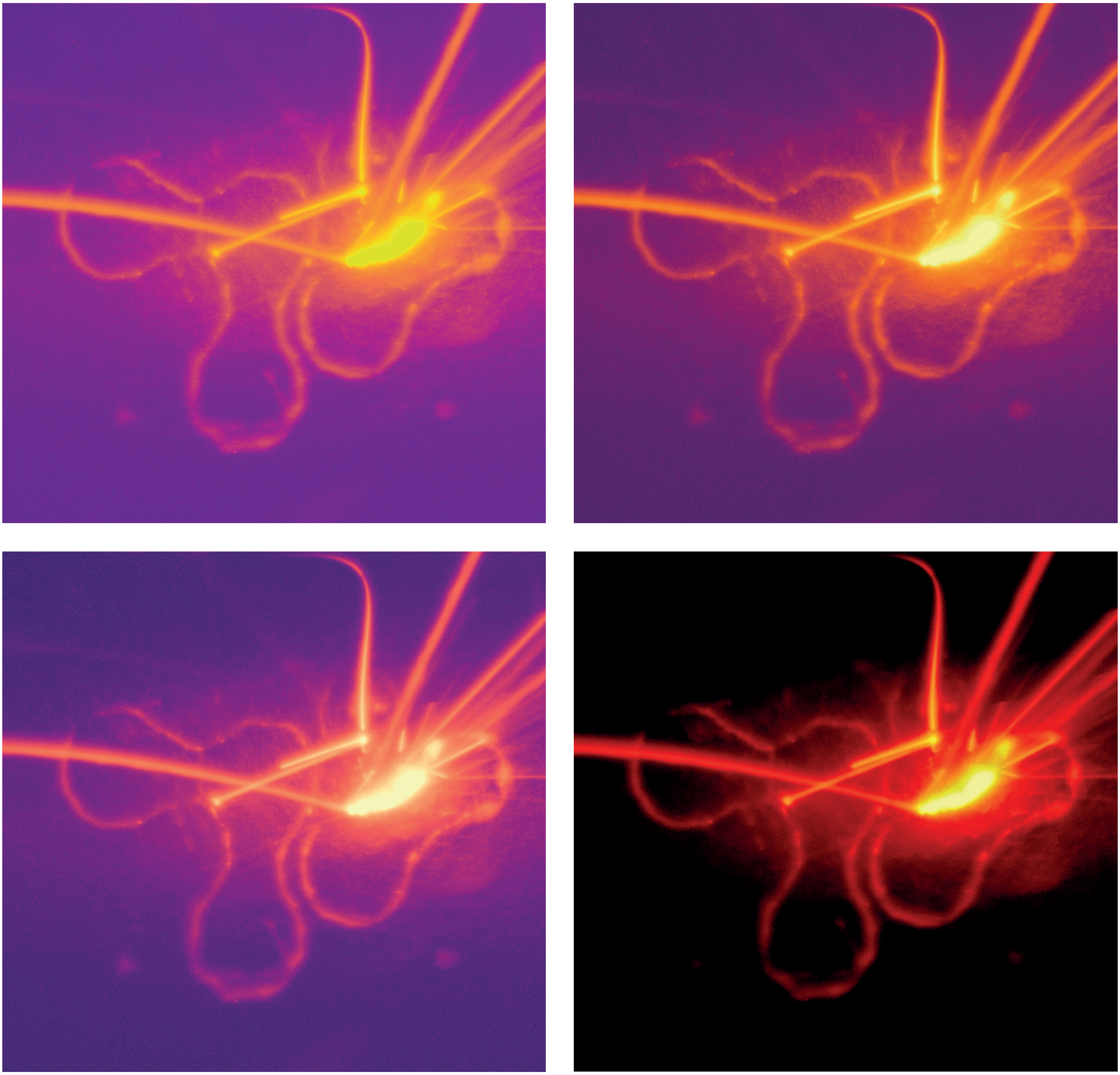
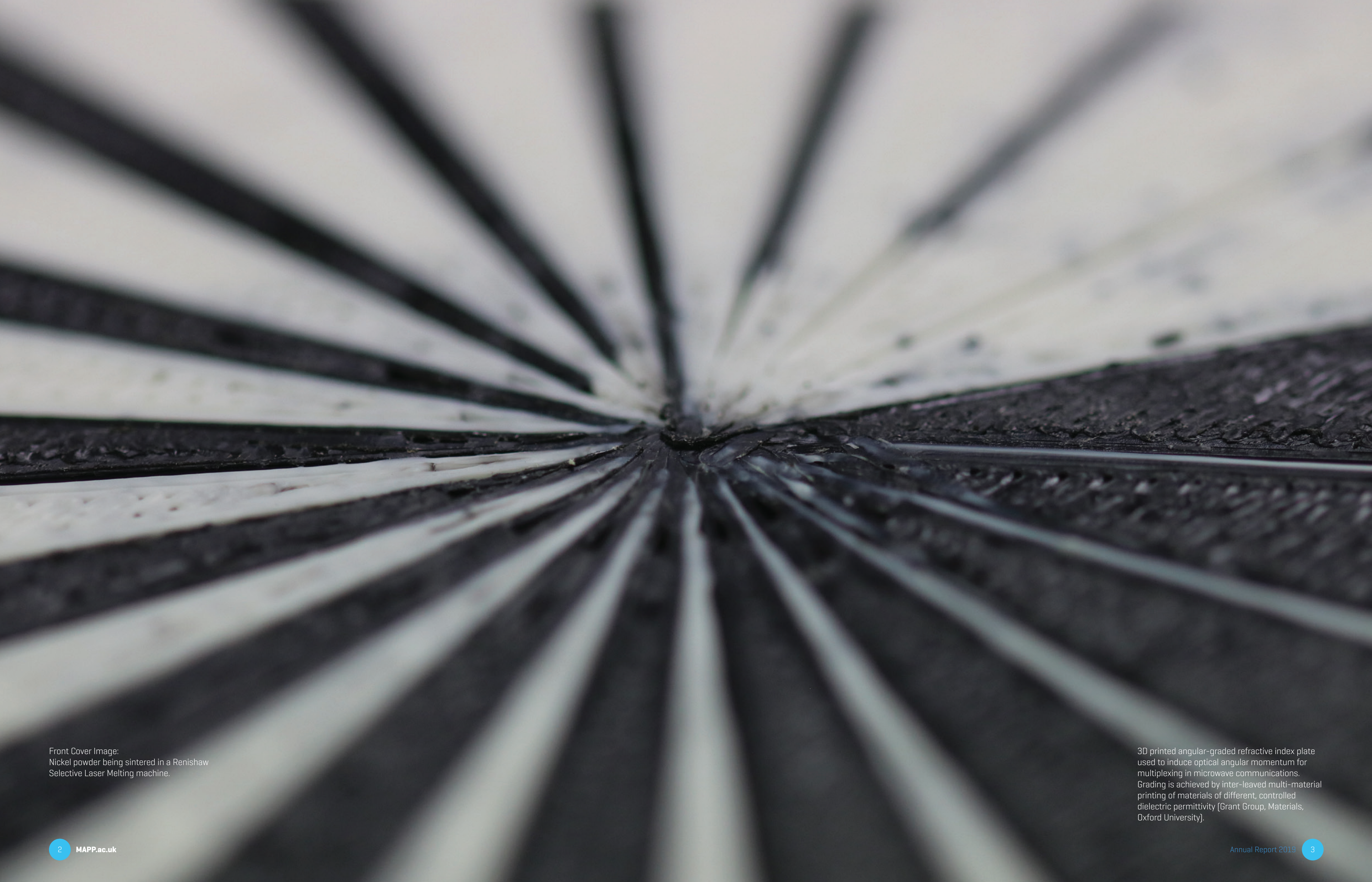
MAPP Annual Report 2019

Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub



EPSRC Engineering and Physical Sciences Research Council
The University Of Sheffield.
Imperial College London
UNIVERSITY OF LEEDS
MANCHESTER 1824 The University of Manchester
UNIVERSITY OF OXFORD
UCL



Front Cover Image:
Nickel powder being sintered in a Renishaw Selective Laser Melting machine.

3D printed angular-graded refractive index plate used to induce optical angular momentum for multiplexing in microwave communications. Grading is achieved by inter-leaved multi-material printing of materials of different, controlled dielectric permittivity (Grant Group, Materials, Oxford University).

CONTENTS

WELCOME

Welcome to our second annual report. It has been another busy and successful year for the MAPP EPSRC Future Manufacturing Hub and we are delighted to be able to share some of our successes with you here.

In March 2018, MAPP announced its first round of feasibility funding to UK academics eligible for EPSRC funding. We received some excellent applications from across the UK academic community and our Scientific Advisory Board were part of the selection process which sees us now working with potential new collaborators from institutions and industrial partners new to our network.

Professor Iain Todd
MAPP Director

In September we hosted the third Alloys for Additive Manufacturing Symposium (AAMS). This proved to be another successful event for MAPP with more than 100 delegates and an outstanding set of speakers and defining talks. You can read more about it later in the report.

We have continued with our well-attended speaker series this year too, inviting both academics and industrialists to come and share their innovative approaches to solving the issues facing us as engineers in powder processing.

There have been a wealth of new publications from across the partners and we are delighted that the groundbreaking work conducted within MAPP has featured in leading journals such as Nature, Nature Communications and Acta Materialia over the past year.

At the grass-roots level, our talented researchers are collaborating across the sites to deliver results in our cross-cutting themes. Exciting results are starting to emerge from these collaborations related to powder characterisation and process understanding some of which you will encounter in this report.

You may also notice that we have a new partner university this year. As Prof. Peter Lee has taken up a new position at University College London, the MAPP network has grown as we have made the move with him. The Diamond Light Source at Harwell continues to be under his direction. We do, however, retain Manchester as partners who continue to focus on advanced characterisation and HIP.

It's an exciting time for us here - I hope you enjoy reading about some of our highlights of 2018 and I look forward to continuing to work with you.

HEADLINE SUCCESSES

>150
Engagement incidences across a wide range of industry, academic and public events.

50
Collaborations strengthening our relationships with industry, academia and the High Value Manufacturing Catapult (HMVC).

>£6m
Further funding for aligned projects (total value £34m)

6
University Partners. University College London joined MAPP in 2018.

7
MAPP HVMC Partners

>£2m
Funding from our industry partners

57
Personal invitations to MAPP researchers as keynote/named speaker at conferences across the globe.

17
MAPP founding industry partners

30
Publications including Nature, Nature Communications and Acta Materialia.

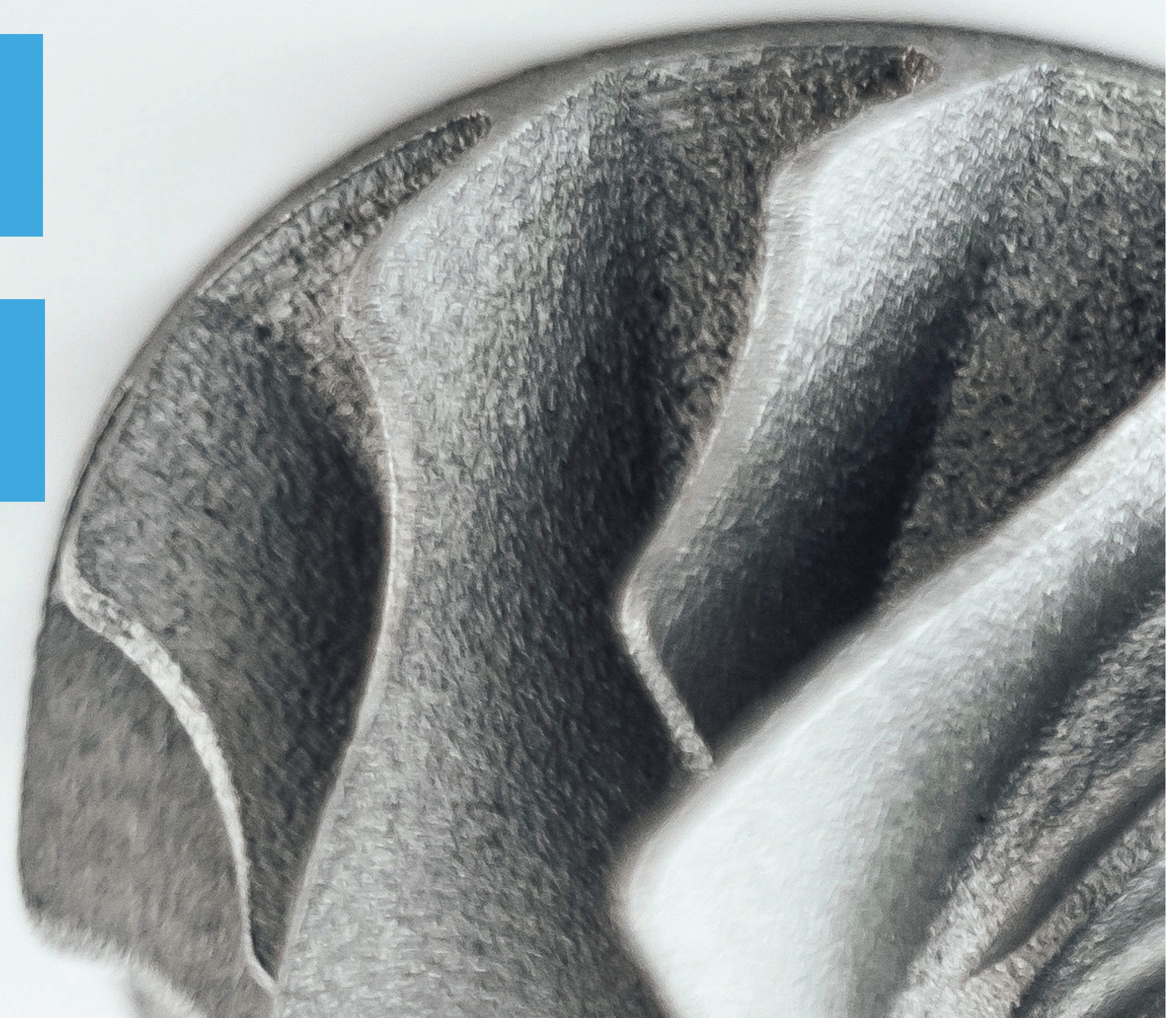
>400
Delegates engaging with MAPP events

The figures and information on this page relate to the time period January 2017 to March 2019.

Many new publications have contributed to our headline successes this year (see pages 25-27).

We have established new collaborations with a number of industrial partners, who have engaged with us in different ways.

The hub is growing its network, not only with new collaborative partners, but also more widely as our investigators lead on key research for the UK such as involvement in the Faraday Institution, the Henry Royce Institute and several EPSRC Programme Grants and Research Hubs.



FEASIBILITY FUNDING

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.

Our external Scientific Advisory Board formed part of the three stage evaluation process and the four successful applications are all now connected with MAPP and making great progress.

The successful applications (alphabetically) are:

- **Dr 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.'

RESEARCH PROGRAMME OVERVIEW

MAPP RESEARCH PROGRAMME UPDATE

CORE RESEARCH PROGRAMME

Our **Research Themes** are fundamental to understanding and delivering on our outcome promises to deliver on 'Right First Time Manufacturing' and 'Future Manufacturing Challenges'.

Platform Research Theme 1 – 'Powders by Design' enables us to understand the complexity in powder systems and develop a systems level approach to deepen understanding of their morphology and interaction.

Platform Research Theme 2 – 'Process by Design' encompasses various powder bed systems, developed through advanced processing, control and monitoring to ensure consistent performance and enhanced manufacturing rates.

PLATFORM RESEARCH

P1.1 Powder Descriptors

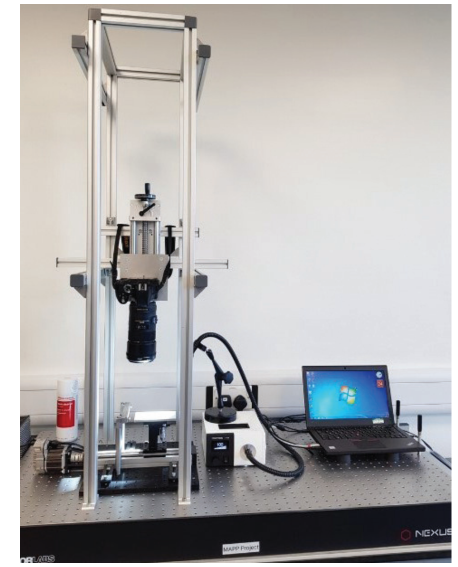
Leads – PI Prof. Andrew Bayly & Co-I Dr Ali Hassanpour, University of Leeds

Collaborators – Sheffield [X3/X2], Manchester, Imperial, UCL [DLS] [X1]

Powders produced for additive manufacturing processes typically have a wide particle size distribution. 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.

This year has focussed on metal powders used in EBM (electron beam melting) and SLM (selective layer melting) 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 & 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 data.

The MAPP researchers at Leeds 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 will be calibrated and applied to the study of particle behaviour during powder spreading in additive manufacturing.



The powder spreading experimental test rig

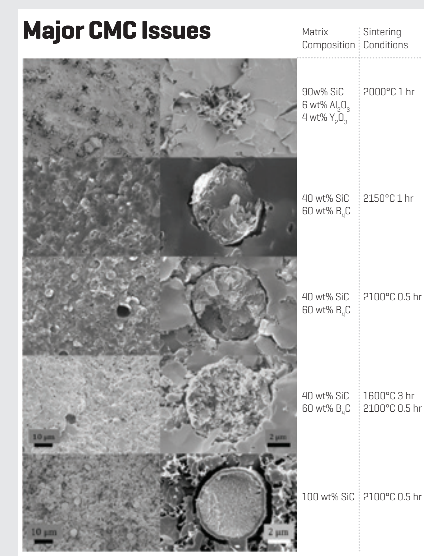
P1.2 Two Phase Powder Flow

Lead – Prof. Eduardo Saiz, Imperial College London

Collaborators – Oxford, Leeds, UCL [DLS] [X1] and Sheffield [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 have been manipulating ceramic pastes to show how robocasting can be used to build composite parts with a range of geometries. An early focus has been to study carbon fibre reinforced silicon carbide-based ceramic matrix composites (CMC). Key studies have included ways to manipulate fibre alignment and reduce the porosity; how to prevent degradation of the in-composite carbon fibre during sintering; and how to achieve more defined CMC printed structures.

Over the coming months the group will examine the fabrication of composites with continuous carbon fibre instead of milled fibre; investigate the printing of thermoelectric devices and will work with MAPP partners across the sites to look at real-time machine learning as assisted quality control of the printed structures.



P1.3 Heterogeneous Powders

Lead – Prof. Andrew Mullis, University of Leeds

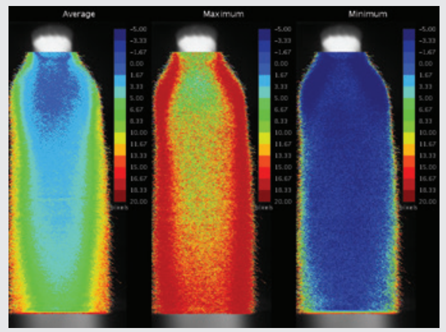
Collaborators – University of Sheffield, Royce@ Sheffield, industry

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.

Initial work has focussed on the development of 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 next phase of work will begin to use the tools being developed to characterise the effect of design changes to the melt nozzle and gas delivery system.



Heat maps showing average, maximum and minimum displacement of features within the melt plume as determined by tracking between consecutive frames shot at 16,000 fps.

P1.4 Functionalisation of Powders

Lead – Prof. Michael Preuss, University of Manchester

Collaborators – University of Sheffield, Imperial, University of Oxford

Hot isostatic pressing (HIPping) is a near net shape manufacturing route by consolidation and densification of metallic powder under high temperature and pressure in a canister that represents the final geometry of the component.

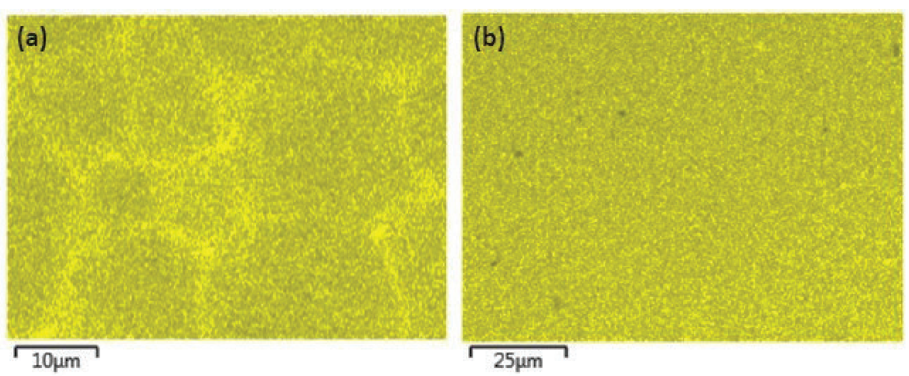
The high temperature and pressure result in a highly dense final product with reduced internal porosity thereby providing superior mechanical properties to a cast or forged component.

Recently there has been an interest in producing austenitic and low alloy steel reactor pressure vessel components using this method. But one of the major challenges with metallic powder is the pick-up of oxygen, which leads to oxide inclusions when considering materials with low oxygen solubility. Oxide inclusions are likely to reduce fracture toughness and hence oxygen pick-up needs to be kept to a minimum during powder handling and HIPping.

This project focuses on designing coatings to protect powders from oxygen pickup which will diffuse homogeneously into the bulk material during processing.

As a pilot experiment, Cr (chromium) was coated on 316L and SA508 alloy powders using plasma spherodiser and magnetron sputter instruments. Cr coating was found to homogeneously diffuse into the powder after complete HIPping. The coated powders have been characterised using electron microscopy and X-ray photoelectron spectroscopy to understand the quality of coating and the chemical state of the oxide layer to optimise the coating process. Also, a detailed microstructural characterisation is being carried out to study the effect of coatings on the oxide inclusions in HIPped product.

Future work will focus on studying the effect of Cr- coating on oxygen pick up on alloy powders.



SEM EDS map of Cr (Kα 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)

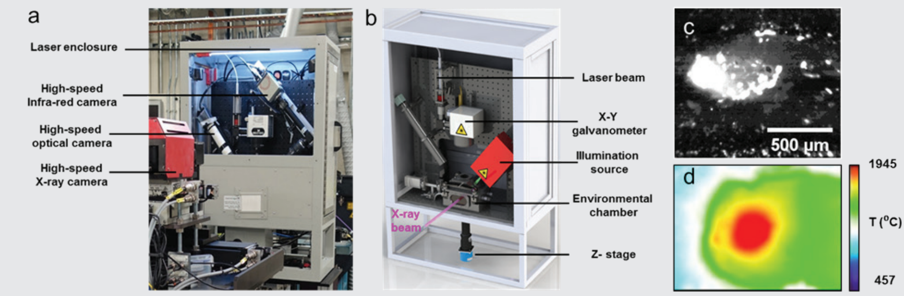
Lead – Prof. Iain Todd, University of Sheffield

Collaborators – University of Sheffield (X2 & X3), University of Manchester, UCL (DLS) (X1) and industry

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 at Sheffield have begun investigating 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 XCT to identify and classify defect populations and these 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 next phase of work will be the application of these insights and models to enable real-time control of the PBF process.



a) LAMPR installed at Diamond Light Source

b) CAD drawing of the system with high-speed optical imaging only.

c) A high-speed optical image

d) An IR image with temperature profile

P2.2 Process definition and control for FAST/SPS

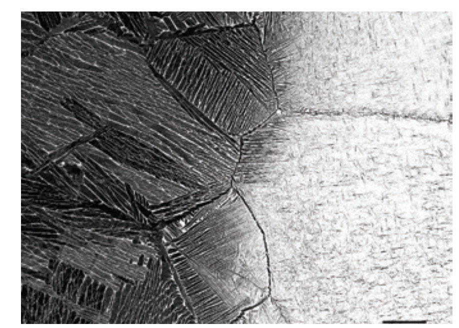
Lead – Dr Martin Jackson, University of Sheffield

Collaborators – University of Sheffield (X2) and (X3), University of Manchester, University of Oxford, UCL (DLS) (X1)

The development of Field Assisted Sintering Technology (FAST, also known as Spark Plasma Sintering) is being used for producing fully dense parts from high strength titanium and nickel based super alloys. Recent work has 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 researchers at Sheffield to produce a range of functionally graded parts.

Over the last year the MAPP team have increased the complexity of near net shape FAST parts using conventional metallurgical techniques. To further extend this, finite element modelling software (FEM) 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. This is a collaboration with electrical engineers to produce high speed, high response rate, high temperature measurement in FAST tools and samples using sapphire fibre optics. The FEM software, (COMSOL Multiphysics) will also allow the team to develop a bespoke FAST simulation application that can be shared between the relevant MAPP partners, enabling the current knowledge base to be shared widely.



FAST-DB demonstration parts. Dissimilar titanium alloys have been bonded through FAST. Tensile samples failed in the bulk of weakest alloy, not in the bonded region.

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 (P) activities to enable a deeper understanding that allows MAPP to deliver on outcome.

X1. *In-Situ* Process and Performance Characterisation

Lead – Prof. Peter Lee, University College London

Collaborators – University of Sheffield, Imperial, University of Leeds, University of Manchester, University of Oxford

Over the past year X1 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 imaging techniques, including X-ray (>10 kHz), Infra-red (>2kHz) and optical imaging (>10kHz). Additionally, the project aims 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.

Research is currently focusing on two types of LAM: (1) Laser powder bed fusion (LPBF) and (2) blown powder additive manufacturing (BAM). Data from material characterisation is underway following beamline experimental work at the Diamond Light Source.

Read more about X1 highlights on page 16.

X2 Advanced Characterisation

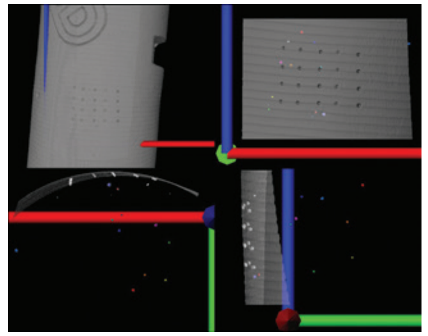
Lead – Prof. Mark Rainforth, University of Sheffield

Collaborators – University of Sheffield, Imperial, University of Leeds, University of Manchester

Researchers at Sheffield have been developing and employing advanced characterisation techniques to greater understand the detailed structure of pores within titanium after HIPping using X-ray tomography and focused ion beam.

Following the development of successful methodology for pore characterisation they are now looking at single particle, surface and bulk powder characterisation. Porosity studies of High Speed Sintered (HSS) parts have produced scanning data for analysis and further *in-situ* porosity characterisation is planned.

X-ray CT has been conducted for analysis of melt strategy geometry and post processing in pores for selective laser melting. Ongoing work will include CT of a wider range of materials and studying how the powder materials and their behaviour alters when subjected to various processes at very high resolution.



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

X3. Modelling, Optimisation and Control

Lead – Prof. Visakan Kadirkamanathan and Prof. George Panoutsos, University of Sheffield

Collaborators – University of Sheffield, University of Leeds, University of Manchester

In the X3 cross-cutting theme researchers 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 will be 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).

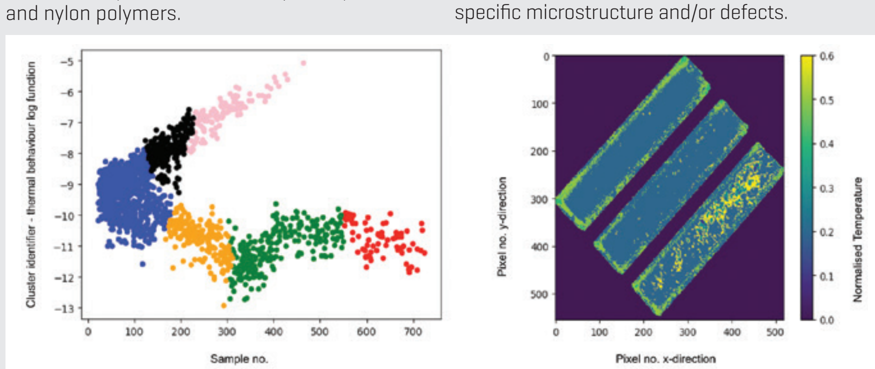
In the second year of the MAPP hub, X3 have been working on a range of processes, including Selective Laser Melting, Electron Beam Melting, and High Speed Sintering, and materials such as titanium alloy Ti64, Ni-based superalloy CM247 and nylon polymers.

Part of the vision of the MAPP hub, is through employing CI and ML methodologies to directly address the inevitable uncertainties that exist with these processing technologies which are relatively immature.

The abundance of process data that can be captured from our processes via real-time process monitoring, historical data, or *in-situ* monitoring provides enormous systems-based modelling opportunities.

For example, X3 developed last year, a multi-objective optimisation algorithm based on Gaussian processes for generating experimental designs for Selective Laser Melting.

Separately, while investigating Electron Beam Melting, they developed a new unsupervised learning method, achieving very efficient data use suitable for real-time monitoring. Thermal monitoring data was used, to demonstrate how X3 can capture and classify thermal behaviours during EBM. The thermal patterns captured were mapped onto 2D to reveal relevant regions of interest, potentially linking areas of the part to specific microstructure and/or defects.

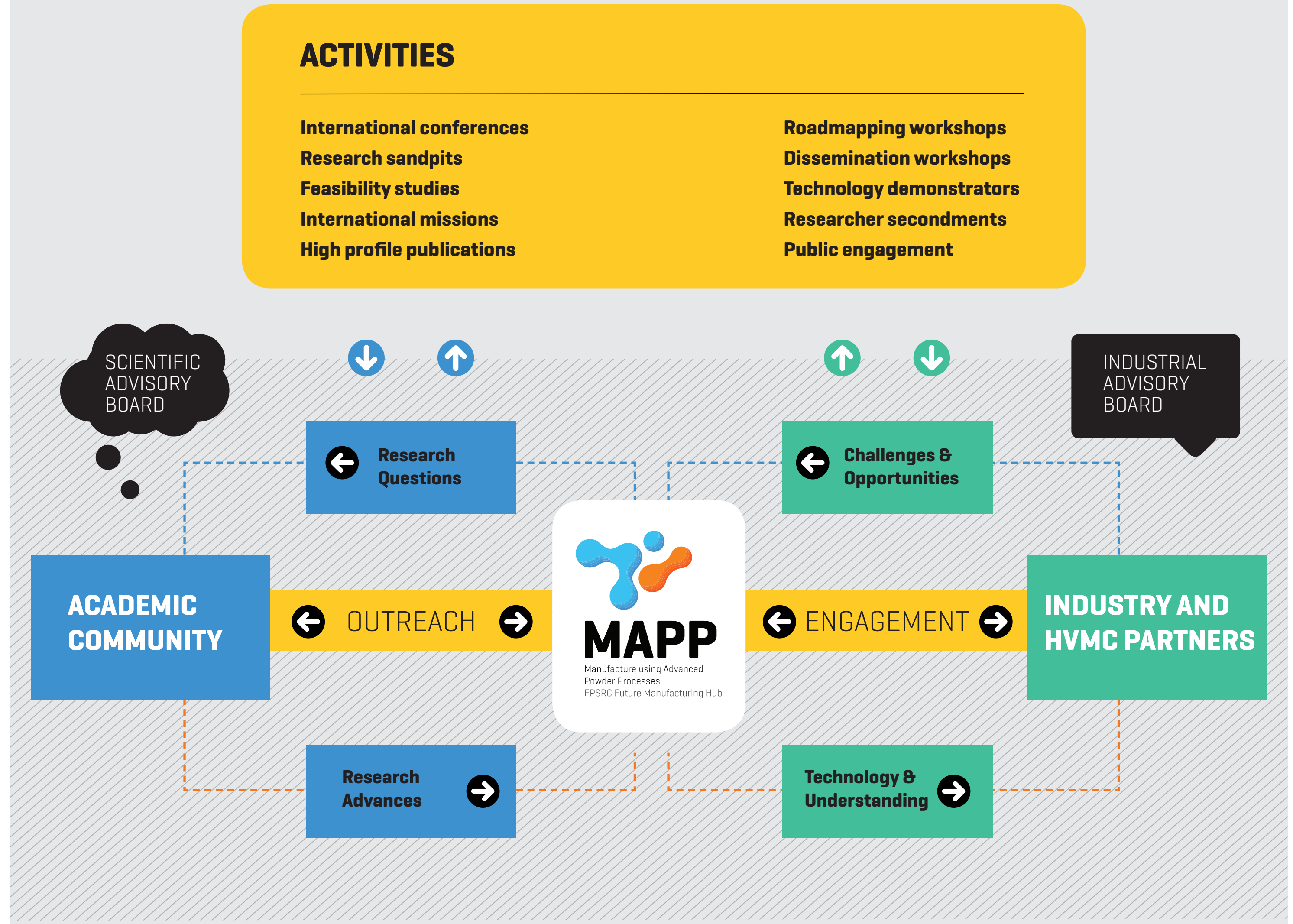


Electron Beam Melting, Ti64, thermal pattern detection

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.



MAPP PROJECT
ORGANISATION CHART

Industrial Advisory Board

MAPP Director
Prof. Iain Todd

Scientific Advisory Board

MAPP Operations Team

P1 Powders by Design

P1.1 Powder Descriptors
Lead Prof. Andrew Bayly, University of Leeds

P1.2 Two Phase Powder Flow
Lead Prof. Eduardo Saiz, Imperial College London

P1.3 Manufacturing Heterogeneous Powders
Lead Prof. Andrew Mullis, University of Leeds

P1.4 Functionalisation for Protection of Metal Powders
Lead Prof. Michael Preuss, University of Manchester

Co-Investigators

- Dr Finn Giuliani, Imperial College London
- Prof. Patrick Grant, University of Oxford
- Dr Candice Majewski University of Sheffield
- Prof. Luc Vandeperre, Imperial College London

P2 Process by Design

P2.1 Process Definition and Control for PBF in metal AM
Lead Prof. Iain Todd, University of Sheffield

P2.2 Process Definition and Control for FAST/SPS
Lead Dr Martin Jackson, University of Sheffield

Co-Investigators

- Dr Finn Giuliani, Imperial College London
- Prof. Patrick Grant, University of Oxford
- Dr Kamran Mumtaz, University of Sheffield
- Prof. Philip Prangnell, University of Manchester
- Prof. Eduardo Saiz, Imperial College London
- Prof. Luc Vandeperre, Imperial College London

X1 *In-situ* Process and Performance Characterisation

Lead Prof. Peter Lee, University College London

Co-Investigators

- Dr Finn Giuliani, Imperial College London
- Prof. Patrick Grant, University of Oxford
- Prof. Andrew Mullis, University of Leeds
- Prof. Michael Preuss, University of Manchester
- Prof. Iain Todd, University of Sheffield

X2 Advanced Characterisation

Lead Prof. Mark Rainforth, University of Sheffield

Co-Investigators

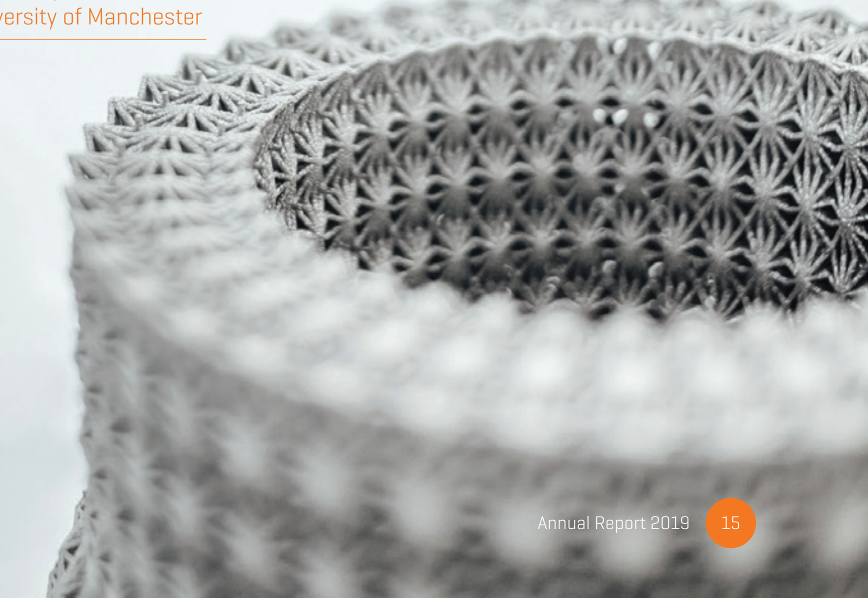
- Prof. Andrew Bayly, University of Leeds
- Dr Finn Giuliani, Imperial College London
- Dr Candice Majewski University of Sheffield
- Prof. Michael Preuss, University of Manchester
- Prof. Luc Vandeperre, Imperial College London
- Prof. Philip Withers, University of Manchester

X3 Modelling, Optimisation and Control

Lead 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



UNIVERSITY COLLEGE LONDON AT THE DIAMOND LIGHT SOURCE

X1: *In-Situ* Process and Performance Characterisation by Dr Chu Lun Alex Leung, MAPP PDRA

Lead – Prof. Peter Lee, University College London

Collaborators – University of Manchester, University of Sheffield, University of Leeds, Imperial College London, TWI, McMaster, Diamond Light Source, ESRF and the Central Laser Facilities

In 2018, the X1 team established key academic and industrial collaborations with a focus on accelerating new alloy development and process control for additive manufacturing, with a final goal of scaling up from synchrotron experiments to commercial component optimisation.

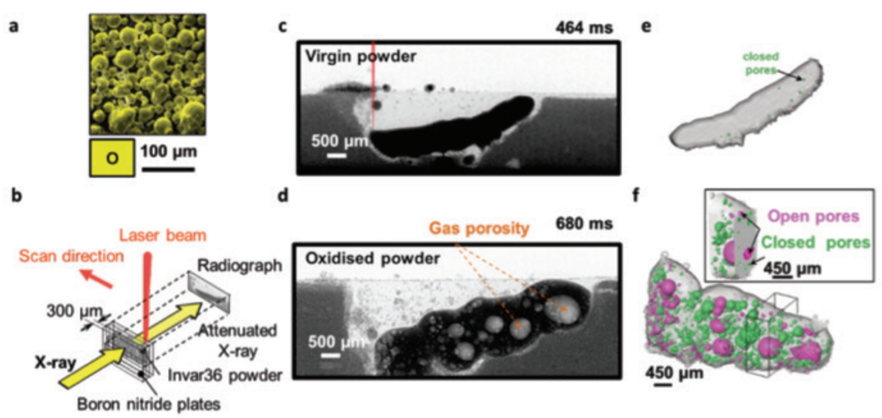
Both laser powder bed fusion (LBPF) and direct energy deposition (DED) experiments were performed.

These experiments revealed the complex molten pool and defect dynamics in LAM of SS316L, 13-93 bioactive glass as well as virgin and oxidised Invar 36 alloys. Our latest research revealed the mechanisms by which powder oxidation promotes porosity formation and spatter, degrading final component properties. The results suggest there is a maximum tolerable oxygen content in powder feedstock before the flow in the weld pool is reversed due to changes in the surface tension (termed Marangoni flow). For the DED project, we have successfully commissioned a DED process replicator, including customised laser optics and a 3-axes motion stage.

We have undertaken five major collaborative synchrotron imaging and diffraction experiments at Diamond Light Source and the European Synchrotron Radiation Facility, Grenoble, France, studying the underlying phenomena controlling the additive manufacturing of non-weldable alloys, polymers (UoS), ceramic (ICL), oxidised feedstocks (TWI), *in situ* alloying (McMaster) and during the DED of SS316L. Data analysis is underway for the aforementioned experiments.

Key highlights: We have successfully performed experiments with two brand-new LAM machines that enable X-ray, Infra-red, and optical imaging together with partners from Photron Ltd., UoS, and Oxford Laser ltd., respectively.

Automotive intercooler for formula student race car. Courtesy of Renishaw.



The impact of powder oxidation on AM revealed: (a) oxidised invar36 powder was examined by (b) high-speed imaging during LAM. X-ray images show the melt track produced by (c) virgin powder and (d) oxidised powder, and their corresponding XCT scans are shown in (e) and (f). [Reprinted from C.L.A. Leung et al. Copyright (2019) The effect of powder oxidation on defect formation in laser additive manufacturing. *Acta Materialia*. **166**, 294-305 with permission from Elsevier).

SPOTLIGHT ON CERAMICS AT IMPERIAL COLLEGE LONDON

Developments in robotic assisted deposition (robocasting) by Professor Eduardo Saiz, MAPP Executive

We have been working on the development of strategies to control the microstructure and properties of ceramic-based materials produced by robotic assisted deposition (robocasting).

This technique uses the continuous extrusion of a paste to build parts layer by layer following a computer design.

Different formulations can be used to design a paste or ink with the right viscoelastic response for the printing process.

This ink should flow through the printing nozzle and then hold the weight of the printed part.

We have developed pastes based on thermally reversible hydrogels containing anisotropic ceramic particles (fibers or platelets).

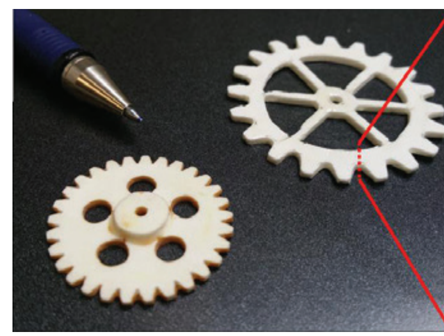
By manipulating the rheology of the pastes and the shear forces they experience during printing it is possible to control the orientation of the particles during the printing process.

In this way, we have been able to fabricate ceramic-based composites with unique, complex microstructures designed to guide crack propagation and promote fracture resistance.

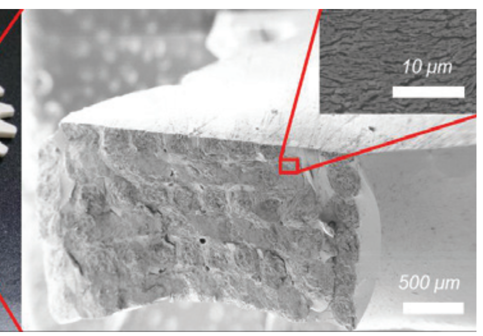
For example, we have aligned ceramic platelets in composites with microscopic Bouligand structures mimicking those of some biological composites. These structures can replicate some of the toughening strategies exhibited by natural materials, promoting simultaneous crack tilting and twisting.

The results open new possibilities on the design of light-weight, ceramic-based composites that will exhibit unprecedented combinations of strength and toughness.

Currently, we are working on extending the process to the fabrication of composites containing continuous fibres.



Photograph of composite parts produced from arbitrary CAD files to demonstrate the flexibility of the technique. Feilden, E. et al. (2017) 3D Printing Bioinspired Ceramic Composites. *Scientific Reports*. **7**, 13759.



SEM images showing the microstructure of the printed part. Feilden, E. et al. (2017) 3D Printing Bioinspired Ceramic Composites. *Scientific Reports*. **7**, 13759.

MAPP
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.

HIGH VALUE MANUFACTURING CATAPULT CENTRES

The University Of Sheffield. Advanced Manufacturing Research Centre — Boeing

AFRC — Advanced Forming Research Centre — University of Strathclyde

Catapult — High Value Manufacturing

cpi

mtc — Manufacturing Technology Centre

Nuclear AMRC

WMG — Innovative Solutions

INDUSTRY PARTNERS

Eastman

element six

freeman technology

GKN Aerospace

JM Johnson Matthey — Inspiring science, enhancing life

LPW Carpenter Additive

Maher

Metalysis

Morgan Advanced Materials

PSI

Renishaw — apply innovation™

Rolls-Royce

Safran Messier-Bugatti-Dowty

Seco

Weir

Xaar

Zeiss

UNIVERSITY PARTNERS

The University Of Sheffield.

Imperial College London

University of Leeds

Manchester 1824 — The University of Manchester

University of Oxford

UCL

MAPP HOSTS
INTERNATIONAL ALLOYS FORUM

By Dr Richard France, MAPP Operations Team

MAPP hosted the third Alloys for Additive Manufacturing Symposium (AAMS) in September 2018.

AAMS is a Europe-wide additive manufacturing (AM) symposium which has previously been hosted by the Max-Planck- Institut für Eisenforschung GmbH in Germany in 2016 and EMPA in Switzerland in 2017.

The two-day symposium brought together more than 100 international delegates from academia and industry to discuss recent research advances in metal AM across five themes: phase transformations in AM-produced alloys, alloy design, advances in processing, structural control by design, and novel concepts in alloy metamaterials.

The format of the symposium was a series of sessions focused around one of the themes, each session started with one or two invited keynote speakers followed by several shorter talks. The symposium included a poster session, which was well represented by early career researchers and PhD students.

Prof. Iain Todd, MAPP Director, welcomed delegates and gave some background to the event. He outlined his two hopes for the conference – that delegates see something new which stimulates a different viewpoint and that they find new collaborators from within and outside this growing community.

The keynotes were interesting and thought-provoking. They included:

Prof. Roger Reed from the University of Oxford presented a keynote entitled 'New Nickel-based Superalloys for AM by Alloys-By-Design Approach' in which he outlined some of the challenges and approaches to designing complex superalloys. Microstructure control during processing is the key challenge and many existing 'heritage' alloys are not appropriate for AM. The approach at Oxford, and the spinout company OxMet Technologies considers and optimises a number of design parameters, such as creep resistance, oxidation resistance and manufacturability, and uses high throughput techniques to screen and down select the most promising candidates. The team at Oxford has developed new generation Ni alloys which overcome problems such as lack of fusion and edge cracking in AM.

Dr Christopher M. Spadaccini from Lawrence Livermore National Laboratory (LLNL) gave a keynote entitled 'Additive Manufacturing and Architected Materials: New Process

MAPP Director Prof Iain Todd with the keynote speakers at Alloys for Additive Manufacturing Symposium (AAMS) 2018.

Front row left to right: Dr Blanka Szost, Additive Manufacturing Competence Centre (EU), OerlikonAM, Germany, Dr Eric Jägle, Max-Planck-Institut für Eisenforschung GmbH, Germany, MAPP Director Prof. Iain Todd, Dr Hector Basoalto, University of Birmingham.

Back row left to right: Professor Roger Reed, University of Oxford, Dr Christopher Spadaccini, Lawrence Livermore National Laboratory, Dr Phil Carroll, LPW Technology, Professor Eduard Hryha, Chalmers University of Technology, Gothenburg.

Development and Materials'. Design is now one of the bottlenecks in AM development and Chris showed work from LLNL on computer-driven optimisation of novel structures to tune component mechanical properties. Using these approaches the team were able to get into areas on Ashby Property Charts which were difficult to achieve by any other means, such as combinations of low density and high strength. Finally, Chris also showed some recent exciting work on polymer AM using holographic type approaches to photocure components in a volumetric approach, rather than a layer by layer approach, which could rapidly increase the speed of polymer AM.

Overall summary and conclusion

There were a lot of common themes throughout the event. One of the key messages emerging was a common approach to alloy development – starting with the screening of large numbers of potential new alloys *in silico* employing data and models, moving to small scale tests to predict likely behaviour in process and de-risk the development before moving to the (expensive) production of new powders. The link between experimental data and models is key to continuously improve and develop the predictive capability of the models. The link between chemistry and process is also critical and the ability to explore new processing windows with new materials is being enabled by some new, open and more flexible AM machines, and these approaches are essential to move the field forward.

The format of the event gave plenty of opportunity for networking and this coupled with the size of the symposium meant that delegates were able to talk to each other and forge new connections. The next AAMS event will be held in Gothenburg, the spiritual home of electron beam AM, and is scheduled for 18th & 19th September 2019.

SPOTLIGHT ON FAST AT THE UNIVERSITY OF SHEFFIELD

Developments in field assisted sintering technology (FAST)

MAPP researchers are at the heart of the latest developments in manufacturing using titanium alloys.

The Defence Science and Technology Laboratory (Dstl) in Porton Down announced in March 2018 it has revolutionised the production of titanium by reducing the 40 stage process down to just two steps and potentially halving the cost.

Titanium is as strong as steel and half the weight – but around ten times the cost. It is notoriously difficult and expensive to make which limits its wider use.

Titanium's high strength, light weight and corrosion resistance mean it is widely used in defence, in military aircraft and submarines, but its high production costs make it difficult to justify in all but essential areas.

Dstl has invested almost £30,000 in the new research project carried out in the Department of Materials Science and Engineering at the University of Sheffield, which led to the development of the new ground-breaking manufacturing process.

The pioneer of this revolutionary technique, MAPP aligned PDRA Dr Nicholas Weston, University of Sheffield, said:

"FAST-*forge* is a disruptive technology that enables near net shape components to be produced from powder or particulate in two simple processing steps. Such components have mechanical properties equivalent to a forged product.

"For titanium alloys, FAST-*forge* will provide a step change in the cost of components, allowing use in automotive applications such as powertrain and suspension systems."

The process gets its name from the Field Assisted Sintering Technology, which is used to produce a preformed billet, which are close to the size and shape of the finished part (near net shape), directly from titanium alloy powders before a single hot forging operation produces the final part.

So far, small-scale trials have been carried out, but a new large-scale fast furnace facility jointly funded by Dstl and Kennametal Manufacturing (UK) Ltd has been built and will enable larger components to be produced for testing.

By Dr Martin Jackson, MAPP Investigator

Field assisted sintering technology (FAST), also referred to as spark plasma sintering (SPS) or pulsed electric current sintering (PECS), enables a wide range of material powders - including ceramics, metals, and composites - to be rapidly sintered to high densities. This is often at lower temperatures, for shorter times, and with an improvement in microstructure and/or properties when compared to conventional sintering techniques.

Exciting possibilities also exist to produce functionally graded materials or directly manufacture components to near net shape.

FAST simultaneously utilises temperature and uniaxial pressure to achieve the rapid densification of powders. The temperature is achieved by applying a current directly through the material powder (and mould assembly), which creates Joule heating and enables higher heating rates to be achieved than in conventional sintering.

FAST has successfully sintered materials that were previously considered impossible to consolidate.

However, the underlying mechanisms occurring during the process that allows FAST to achieve these results are not fully understood.

One important objective of MAPP is to further characterise and understand these underlying mechanisms in a range of ceramic and metallic systems. This will aid in exploiting this fascinating technique and, working with industry partners, to develop innovative processes around the FAST technology.

One such process that has been shown to provide a competitive advantage over hot isostatic pressing (HIP) and/or conventional forging is the University of Sheffield invented FAST-*forge* process, which produces forged components from powder in two simple steps [1,2].

Metallic powder is shaped into a forging preform using FAST, followed by a one-step precision forge to improve the mechanical properties and fatigue performance of (in some cases) safety critical components for both the aerospace and automotive sectors.

Once seen as merely a research tool, today the majority of the investment into FAST is from industry, perhaps due to the fact that materials graduates are educating their seniors about this exciting manufacturing technology.

With FAST units becoming larger and semi-continuous in capability, the technology is sure to become the convention in a number of manufacturing sectors in the near future.

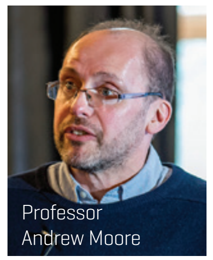
1. Weston, N.S., Derguti, F., Tudball, A., Jackson, M.,(2015). Spark plasma sintering of commercial and development titanium alloy powders. Journal of Materials Science. **50** (14), 4860–4878.
2. Weston, N.S., Jackson, M., (2017). FAST-forge – A new cost-effective hybrid processing route for consolidating titanium powder into near net shape forged components. Journal of Materials Processing Technology. **243**, 335–346.

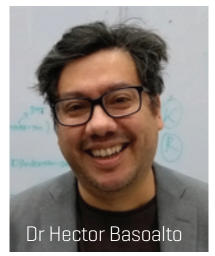
MAPP LECTURE SERIES

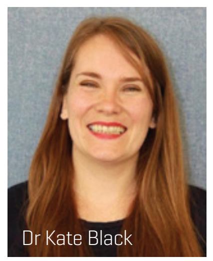
Dr Sarah Everton

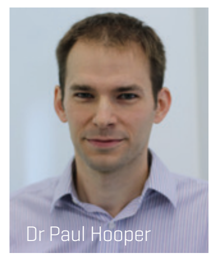
Director of MAPP, Professor Iain Todd said:

"The MAPP lecture series is providing a great opportunity for leading experts in our field to share their insights. We have had some fantastic talks this year."


Professor Andrew Moore


Dr Hector Basoalto


Dr Kate Black


Dr Paul Hooper

From metrology to Reactive Organometallic (ROM) precursors 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 more than 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 speaker.

Richard Leach, Professor of Metrology at the University of Nottingham, gave the inaugural talk in the MAPP Lecture Series in November 2017.

Examples of Information-rich metrology (IRM) in action in additive manufacturing (AM) were presented, including the measurement of form and texture, external and internal features, and post- and in-process metrology.

Dr Hector Basoalto, University of Birmingham, gave the second lecture in February 2018. He presented a multiscale materials modelling approach that aims to capture both the microstructural evolution and micromechanical fields and link these to the resulting macroscopic behaviour during selective laser melting (SLM).

Dr Kate Black, University of Liverpool, presented the third lecture in May 2018. The talk explored the use of Reactive Organometallic precursors to produce materials spanning metals, oxides and nitrides, which can be processed to print novel functional 2D and 3D materials.

The fourth lecture was given by Dr Paul Hooper, Imperial College London, in September 2018. The talk detailed the development of a high-speed temperature monitoring system for laser powder bed fusion and discussed opportunities and challenges for *in-situ* monitoring of AM processes.

In October 2018 Professor Andrew Moore, Heriot-Watt University, gave the fifth lecture which described detailed, in-process imaging of the interaction of the laser beam with the powder bed during the build of fully dense parts by laser powder bed fusion (PBF).

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. Currently, quantum sensing devices are large pieces of laboratory equipment with limited industrial applications. However, utilising the benefits afforded by AM, an order-of-magnitude reduction in size, weight and power requirement is plausible.

CENTRE FOR ADVANCED STRUCTURAL CERAMICS (CASC)

Imperial College London

Our partners are engaged in activities which support the wider MAPP network.

One example is the Centre for Advanced Structural Ceramics (CASC) Ceramic's Summer School, Imperial College London, which took place from Monday 10th to Wednesday 12th September.

The first day was focused on mechanical properties of ceramics and their use in Thermal Barrier Coatings and Solid Oxide Fuel Cells, with the talks of Dr Finn Giuliani, Imperial College London, Professor Ping Xiao, University of Manchester, and Professor Alan Atkinson, Imperial College London.

Members of the Additive Manufacturing Initiative for Transnational Innovation in Europe (AMITIE) visited on Tuesday 11th September when the day was focused on additive manufacturing.

There was a masterclass on the basics of additive manufacturing by Stephane Richaud, Saint Gobain, and Dr Andrea Zocca, Young Ceramists Additive Manufacturing Network, together with two lab sessions focused on 3D Printing and on the demonstration of some of the mechanical properties discussed on the first day.

The ninth edition of the Summer School finished with the invited talk of Dr Rachid M'Saoubi, SECO Tools, that gave some industrial examples of the use of ceramics.

Professor Eduardo Saiz, who sits on the MAPP Executive Team, is the director of CASC at Imperial College London and MAPP Investigator Professor Luc Vandeperre is CASC deputy director.

CASC ran its first ceramics summer school at Imperial College London in September 2010.

Read more in our next annual report about events at our other sites.


Some of the participants in the CASC Ninth Summer School

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. As noted earlier in the report 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.

At the University of Manchester, the Multidisciplinary Characterisation Facility represents one of the most extensive characterisation facilities in the UK and is able to provide:

· Multiscale imaging

· Correlative imaging

· Multidimensional imaging

MAPP also has the use of a range of equipment shared with Royce@Sheffield. 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's Advanced Manufacturing Campus.

Examples include:

Q20plus Electron Beam Melting - Arcam

The Arcam EBM® process is a powder-bed additive manufacturing process taking place in a vacuum and at elevated temperatures, enabling us to manufacture stress relieved components. The uniqueness of the equipment is based on the capability to manufacture much larger components, titanium alloys mainly, making it suitable for the production of aerospace, and structural materials.

Q10plus Electron Beam Melting - Arcam

Similarly to the Q20plus system, the Q10plus Arcam machine uses electron beam melting (EBM®)technology to manufacture stress relieved components. It is able to process smaller quantities of feedstock material and it is suitable for developing new titanium alloys like never before, where powder savings due to prototyping are essential.

Arcam Q10plus

Directed Energy Deposition System – BeAM Magic 2.0

BeAM Magic 2.0

Directed Energy Deposition (DED) is an AM process where focused thermal energy is used to fuse materials by melting them as they are deposited. In this system, a deposition nozzle mounted on the Z-axis of a DED dedicated CNC (computer numerical control) machine is used.

This allows continuous five axes of freedom to build/repair components layer by layer without the need for support structures.

Royce@Sheffield's BeAM Magic 2.0 is a blown powder AM machine.

Blown powder AM is commonly used by the aerospace sector to repair high-value components. The machine's capabilities include creating new alloys *in situ* so the properties of the deposited material can be changed during the build process.

Gas Atomisation-Arcast ATM DM 50

Gas atomisation produces spherical powders. It is used to manufacture high quality, technically advanced metal powders such as titanium, iron, copper, nickel and cobalt-based alloys.

Our atomiser incorporates induction melting capabilities to manufacture high-quality, technically advanced, metal powders from titanium alloys and highly reactive refractory metals.

It is used to develop new powders for AM industries for a diverse range of applications from aerospace to medicine.

Gas Atomisation-ATM DM 50

MAPP works closely with colleagues involved with Royce@Sheffield. As a founding university partner of the wider Henry Royce Institute, Royce@Sheffield is leading the advanced metals processing theme to accelerate the development and adoption of new materials systems to meet global challenges. Royce@Sheffield offers state-of-the-art facilities in a new purpose built Royce Translational Centre where their range of industrial grade machines are capable of delivering research activities spanning TRLs 1-6.

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 across Universities of Manchester, Oxford, Cambridge, Liverpool, Leeds, Imperial College plus the National Nuclear Laboratory and UK Atomic Energy Authority.

PUBLICATIONS

Demonstration artefact showing varying orientations of meso-structures.

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.

Journal Paper: Chen, Y., Han, P., Vandi, L.-J., Dehghan-Manshadi, A., Humphry, J., Kent, D., Stefani, I., Lee, P.D., Heitzmann, M., Cooper-White, J., Dargusch, M., (2019). A biocompatible thermoset polymer binder for Direct Ink Writing of porous titanium scaffolds for bone tissue engineering. *Materials Science Engineering: C.* **95**, 160-165.

Journal Paper: Pham, M-S., Liu, C., Todd, I., Lertthanasarn, J., (2019). Damage-tolerant architected materials inspired by crystal microstructure. *Nature.* **565**, 305-311

Journal Paper: Hancock, D., Homfray, D., Porton, M., Todd, I., Wynne, B., (2018). Refractory metals as structural materials for fusion high heat flux components. *Journal of Nuclear Materials* .**512**, 169-183.

Journal Paper: Leung, C.L.A., Marussi, S., Towrie, M., Val Garcia, J., Atwood, R.C., Bodey, A.J., Jones, J.R., Withers, P.J., Lee, P.D., (2018). Laser-matter interactions in additive manufacturing of stainless steel SS316L and 13-93 bioactive glass revealed by *in situ* X-ray imaging. *Additive Manufacturing.* **24**, 647-657.

Journal Paper: Bajaj, P., Wright, J., Todd, I., Jägle, E.A., (2018). Predictive process parameter selection for Selective Laser Melting Manufacturing: applications to high thermal conductivity alloys. *Additive Manufacturing.* Doi. org/10.1016/j.addma.2018.12.003

Journal Paper: Hancock, D., Homfray, D., Porton, M., Todd, I., Wynne, B., (2018). Exploring complex high heat flux geometries for fusion applications enabled by additive manufacturing. *Fusion Engineering and Design.* **136** (Part A), 454-460.

Journal Paper: Auger, M.A., Huang, Y., Zhang, H., Jones, C.A., Hong, Z., Moody, M.P., Roberts, S.G., Grant, P.S., (2018). Microstructural and mechanical characterisation of Fe-14Cr-0.22Hf alloy fabricated by spark plasma sintering. *Journal of Alloys & Compounds.* **762**, 678-687.

Journal Paper: Smith, C.J, Tammas-Williams, S., Mahoney, P.S., Todd, I., (2018). 3D printing a jet engine: An undergraduate project to exploit additive manufacturing now and in the future. *Materials Today Communications.* **16**, 22-25.

Journal Paper: Wang, Y., Liu, B., Yan, K., Wang, M., Kabra, S., Chiu,Y.L., Dye, D., Lee, P.D., Liu, Y., Cai, B., (2018). Probing deformation mechanisms of a FeCoCrNi high-entropy alloy at 293 and 77 K using *in-situ* neutron diffraction. *Acta Materialia.* **154**, 79-89.

Journal Paper: Boone, N., Zhu, C.,Smith, C.,Todd, I.,Willmott, J.R., (2018). Thermal near infrared monitoring system for electron beam melting with emissivity tracking. *Additive Manufacturing.* **22**, 601-605.

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.

Conference Publication: Thompson, A., Tammas-Williams, S., Leach, R.K, Todd, I., (2018) Correlating volume and surface features in additively manufactured parts. Proc. ASPE/ euspen Advancing Precision in Additive Manufacturing, Berkeley, USA, Jul. 116-120.

Journal Paper: Zavala-Arredondo, M., Ali, H., Groom, K.M., Mumtaz, K., (2018). Investigating the melt pool properties and thermal effects of multi-laser diode area melting. *The International Journal of Advanced Manufacturing Technology.* **97** (1-4), 1383-1396.

Journal Paper: Ali, H., Ghadbeigi, H., Mumtaz, K., (2018). Residual stress development in selective laser-melted Ti6Al4V: a parametric thermal modelling approach. *The International Journal of Advanced Manufacturing Technology.* **97** (5-8), 2621-2633.

Journal Paper: 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.

Journal Paper: Liotti, E., Kirk, C.A., Todd, I., Knight, K.S., Hogg, S.C., (2018). Synchrotron X-ray and neutron investigation of the structure and thermal expansion of the monoclinic Al13Cr2 phase. *Journal of Alloys and Compounds.* **781**, 1198-1208.

Journal Paper: Hong, Z., Morrison, A.P.C., Zhang, H., Roberts, S.G., Grant, P.S., (2018). Development of a Novel Melt Spinning-Based Processing Route for Oxide Dispersion-Strengthened Steels. *Metallurgical and Materials Transactions A.* **49**, (2), 604–612.

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.

Journal Paper: Zavala-Arredondo, M., Groom, K.M., Mumtaz, K., (2017). Diode area melting single-layer parametric analysis of 316L stainless steel powder. *The International Journal of Advanced Manufacturing Technology.* **94**, 2563-2576.

Journal Paper: García-Tuñón, E., Feilden, E., Zheng, H., D'Elia, E., Leong, A., Saiz, E., (2017). Graphene Oxide: An All-in-One Processing Additive for 3D Printing. *ACS Applied Materials & Interfaces.* **9** (38), 32977 - 32989.

Journal Paper: Smith, C.J., Tammas-Williams, S., Hernández-Nava, E., Todd, I., (2017). Tailoring the thermal conductivity of the powder bed in Electron Beam Melting Additive Manufacturing. *Scientific Reports.* **7**, 10514.

Journal Paper: Tammas-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: Tammas-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.

PUBLICATIONS

PAPER:

Thermal near infared monitoring system for electron beam melting with emissivity tracking

PUBLICATION:

Additive Manufacturing (2018)

AUTHORS:

Boone, N., Zhu, C., Smith, C., Todd, I., Willmott, J.R.

In additive manufacturing (AM) parts are created from Computer Aided Design (CAD) models.

Parts can currently have dimensional variations, rough surface finishes and internal defects not present in the Computer Aided Design (CAD) models used to create them.

Improved in-process monitoring systems could be the solution to this problem which can act as a barrier to uptake.

Thermal imaging is ideal for AM in-process monitoring because AM processes typically rely upon heat to fuse particles of deposited materials.

This paper presents the design of a high speed, high resolution, silicon based thermal imaging instrument.

It was used to thermally image the temperature distributions of an electron beam melting AM system.

The system is showing details within thermal fields not seen before.

The paper states: "With this new instrument, *in-situ* thermal imaging of the entire build area has been made possible at high speed, allowing defect detection and melt pool tracking." (Boone et al. 2018, p601)

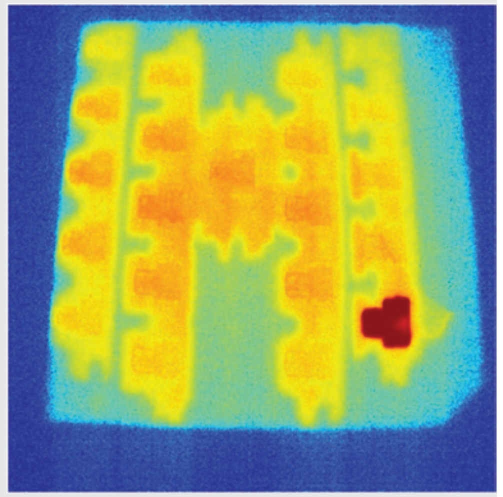
Melt pool tracking was used to implement an emissivity correction algorithm – an important step towards accurate contactless temperature measurement in the Electron Beam Melting (EBM) environment.

The report discusses the advantages of this technology compared to other thermal imaging methods.

The system brings higher speed and spatial resolution over existing solutions, together with an accurate temperature calibration.

It is ideal for in process monitoring of AM systems like EBM thanks to advantages including high resolution and a high frame rate.

The authors anticipate their system will allow accurate online detection of defects based on high speed image analysis in the future.



'T' Shaped test pieces showing the effect of residual heat from the previous layer. Boone, N., Zhu, C., Smith, C., Todd, I., Willmott, J.R., (2018). Thermal near infared monitoring system for electron beam melting with emissivity tracking. *Additive Manufacturing*. **22**, 601-605.

PAPER:

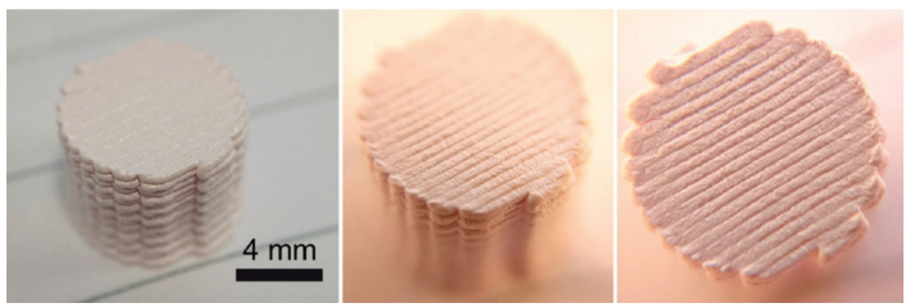
Graphene Oxide: An All-in-One Processing Additive for 3D Printing

PUBLICATION:

Applied Materials & Interfaces (2017)

AUTHORS:

García-Tuñón, E., Feilden, E., Zheng, H., D'Elia, E., Leong, A., Saiz, E.



A 3D printed cylinder made with an Al203 platelets/GO paste after sintering at 1550 °C. Reprinted with permission from García-Tuñón, E., Feilden, E., Zheng, H., D'Elia, E., Leong, A., Saiz, E., (2017). Graphene Oxide: An All-in-One Processing Additive for 3D Printing. *ACS Applied Materials & Interfaces.* **9** (38), 32977 - 32989. Copyright (2017) American Chemical Society.

Controlling and tuning rheological behaviour is key for the successful use of 3D printing technologies like robocasting.

This paper demonstrates how graphene oxide (GO) enables the formulation of water-based pastes to print polymers, ceramics, and steel using robocasting. The GO behaves as a dispersant, viscosifier, and binder.

It states: "This work combines flow and oscillatory rheology to provide further insights into the rheological behaviour of suspensions combining GO with other materials.

"Graphene oxide can be used to manipulate the viscoelastic response, enabling the formulation of pastes with excellent printing behaviour that combine shear thinning flow and a fast recovery of their elastic properties." (García-Tuñón et al 2017, p32977)

The possibilities for materials manufacturing include the robocasting of complex structures and composites as well as new processing approaches for other traditional and modern techniques such as casting, injection, and roll-to-roll processes.

PAPER:

Investigating the melt pool properties and thermal effects of multi-laser diode area melting

PUBLICATION:

The International Journal of Advanced Manufacturing Technology (2018)

AUTHORS:

Zavala-Arredondo, M., Ali, H., Groom, K.M., Mumtaz, K.

Diode Area Melting (DAM) - a highly scalable additive manufacturing (AM) process using energy efficient diode lasers - has opened the door to faster, smaller and cheaper technologies.

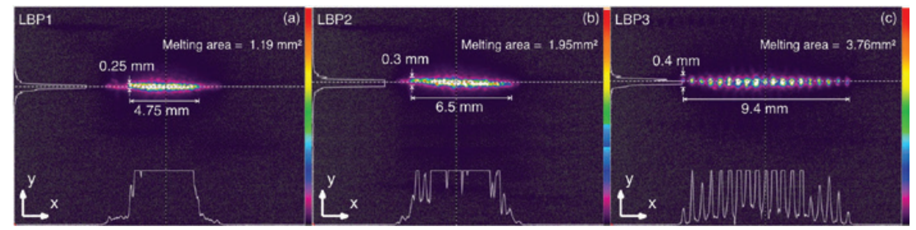
This is important as one of the challenges to the adoption of AM in high volume sectors such as automotive is overcoming the slow speed of the process.

This paper presents the first work investigating the melt pool properties and thermal effects of the multi-laser DAM process by modelling generated melt pools. The melt pools are the unique thermal profiles created along a powder bed during processing.

The computer model of the DAM process simulated the processing of 316L stainless steel and is validated with experimental trials.

This thermal analysis, as described in the paper, can be used to compare DAM with Selective Laser Melting (SLM) in terms of mechanical behaviour, microstructure and residual stresses of as-built components in future work.

The paper indicates that DAM can reduce residual stress formation compared to the single point laser scanning methods used during SLM by significantly reducing temperature gradients and cooling rates. This is due to DAM's characteristic melting mechanism composed of multiple parallel scanning vectors with low individual power and low scan speeds.



Laser beam profiles dimensions and total melting areas. a) LBP1. b) LBP2. c) LBP3. (Zavala-Arredondo et al. 2018)

PAPER:

Laser-matter interactions in additive manufacturing of stainless steel SS316L and 13-93 bioactive glass revealed by *in situ* X-ray imaging

PUBLICATION:

Additive Manufacturing (2018)

AUTHORS:

Leung, C.L.A., Marussi, S., Towrie, M., Val Garcia, J., Atwood, R.C., Bodey, A.J., Jones, J.R., Withers, P.J., Lee, P.D.

MAPP researchers are using the UK's national synchrotron, the Diamond Light Source, to shed more light on laser additive manufacturing (LAM) technologies.

Previously the *in-situ* real-time measurements used to learn more about LAM, including Schlieren imaging, have captured the temperature field and/or images at above the molten pool surface. But they cannot study the changes inside the melt zone.

Advances in third-generation synchrotron radiation sources allow the use of a high flux X-ray beam to capture LAM radiographically at a high spatial and temporal resolution.

This paper details the use of a custom built LAM process replicator (LAMPR) with *in-situ* and *operando* synchrotron X-ray real-time radiography to study laser-matter interactions and powder consolidation phenomena during LAM of stainless steel SS316L and 13-93 bioactive glass.

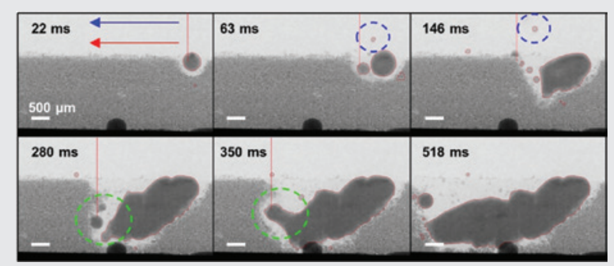
The paper states the LAMPR is: "Designed to mimic the major features of a typical LPBF system while permitting *in situ* and *operando* imaging of the laser-matter interaction and powder consolidation phenomena with synchrotron X-rays. It is a compact, lightweight (ca.15 kg) and portable device that can be integrated into different synchrotron X-ray imaging and diffraction beamlines." (Leung et al. 2018, p649).

Two powders with large differences in chemical, optical and thermophysical properties were chosen for the study. This was to better understand the effects of powder properties on laser absorption mechanisms, melt flow behaviour and the evolution of the melt track and defects.

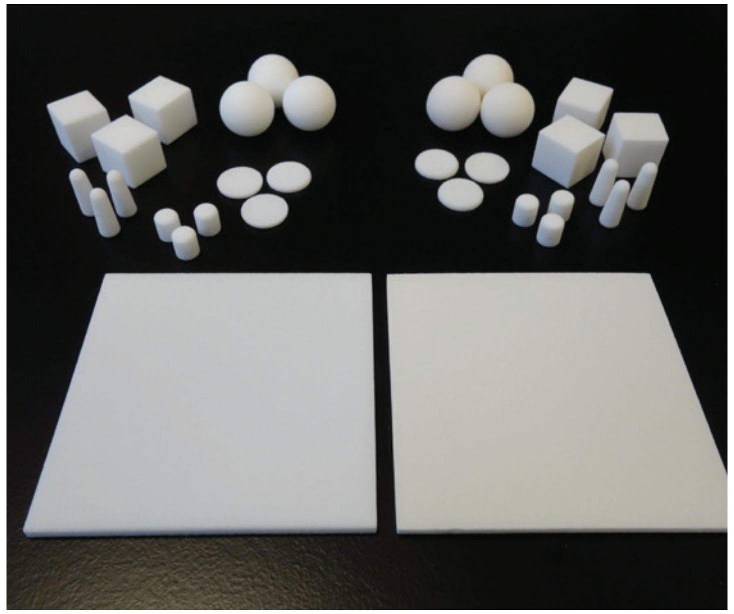
The study revealed the very different melt behaviours of the two powders during LAM.

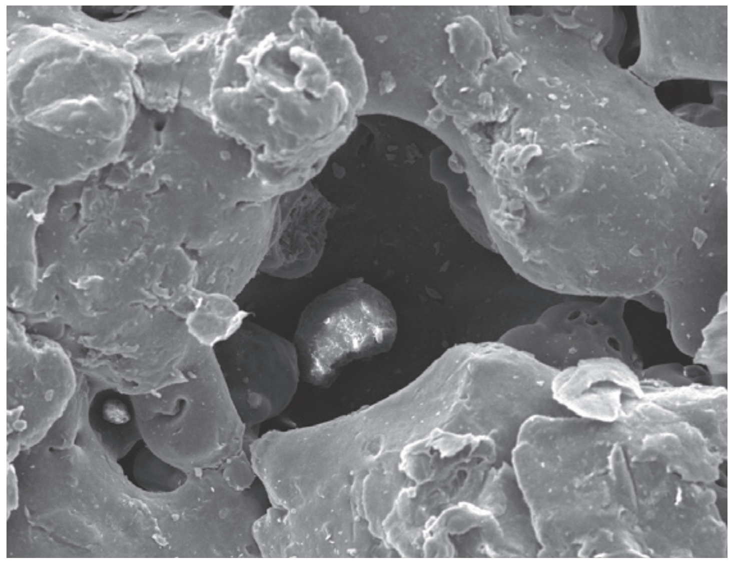
The work is useful in understanding the mechanisms behind the formation of defects and other technical challenges.

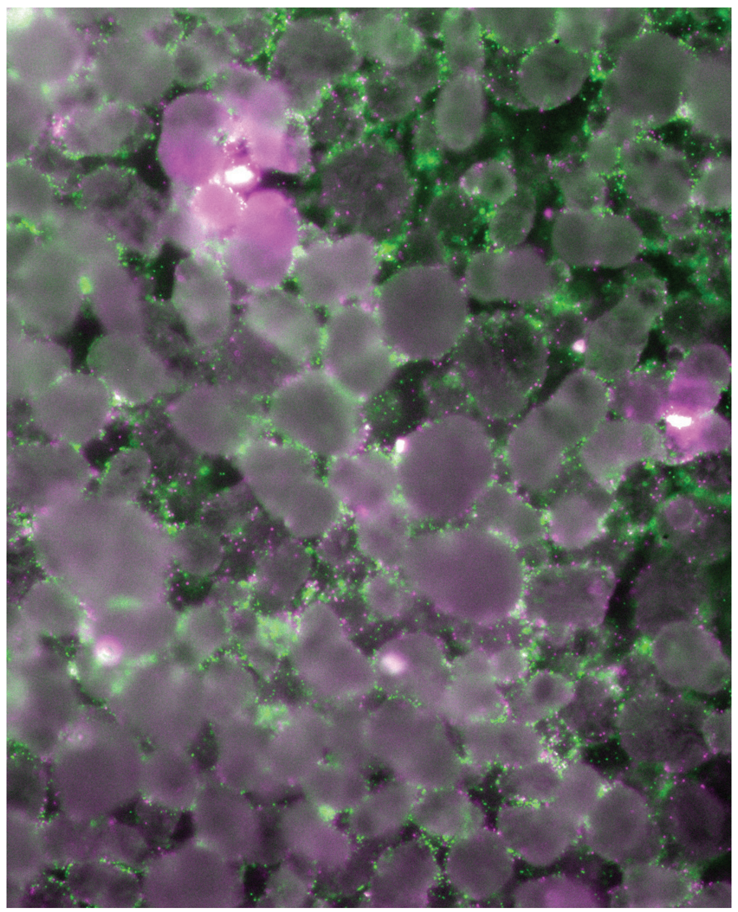
This understanding will help control technical challenges that can affect the use of LAM technologies for high-performance structural applications.

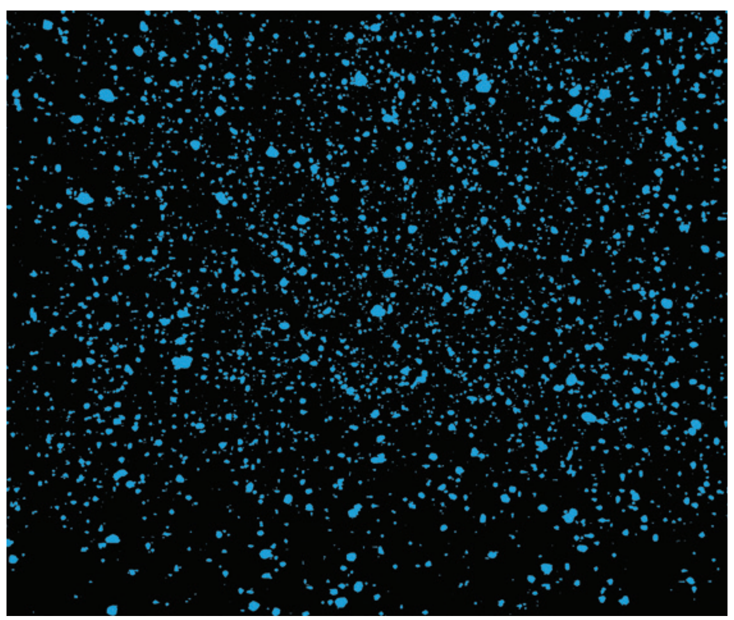


"Typical time-series radiographs showing melt track evolution during SS316L LAM (P = 150 W and v = 5 mm s^{-1}). Directions of the laser beam (red arrow) and gas flow (blue arrow) are shown in the 22 ms frame. The overlaid vertical red lines indicate the laser beam position as it moves from right to left. Red outlines highlight tracked and quantified objects. Blue circles highlight the droplet spatter movement. Green circles show track growth *via* molten pool wetting." (Leung et al. 2018).









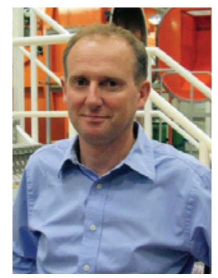
MAPP EXECUTIVE TEAM

Professor Iain Todd

MAPP Director Professor Iain Todd 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 Process by Design [P2.1].

Professor Andrew Bayly

Professor Andrew Bayly 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 leads the theme Powders by Design [P1.1].



Professor Patrick Grant

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.

Professor Peter Lee

Professor Peter Lee is Assistant Director, Physical Sciences, of the Research Complex at Harwell (RCaH). He is an expert in characterising microstructural evolution during manufacturing, and predicting processing-structure-property relationships using Integrated Computational Materials Engineering (ICME), with more than 30 years' experience at Alcan, Imperial, Manchester and now University College London. He has published more than 250 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 and Performance Characterisation'.

Professor Michael Preuss

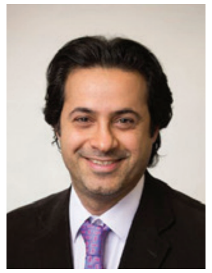
Professor Preuss' research focuses on microstructure, mechanical properties and residual stresses in high temperature materials - zirconium alloys, titanium alloys and nickel-base superalloys - for application in aerospace, oil and gas and nuclear sectors. Michael is Champion of the Materials for Demanding 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 for Protection of Metal Powders [P1.4].

Professor Eduardo Saiz

Professor Eduardo Saiz 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].

MAPP INVESTIGATORS

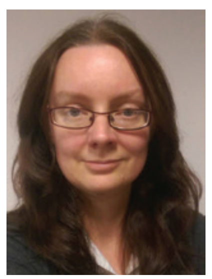
Dr Finn Giuliani, Imperial College London.
Dr Giuliani's research interests are in ceramic materials, particularly powder manipulation, characterisation and small scale testing, especially of interfaces. He has published more than 50 papers and holds more than £3M in active grants. He has collaborated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



Dr Ali Hassanpour, University of Leeds.
Dr Hassanpour 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.

Dr 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 Lead.
Professor Visakan Kadirkamanathan 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.



Dr Candice Majewski, University of Sheffield.
Dr Majewski 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. Prof Mullis' 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 atomization 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.
Dr Kamran Mumtaz' 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.

Prof. George Panoutsos, University of Sheffield, X3 Theme 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, X2 Theme Lead. 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.

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.

MAPP PDRAs:

Dr Timothy Bigg
Dr Yunhui Chen
Dr Sam Clark
Dr Wen Cui
Dr Iuliia Elizarova
Dr Jabbar Gardy
Dr Oliver Hatt
Dr Yi He
Dr Alex CL Leung
Dr Ping Li
Dr Jo Sharp
Dr Ben Thomas
Dr Rahul Unnikrishnan
Dr Zicheng Zhu

MAPP aligned PhDs:

Abdullah Alharbi
Alaa MM Almansoori
Mohammed Alsaddah
Nick Boone
Ryan Brown
Lev Chechik
Sarah Connolly
Lukas Feiber
Luke Fox
Simon Graham
Guy Harding
Abdul Haque
Oliver Levano
George Maddison
Mozdeh Mehrabi
Maha T Omran
Sourabh Paul
Edd Rowe
Lorna Sinclair
Leigh Stanger
James Wingham
Yingwei Wu
Zhang Zhouran

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.

Prof. Pollock 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)

Prof. Kőrner 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

Prof. Llorca 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

Prof. Jin Ooi 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, Italy

Prof. Previtali 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), France

Prof. Rossignol 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, Chief Executive Officer, LPW Technology

Dr Phil Carroll founded LPW Technology Ltd, the 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. 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. He has overseen the development of LPW's highly-respected applications and R&D team, creating AM metal powder hardware and software systems to control risk in critical manufacturing processes.
Phil has demonstrated what an enterprising individual can accomplish in business, achieving significant sustainable growth and financial performance through a culture of quality, innovation and operational efficiency. His vision and ambition have led LPW to establish a global presence and 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 Additive

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,
Johnson Matthey, Scientific Consultant

Dr Hamilton 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 3D Printing, Xaar

Prof. Hopkinson 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 where he is building a 3D printing business utilising Xaar's world leading piezo-electric inkjet printing technology across a range of 3D printing technologies including one of his own 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

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 repair R&D project. In his current role Ian leads repair technology globally and is responsible 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-whole surgery for jet engines'), as well as the next generation of component repair and inspection technologies for use in overhaul shops.

Marc Saunders,
Director - Global Solutions Centres, 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 manages a global network of Solutions Centres for metal additive manufacturing (AM), enabling customers who are considering deploying AM as a production process to gain hands-on experience with the technology before committing to a new facility.

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

Dr Tsopanos' specialities are rapid prototyping & 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

Prof Young 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 500 and has become a £40m turnover business. It has already delivered complete world-leading production facilities into UK factories.

ADDITIVE MANUFACTURING AT PINT OF SCIENCE

By Dr Robert Turner, MAPP aligned PDRA, Department of Mechanical Engineering, University of Sheffield

Public engagement is fun! I've been involved with taking University of Sheffield research all over the country and explaining it to members of the public of all ages.

James Wingham, Ryan Brown, Luke Fox and Robert (Bob) Turner outside the pub.

It's always fantastic to get the opportunity to bring research to an adult audience. For example, Pint of Science, the brainchild of Michael Motskin and Praveen Paul who were at the time working at Imperial College London, is a long-running annual festival bringing top engineers and scientists into pubs (or equivalents) all over the world to talk about their work.

For 2018's Pint of Science in Sheffield, myself, PhD students Luke Fox, Ryan Brown and James Wingham and group leader MAPP Investigator Dr Candice Majewski were part of an event at the Millowners Arms at Sheffield's Kelham Island Museum.

All of us are from the Advanced Polymer Sintering Laboratory in the Department of Mechanical Engineering at the University of Sheffield.

We took a 3D printer, 3D pens and specially designed event keyrings printed using Laser Sintering to give away.

Through our interactive demonstrations, we were able to explain additive manufacturing to event visitors and give detailed information on specific work in the lab, including our new research on antimicrobial materials for 3D printing.

There was a great deal of interest in what we were doing and we had loads of good chats – plenty of people entered our competition to make the strongest part with a 3D pen.

We were part of two events in the "Tech Me Out" theme featuring talks on cutting-edge technologies that are having an increasing impact on our lives, from big data and machine learning to rockets, to simulating the behaviour of living cells for personalised medicine.

Whilst we all enjoyed the event, it's important to remember that public engagement is a huge opportunity to connect with the next generation of students (and their parents), supporting long-term recruitment onto courses.

It justifies why we need state funding for research directly to the people paying for it and it consolidates our reputation for excellent research amongst the broader public and those of them that might want to retain our services. I'm looking forward to taking our work to an even a wider audience in the future!

SCHOOL CHILDREN, PIANOS, AND CHICKEN NUGGETS...

By Dr Candice Majewski, MAPP Investigator

Some days you receive the strangest emails... On the 28th March 2018 Julian Allwood, a colleague from Cambridge University, popped up in my inbox. He asked, would I like to help break the world record for the most people playing a single piano at one time?

Of course, by that he actually meant 'let's get 88 people playing it at once, one per key' (thereby rendering the record unbreakable unless you start putting multiple players per key). Oh, and it would be a group of 88 school children playing it, and we'd get school children around the country to design 5m long mechanical contraptions to allow that many people to reach the keys...

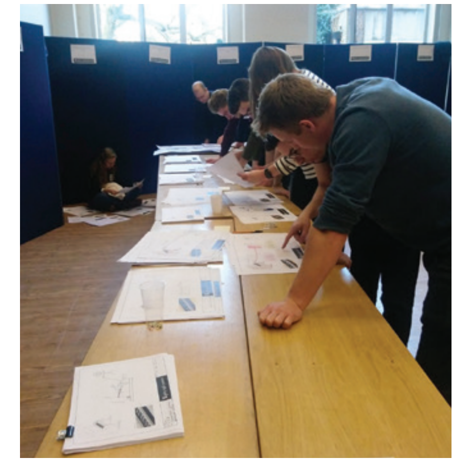
A daunting task for sure, but Julian is the same person who, a couple of years ago, coordinated and cajoled a group of 18 of us into writing a joint manufacturing paper (Manufacturing at double the speed, Journal of Materials Processing Technology). If he could manage that, surely this couldn't be that much harder? It seemed that the answer was an obvious yes to taking part, and so I committed The University of Sheffield (or at least our small part of it) to help make it a reality.

Several colleagues at other Institutions were equally convinced, and so it began.

Of course, as any good academic knows, this type of activity can only work if you have a strong team behind you. Thankfully two of our MAPP-aligned PhD students, Ryan Brown and James Wingham, were up for the challenge, as well as Undergraduate Engineering students James Rayson, Jack Trethewey, Robin Watkins-New and James Whitehead, recruited through our Sheffield Engineering Leadership Academy.

Step one was to come up with concept designs for the piano-playing contraptions. Two local schools, Hallam Primary School and Lydgate Junior School, signed up (thank you very much to all the children and teachers who took part with such enthusiasm!). We went in with a variety of musical, engineering and design activities, culminating in asking the children to come up with wild and wacky concepts (think Wallace and Gromit) for how a person might play a piano key from five metres away.

It's fair to say we were a mix of excitement, nerves, and a jumble of other emotions on the morning of the first visit, but the first thing we noticed was how excited the children were to see us. Their enthusiasm, creativity, and general thirst for new things were inspiring to say the least, and the children were coming up with ideas from pretty much the moment we arrived. Concept designs included unicorns, TNT, and a reindeer chasing a chicken nugget...


Choosing the winning designs.


Some of the engineers taking part in the classroom.

Since then we all got together down in Cambridge to choose the final 88 designs, and we're currently working on converting the designs into workable mechanical solutions. Massive thanks to James Wingham for taking the lead on this, as well as for his excellent CADwork, and to Ryan Brown and Oliver Leete for helping out too. After a final check that all the designs will work together, we'll start on the manufacturing stage. We'll hopefully also be calling on our local schools again, to help us with putting the final touches to them.

Alongside all of this our wonderful composer, Martin Riley, has been coming up with an entirely new piece of music for the final performance, which will take place at the Birmingham Conservatoire on the 19th August 2019. I'm reliably informed you'll be able to watch the big event online at some point, so watch this space!

You can follow our progress at www.88Pianists.com or on Twitter via @88Pianists

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.

LIVE PROJECTS

DARE (Designing Alloys for Resource Efficiency)

Funder: EPSRC

Project costs: £4,033,113

Funded value: £3,226,490

Funding period: September 2014 – September 2019

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

FAST STEP 3 Swarf Titanium to Engine Parts in 3 Steps

Funder: Innovate UK

Project costs: £634,440

Funded value: £507,551

Funding period: March 2018- February 2021

Organisations: Participants include Force Technology Limited, Northern Automotive Alliance, Transition International Limited, University of Sheffield and W.H. Tildesley.

The aims of the FAST STEP 3 project are to:

- Achieve lightweighting for automotive engines in order to lower emissions including CO2, NOx and particulate matter. Initially at low volume, but it can move into higher volume applications when there is increasing confidence with the product and manufacturing processes.
- Provide growth opportunities for the supply chain. For the automotive sector and the wider advanced manufacturing sectors of offshore, rail, aerospace, non-auto engines and defence.
- Enable the metal-forming industry to stay abreast of new technology in alternative metals and use world-leading materials research to assist in halting the decline of the industry within the UK.

High value alloyed titanium swarf will be used as a feedstock for the novel hybrid technology of Field Assisted Sintering Technology followed by one-step hot forging – known as the FAST-*forge* process – into near net shapes for use in the high strength and good fatigue life applications typically required within an automotive engine.

FAST STEP 3 involves three processes to produce components. Firstly, the FAST process uses titanium swarf to produce a shaped consolidated pre-forged billet.

Secondly, a hot forging process produces a near net shape with high strength.

Thirdly, final machining produces a component that is net shape and engine-ready.

The process will produce titanium at 20% of the cost of current titanium billet and with minimal waste.

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

Funder: Horizon 2020

Funded value £661,924

Funding period: January 2019-December 2022

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

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

COMPLETED PROJECTS

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

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

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

Project costs: EUR 3 439 420

Funded value: EUR 3 439 420

Funding period: January 2015-December 2017

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

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

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

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

REMASTER (Repair Methods for Aerospace Structures using Novel Processes)

Funder: Aerospace Technology Institute and Innovate UK

Project Costs: £3,484,901

Funded value: £1,742,390

Funding Period: January 2016 – December 2018

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

SHAPE (Self Healing Alloys for Precision Engineering)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £2,127,805

Funded value: £1,071,094

Funding period: September 2015 – August 2018

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

TiPOW (Titanium Powder for Net-shape Component Manufacture)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £3,129,835

Funded value: £1,555,610

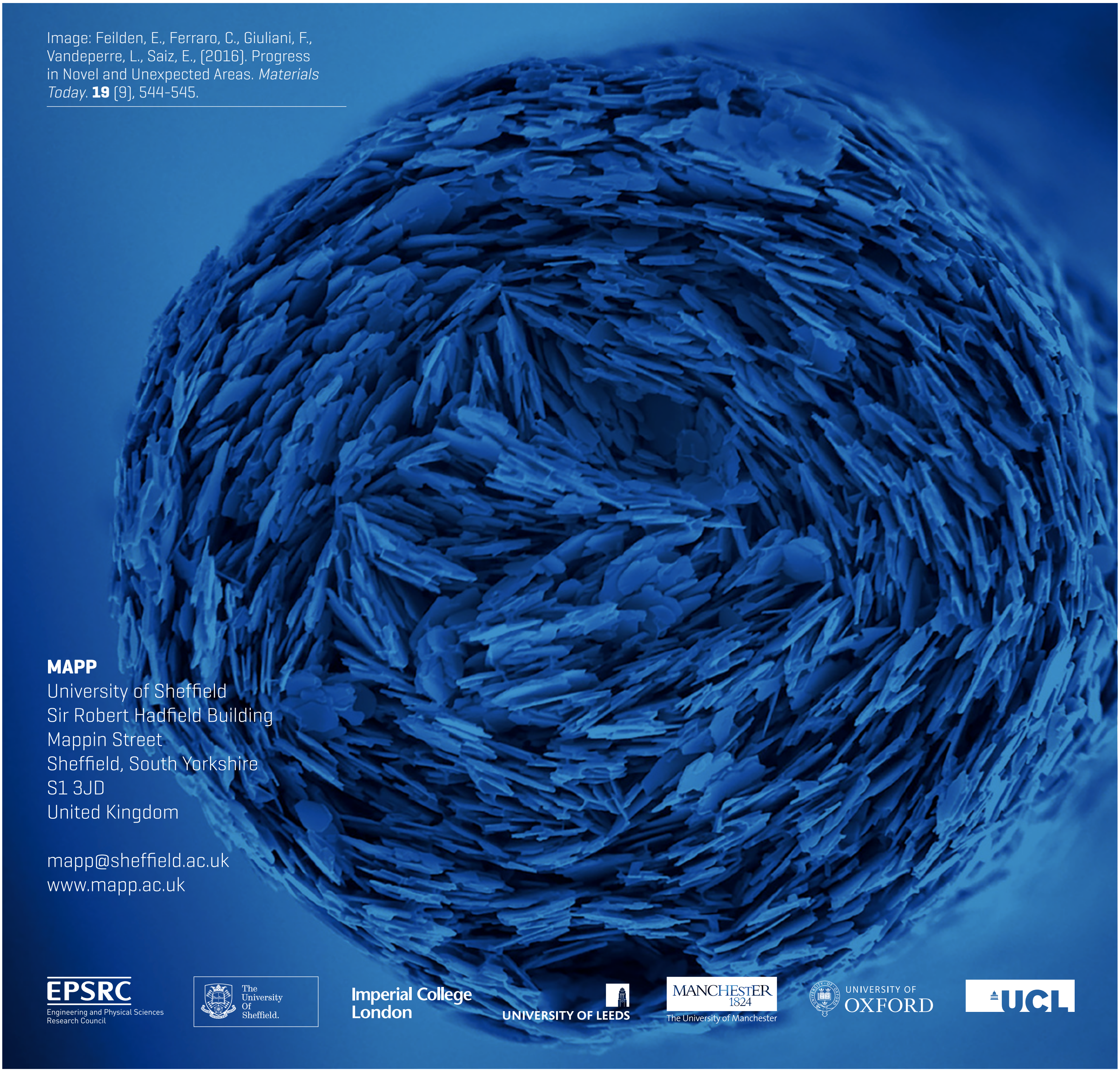
Funding period: March 2015 – February 2018

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

MAPP

Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

Image: Feilden, E., Ferraro, C., Giuliani, F., Vandeperre, L., Saiz, E., (2016). Progress in Novel and Unexpected Areas. *Materials Today*. **19** (9), 544-545.



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