and supported by the University of Sheffield's Faculty of Engineering, the event gave pupils a chance to find out more about engineering, in particular, additive manufacturing [AM].

Dr Charis Bronze, Widening Participation Officer, Faculty of Engineering, University of Sheffield, opened the event with an introduction to engineering, including a fun exercise illustrating the importance of communication to engineers.

MAPP investigator Dr Kamran Mumtaz then gave a talk about AM, pitched perfectly for the audience, explaining AM and its uses. The talk led to lively discussion throughout the day about the future of AM, what AM can and cannot do and the cost of AM machines and materials.

The interesting talk included the use of the development of bicycles as an example of how engineers continually improve upon designs using new technology and a case study looking at the AM design of a Bugatti brake caliper.

The talk was followed by tours of two laboratories that carry out research in powders and processes.



MAPP academics, PhD students and colleagues explained what the Hub does and the capabilities of the AM machines in the laboratories. Students also had a chance to handle a wide range of items made on the machines.

The pupils were also taken on a tour of the University of Sheffield's Diamond building, a striking structure that is home to more than 5000 students from the Faculty of Engineering, state of the art laboratories and a student maker space.

The day closed with a fun Engineering Challenge Activity led by Dr Bronze. It was great to see the school children working together against the clock, using straws, paper and sticky tape, to build towers that would hold a small load without collapsing.

Elinor Noble said:

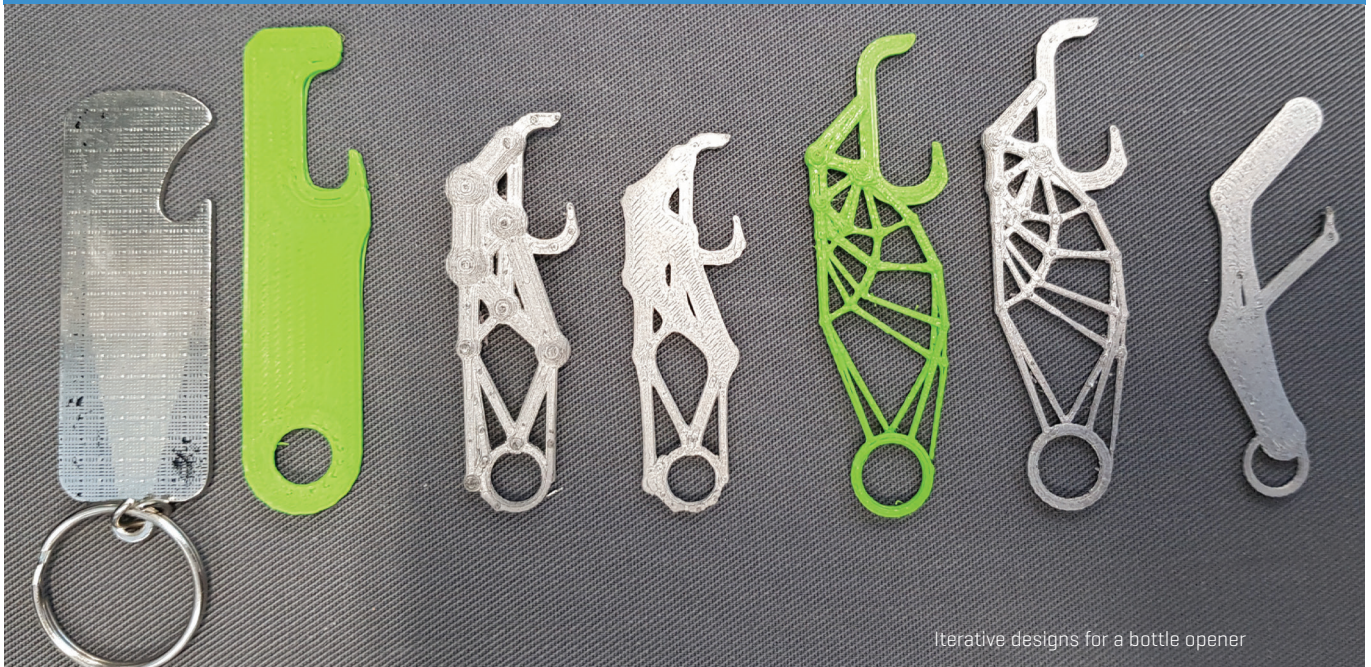
"The running of the event was supported by some of the University's fantastic Student Ambassadors. They answered a lot of interesting questions from the Kirk Balk pupils about studying engineering and University life.

It was great to meet all the pupils and their teachers and hear some of the young people's enthusiasm for AM."

WORK EXPERIENCE

PROJECT

To study the effects of reducing the amount of material in an item whilst retaining its strength and usability.



Iterative designs for a bottle opener

MAPP has been involved in a variety of outreach and engagement activities this year, some of these have been large scale like the 'Get Up to Speed with STEM' event in South Yorkshire which attracts many thousands of visitors each year, and some are more focused.

One of these was the hosting of a sixth form student on work experience for one day per week over a six month period.

MAPP researchers and colleagues from the Henry Royce Institute, Sheffield worked with Josh at the Royce Translation Centre (RTC). The pupil at Lady Manners School in Bakewell, Derbyshire, learned about advanced manufacturing machines, processes and materials.

He began by working with a technician John to understand how some of the equipment worked and how to troubleshoot problems.

He went on to learn how to use Autocad software to design several items and became so proficient in its use he was able to transfer his new knowledge to his A level project work.

Josh was set a project to study the effects of reducing the amount of material in an item whilst retaining its strength and usability.

The item of choice was a bottle opener which he designed and prototyped on a desktop 3D printer.

Then during his full week on-site in June he spent time learning how to use the Desktop Metal System and went on to print his designs in 316L stainless steel material.

The photograph above shows how much material he was able to remove from the design – and testing showed that they all still work.

Josh said: "I liked that the learning process of how to use the machines was not like at school, although I learnt about what they do at the RTC, and about all of the machines there, I was mainly working on a project where I learnt how to use a new piece of software from civil engineering.

"I had the chance to experiment with the software to see how it could be used for smaller-scale 3D Printing on their Desktop Metal systems. In this project, I used iterative design to design and manufacture a key chain bottle opener using this software.

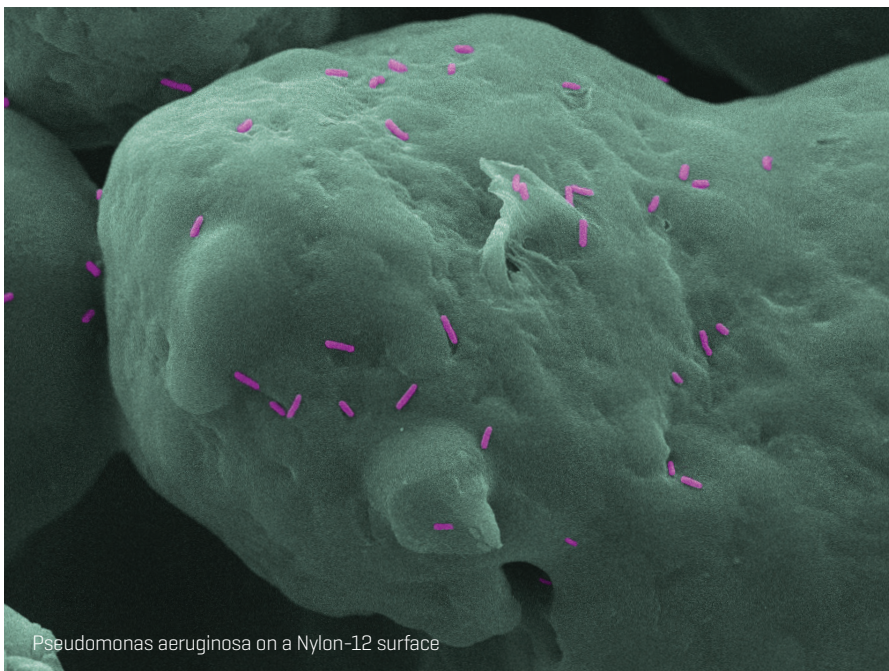
"I also felt pleased that I was then able to share what I had learned with the researchers there. I'm really grateful for the opportunity and would especially like to thank Dr Rob Deffley for his support."

WHEN THE DRUGS DON'T WORK...

MANUFACTURING OUR PATHOGEN DEFENCES

ONE OF MAPP'S ALIGNED PROJECTS

In 2018 the Engineering and Physical Sciences Research Council (EPSRC) announced support for 28 pioneering new research projects - including one led by MAPP Investigator Dr Candice Majewski, University of Sheffield.



A one year investigation into the incorporation of anti-bacterial properties into parts manufactured by powdered-polymer additive manufacturing (AM) processes.

'When the Drugs Don't Work... Manufacturing our Pathogen Defences' was a one year investigation into the incorporation of anti-bacterial properties into parts manufactured by powdered-polymer additive manufacturing (AM) processes. Whilst the requirements for AM parts often tend to be focused around geometric complexity and mechanical properties, this project provided an opportunity to incorporate additional functionality. With increasing numbers of bacteria becoming resistant to antibiotics, the ability to produce objects with inherent anti-bacterial properties could help reduce or prevent the spread of infection under certain circumstances.

Silver has been known for its anti-microbial properties for millennia, and is often used in medical applications such as for wound dressings or as anti-bacterial coatings. In this project the team were able to incorporate a silver-based

compound, in this case a silver phosphate glass, into an existing polymer material (Nylon-12) for powdered-polymer AM. Parts produced using the resultant composite material were shown to demonstrate anti-bacterial properties under certain conditions. Crucially, the incorporation of the silver-based compound showed no negative influence on ease of processing or on part strength, meaning parts should be interchangeable for situations in which the original Nylon-12 material has proved suitable.

Moving forward, Doctoral Researcher James Wingham is continuing his PhD studies in this area, and the original team are investigating appropriate sources of funding to investigate a broader range of materials and to fully understand the conditions under which this approach will be effective.

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



DAM and AIRLIFT

MAPP is part of two ground-breaking collaborative additive manufacturing (AM) research programmes, AIRLIFT and DAM.

The University of Sheffield is pooling the knowledge of world-leading experts from across its Faculty of Engineering, Advanced Manufacturing Research Centre (AMRC) and MAPP to partner in the £33m projects which will focus on new technologies and Industry 4.0 processes to revolutionise product design in the aerospace industry

Meso-structure produced using additive manufacturing technologies offer unique design freedom enabling complex designs where additional functionality has been integrally built into a part that traditionally only had a mechanical function.

Combining this with the development of additive manufacturing capability towards right first time production through improved simulation, control and machine robustness will lead to a step change in manufacturing.

One of the main challenges faced by the aerospace industry is the environmental impact, so a key focus for the sector is the development of technologies that will reduce this impact from cradle to grave. Businesses throughout the supply chain are investigating:

- Methods of lightweighting components to make aircraft more fuel efficient and with future electrification in mind;
- Manufacturing techniques that are less resource intensive;
- Sustainability, through the use of alternative and recycled materials.

DAM (Developing Design for Additive Manufacturing) is a £14m programme aimed at developing the next generation of design tools and methods for additive manufacturing using a data driven, material centric approach.

AIRLIFT (Additive Industrialisation for Future Technology) is a £19M technology industrialisation programme that uses Industry 4.0 and simulation competencies to enhance both laser metal deposition with wire (LMD-w) and powder bed AM technologies.

DAM and AIRLIFT are intrinsically linked together and complement each other; with DAM developing the process and AIRLIFT developing the capability to manufacture the final product. The projects are focused on making AM serial production ready at high rates and exploring how AM can revolutionise product design for high-value, high-complexity product manufacture.

The consortium includes academics and engineers from Sheffield's Departments of Materials Science and Engineering, MAPP EPSRC Future Manufacturing Hub and the Henry Royce Institute, Sheffield, Automatic Control and Systems Engineering, and Electronic and Electrical Engineering for DAM, and brings in experts from the Advanced Manufacturing Research Centre (AMRC) for AIRLIFT.

MAPP Director Professor Iain Todd, GKN/ Royal Academy of Engineering Research Chair in Additive Manufacturing and Advanced Structural Metallics at the University of Sheffield, said: "It's not uncommon for our departments to work together to solve research problems.



GKN AEROSPACE

"Our ability to provide the expertise, skills and resources needed to address current and future manufacturing issues, all within the same institution, makes us the ideal partner for businesses, like GKN Aerospace, who want to lead the way in sustainable manufacturing."

The technology developed in these projects will be applicable across a range of aerospace applications, from engine components to aerostructure parts.

DAM and AIRLIFT also involve industrial partners Autodesk, Siemens Digital Industries Software and CFMS (The Centre for Modelling and Simulation). Forty highly specialised engineers and operators from universities, research institutes and industry will work together on the programmes, which will be based out of GKN Aerospace's recently announced £32m Global Technology Centre in Bristol.

Russ Dunn, CTO and Head of Strategy, GKN Aerospace said: "AM is a strategic technology for the Aerospace Industry that will fundamentally change the way we design and manufacture aircraft. AM enables us to control material characteristics enabling benefits in terms of product performance, cost and environment. With AIRLIFT and DAM and the Global Technology Centre in Bristol, GKN Aerospace will further develop and industrialise additive manufacturing within the UK industrial and scientific eco-system. The Aerospace Technology Institute (ATI) is an incredibly valuable resource for UK aerospace and we are delighted they are supporting this project to help the UK stay at the forefront of this exciting and emerging technology as part of the UK's industrial strategy."

ALIGNED 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 - February 2021

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



FAST STEP 3 [Swarf Titanium to Engine Parts in 3 Steps]

Funder: Innovate UK

Funded value: £507,551

Funding period: March 2018 - February 2021

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



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 Recherche Procedes Applicat Lase, Höskolan 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 Automatizacija Y Mantenimiento Industrial Sa, Panepistimio Patron, Brunel University London, Prima Industrie S.p.A., ESI Group.



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.



Living Materials

Funder: ONRG

Value of award to the consortium: £400,000

Funding period: July 2018 - January 2022

Organisations: Cidetec, Imperial College London



OPTICON [Optical Infrared Coordination Network for Astronomy]

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

Funded value: £166,605

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 de Investigaciones Cientificas, Universiteit Leiden, First Light Imaging SAS, Office National D'etudes et de Recherches Aerospatiales, 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.



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



VULCAN

Funder: Innovate UK

Funded value: £267,650

Funding period: January 2020 - December 2021

Organisations: The University of Sheffield, Wayland Additive

ALIGNED PROJECTS

COMPLETED PROJECTS



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], Cavitat 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 Rixson, ArcelorMittal, Timet Ltd, Rolls-Royce PLC, Safran, Sheffield Forgemasters Engineering Ltd



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



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



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



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



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



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



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



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



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



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

Image: Al₂O₃ net similar to those discussed in Elizarova, I.S., Vandeperre, L., Saiz, E., (2020). Conformable green bodies: Plastic forming of robocasted advanced ceramics. *Journal of the European Ceramic Society*. **40** [2], 552-557.



Imperial College
London

