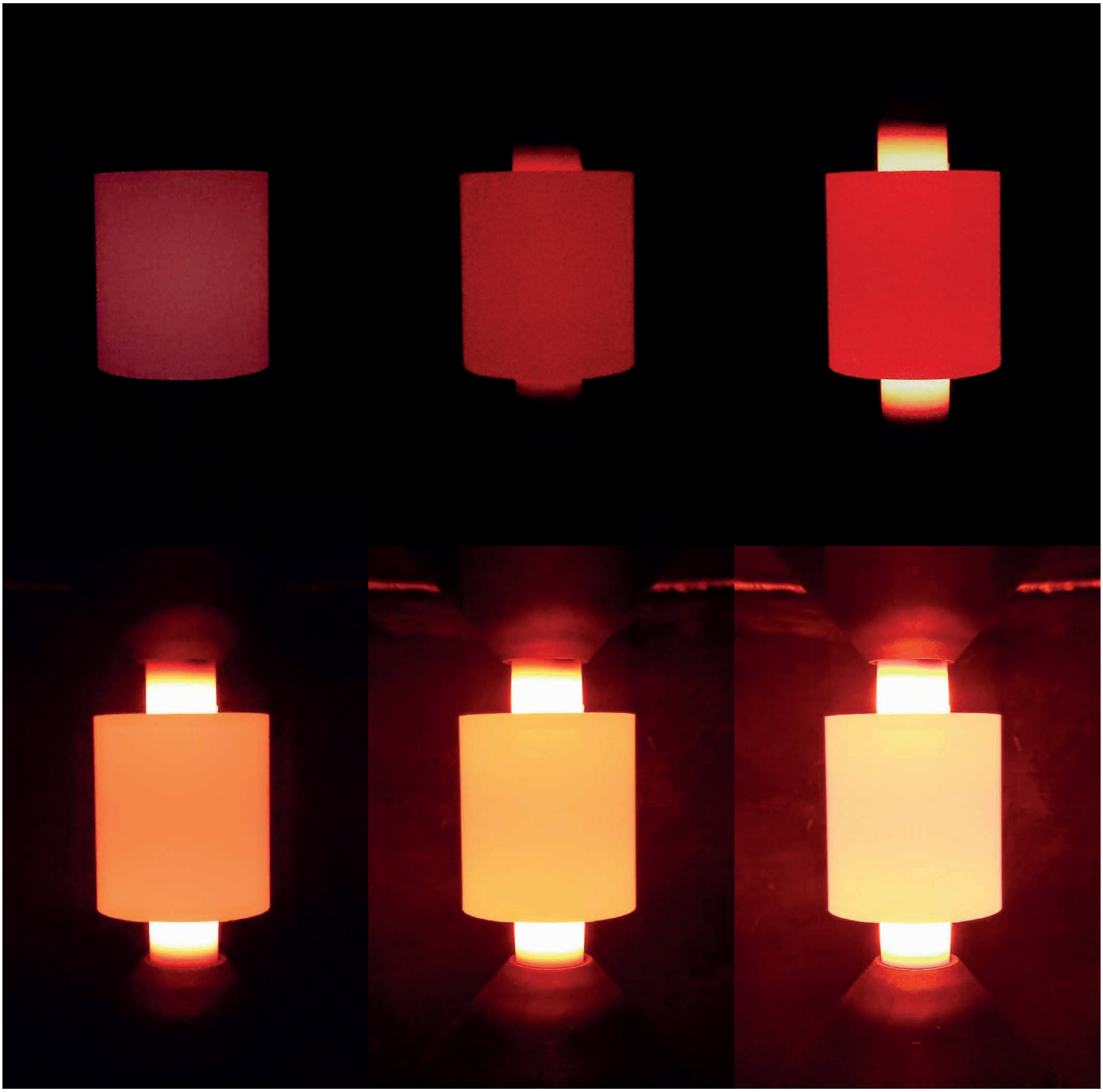
MAPP

Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

Annual Report 2022

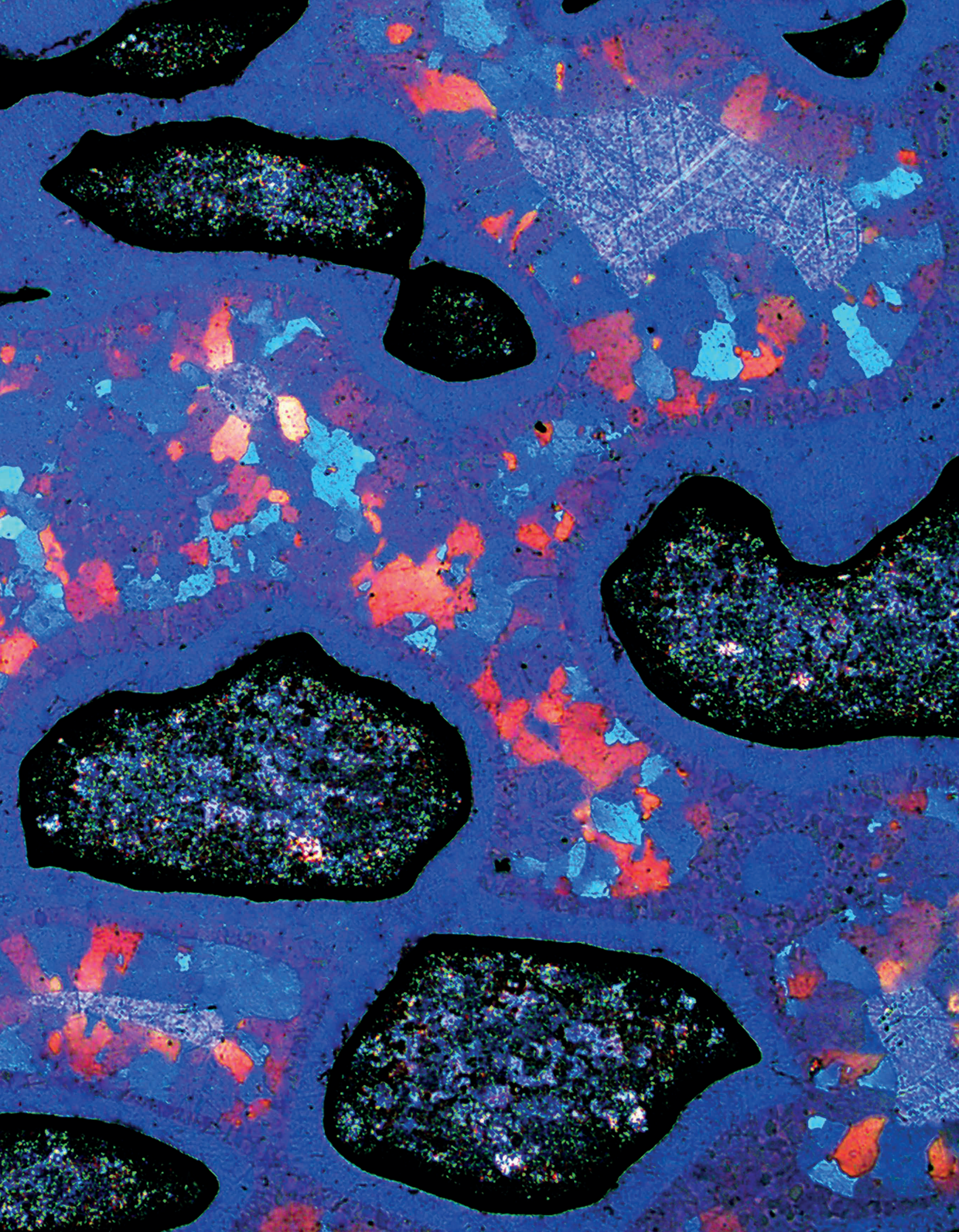
Engineering and Physical Sciences Research Council



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

Front cover image: **A view into Field Assisted Sintering of Ti-6Al-4V powder**. Time lapse images of the graphite tooling radiating optical light during the heating ramp early in the sintering process. The rams and die heat at different rates depending on tooling, sample geometry and process parameters. The maximum temperature in this case was at 1000°C (bottom right image of montage). Images taken by Dr Simon Graham and Dr Ben Thomas.

Image on this page: **Diffusion Kaleidoscope**, by Dr Nicholas Weston. Polarised light micrograph showing the different phases and transitional diffusion zones in the microstructure of a blended elemental Zinc-Silver alloy after processing via Field Assisted Sintering Technology (FAST).



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WELCOME

Welcome to the fifth MAPP Annual Report.

2021 was another challenging year and I am proud of everyone at MAPP who pulled together to continue our work despite those challenges.

This report highlights some of the many fantastic professional achievements of our colleagues in MAPP and I am delighted to see that several have received well-deserved recognition.

Over the course of the last year, members of MAPP have been taking part in a variety of engagement activities, ranging from podcasts to presenting at key advanced manufacturing conferences.

We have also held successful hybrid events including a workshop on Artificial Intelligence in Additive Manufacture. You can read more about the workshop, which was run jointly with the Centre for Additive Manufacture – Metal (CAM^2) on page 23.

We continue to publish MAPP research in leading journals and feature some of the groundbreaking outcomes of our research programme in this annual report.

Our focus now is on ensuring that our research is taken forward with industry, helping to deliver real economic impacts. As we do so we will continue to work closely with our industrial partners to make sure we are still addressing the most relevant research questions and challenges.

It continues to be an exciting time for us here - I hope you enjoy reading about some of MAPP's highlights of 2021 and we look forward to continuing our work together in the future.

Prof. Iain Todd, MAPP Director

Professor Iain Todd
MAPP Director

ACHIEVEMENTS

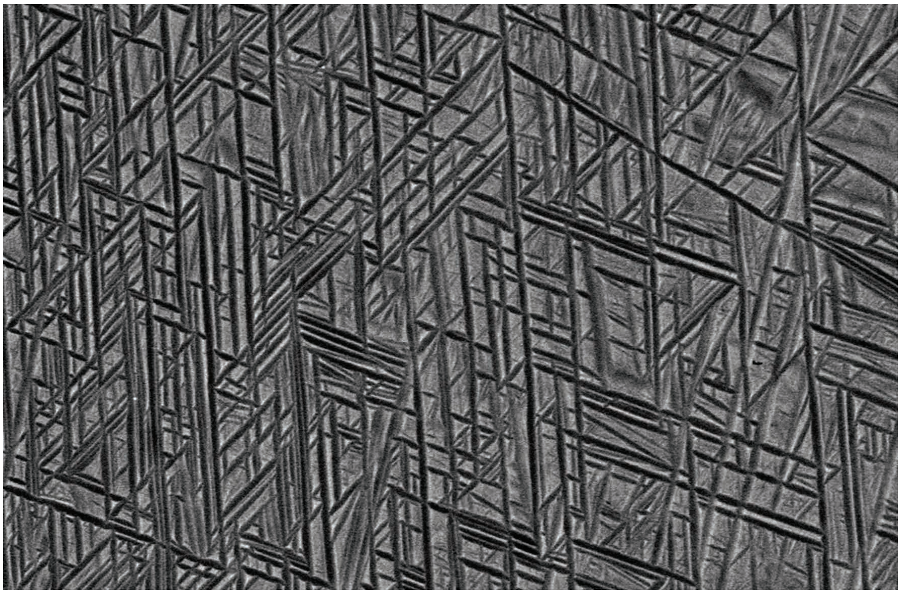
2017–2022

MAPP's collaborative and interdisciplinary research and innovation programme is delivering a new understanding of powder-based manufacturing.

The hub is working with academic, commercial and innovation partners to drive the research needed to solve many of the fundamental challenges limiting the development and uptake of many powder-based processes.

A number of key outputs have been achieved over the past five years including:

- Useful insights into the Hot Isostatic Pressing (HIPing) process of a novel Ti-Fe binary alloy via *in-situ* mimic HIPing experiments under synchrotron X-ray. For the first time, the whole densification process has been recorded by X-ray imaging.
- The extension of robocasting to the fabrication of ceramic composites and glasses.
- Work that opens new opportunities for the extension of digital light processing to non-oxide ceramics.
- Characterising a library of powders at the individual and bulk level.
- Methods to coat stainless steel powders to prevent oxidation.
- Using Field Assisted Sintering Technology (FAST) to optimise and improve process control.
- Developing deep-learning algorithms to enable rapid process parameter development, monitoring components as they are manufactured to enable 'right first time' manufacturing.
- The most in-depth understanding to date of porosity and pore formation as a result of varying levels of energy input in High Speed Sintering (HSS).
- New understanding in process models through the development of a laser powder bed AM replicator, a Directed Energy Deposition (DED) replicator and an *in-situ* synchrotron rig for investigating the field FAST process.
- Use of machine learning to develop data driven approaches to predict printability in AM.



High resolution of geometric perfection by Caterina Iantaffi. A typical basket wave-like microstructure of Ti6Al4V, also called Widmanstätten microstructure.

Some of our research has progressed more quickly thanks to additional links with our aligned projects (you can find out more about these on pages 51-55), and we have successfully leveraged funding to enable us to build a wider team and retain key skills.

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

Our leadership of the national agenda is highlighted by:

- MAPP Director Professor Iain Todd leading the new Materials Made Smarter Centre set to revolutionise the way we manufacture and value materials in the UK (see page 48 for more information).
- Involvement with the Henry Royce Institute agenda in Materials 4.0.
- Our partnerships with catapults.
- Our partnerships with UKRI Critical Mass Activities.
- MAPP Executive member Professor Visakan Kadirkamanathan appointed as the Chair of the UK Automatic Control Council.

Our connections with external partners have increased and we are developing a number of international partnerships, as well as engaging with academia via routes including feasibility studies. You can read more about our feasibility funding on pages 46-47 and our successful workshop held in partnership with the Centre for Additive Manufacture – Metal (CAM²) on page 23.

Our researchers have been hard at work, supporting our online, in-person and hybrid events as well as delivering on our research programme.

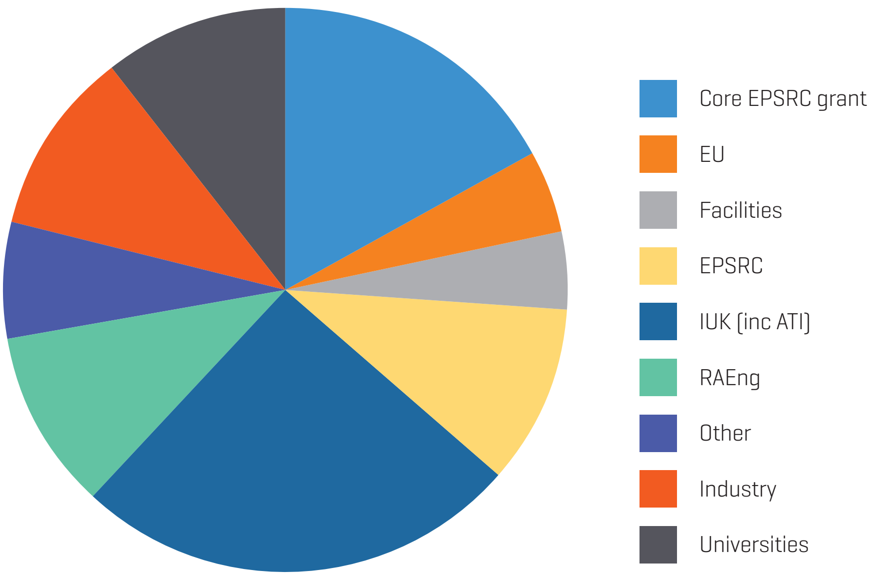
They have also benefited from various training opportunities such as project management and digital communications and we are delighted that several MAPP researchers have moved on to more senior posts and are now attracting funding of their own.

SOME OF MAPP'S KEY PERFORMANCE INDICATORS

128 publications	**>1200** delegates at MAPP events	**60** keynotes given

Delegates during a talk at the workshop on Artificial Intelligence in AM held by MAPP and CAM².

COMPONENTS OF MAPP'S FUNDING PORTFOLIO



The following MAPP researchers have moved to new positions in 2021:

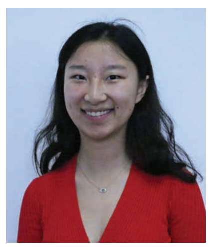
- MAPP Post-Doctoral Research Associate (PDRA) at University College London (UCL), Dr Yunhui Chen, is now working for Professor Philip Withers and is based at the European Synchrotron Radiation Facility (ESRF) in France.
- MAPP PhD at UCL, Dr Lorna Sinclair, has joined the University of Manchester at the Harwell Science and Innovation Campus, Oxfordshire, as an experimental officer.
- MAPP PDRA at Imperial College London, Dr Oriol Gavalda Diaz, is now an Associate Professor in the Advanced Manufacturing Technology Research Group at the University of Nottingham.
- MAPP PDRA at the University of Oxford, Dr Wen Cui, has moved to a research role at the University of Manchester.
- MAPP PDRA at the University of Sheffield, Dr Ashfaq Khan, has moved to Robert Gordon University in Aberdeen as a lecturer in Design and Manufacture.
- MAPP PhD at the University of Sheffield, Dr Rhys Williams, has moved to Manchester Metropolitan University as a PDRA.

Our colleagues have taken part in a wide range of leading conferences and public engagement events - both online and in person. You can read more about some of these activities on page 22.

MAPP researchers were successful in securing funding for two Henry Royce Institute Materials 4.0 Feasibility Studies.

Some of our other colleagues' professional successes in 2021 are highlighted on page 24.

Dr Lorna Sinclair

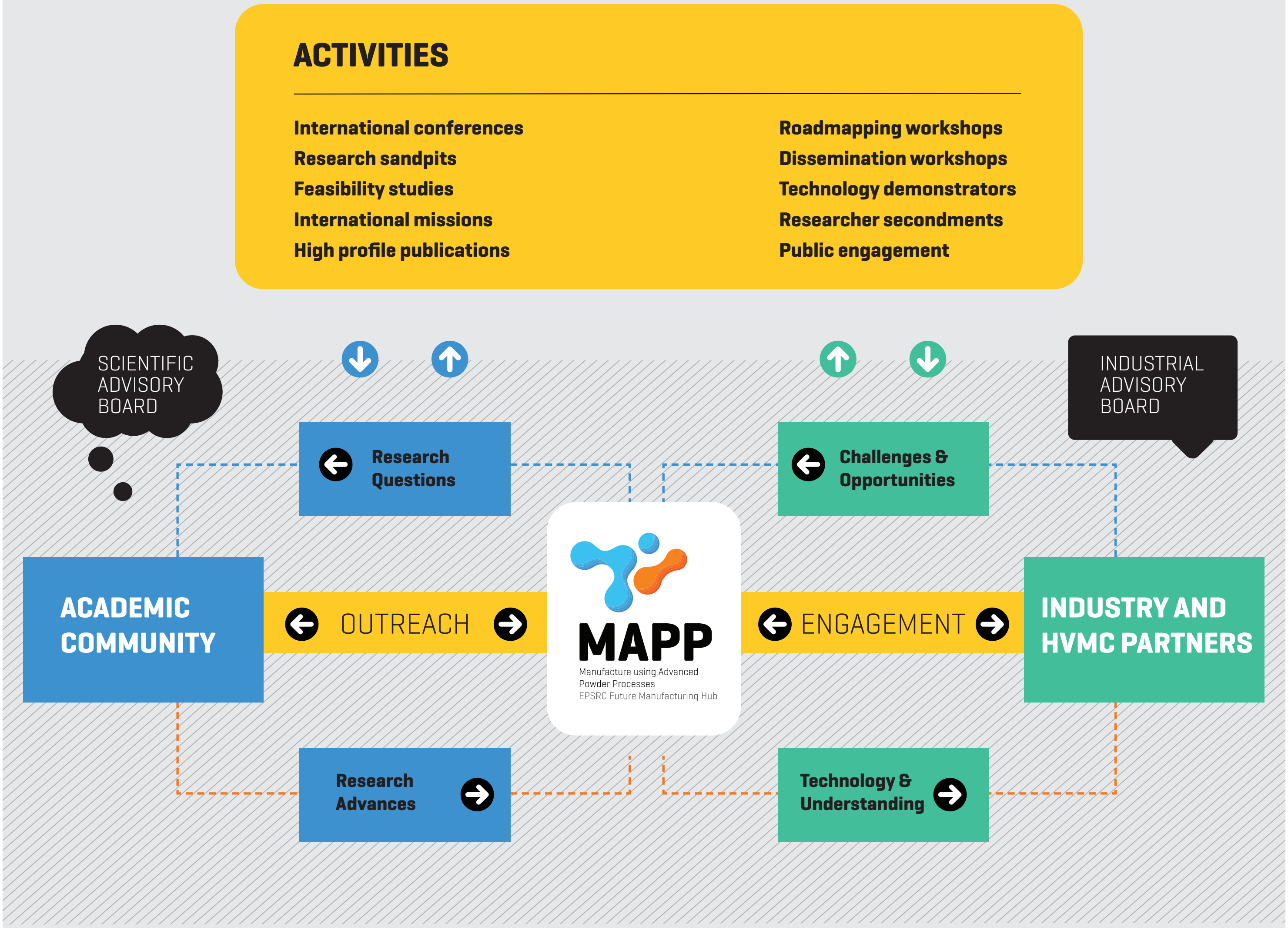


Dr Wen Cui

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 are delivering on promises of user engagement, commercial outputs, academic outreach, public engagement and the training of the next generation of engineers.



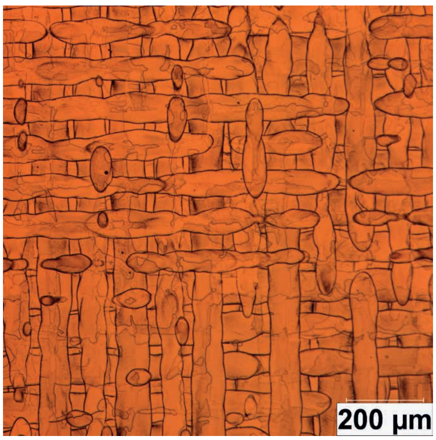
RESEARCH PROGRAMME OVERVIEW

CORE RESEARCH THEMES

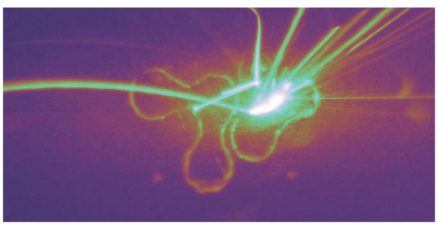
PLATFORM RESEARCH: POWDERS AND PROCESS BY DESIGN

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

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



Bidirectional scan tracks in additively manufactured Fe-Si, by Alex Goodall.



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

GRAND CHALLENGE (GC) THEMES

GC1: Right First Time Manufacturing

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

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

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

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

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

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

GC3: Enhanced Product Performance

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

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

Manufacturing of products with properties that are currently impossible.

CROSS-CUTTING GRAND CHALLENGE THEMES

Facilities and Demonstrators

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

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

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

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

Sustainability

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

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

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

Digital Twin

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

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

RESEARCH PROGRAMME UPDATE

P2.1 METAL ADDITIVE MANUFACTURING (AM)

P2.1a Process Definition and Control in Laser Powder Bed Fusion (LPBF)

Investigators – Prof. Andrew Bayly, University of Leeds, Prof. Iain Todd, University of Sheffield.

Collaborators – University of Sheffield [X2 & X3], University of Manchester [X2], University College London [X1], University of Cambridge [X3] and Industry.

Powder descriptors

Dr Mozhdeh Mehrabi, Assoc. Prof. Ali Hassanpour, Prof. Andrew Bayly, University of Leeds

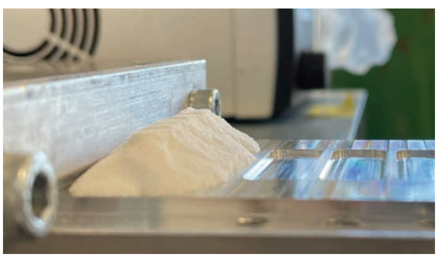
We are focusing on different ranges of powders used for the Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition (DED) processes and understanding powder feeding and spreading behaviours during the processes, which would significantly influence the performance and quality of the final product.

Our main aim is to establish a link between powders characteristics and process performance. We are fully characterising powders based on their morphology (particle size and shape), particle surface properties (satellite and surface roughness) and their bulk properties (flowability and electrostatic charging).

To understand the spreading behaviour of powders, we have developed a spreading test rig to assess powder feeding behaviour and spread layer quality in terms of packing density and surface topography, as a function of spreading speed for different powder layer thicknesses.

We are characterising the spreadability of powder with respect to different powder feeders and blade types and shapes to understand the impact of feeding and spreading methods on the powder spreading behaviour.

We are working with our MAPP partners to identify key powder descriptors and process conditions which can have an impact on the LPBF and DED processes, to inform the selection and design of powder feedstock.



Characterisation of packing density variation during the spreading process using the spreading test rig.

P2.1b Process Definition and Control in Directed Energy Deposition (DED)

Investigator – Prof. Iain Todd, University of Sheffield.

Collaborators – University of Sheffield [X2 & X3], University of Manchester [X2], University College London [X1], University of Cambridge [X3] and Industry.

Understanding scalability and design of experiment (DoE) methodologies for DED.

Continued efforts are being made to match DED-AM builds on the Blown Powder Additive Manufacturing Process Replicator (BAMPR) and the BeAM machine in Sheffield.

This is a collaborative effort between University College London and the University of Sheffield which demonstrates how the MAPP hub brings together academic institutions to solve industrial problems.

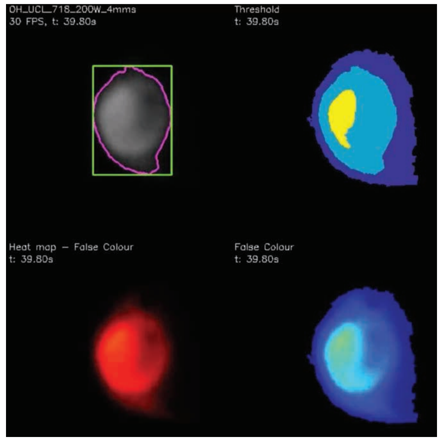
The BAMPR uses synchrotron X-rays to capture radiographic video which reveals underlying mechanisms and dynamics of the DED process on a small scale. However, there is currently a gap between the input parameters used on the replicator and the input parameters used on the BeAM (large scale). The latter parameters are more aligned with what industry would use for a build or component repair.

Therefore, we look to achieve clarity as to whether the observed phenomena occurring on the BAMPR are equal to those observed on the BeAM. After initial experimental studies across both machines, it is clear that we have achieved structural equivalence for DED-AM builds using IN718 powder. Analysis of dendrite arm spacing in nickel samples has shown strong agreement between the BAMPR and BeAM at different energy densities. We currently do not have shape equivalence between the machines which is important due to the complex geometries of repairs for safety-critical components. There are many challenges and complexities to consider in order to achieve both shape and structural equivalence.

A new laser has been procured for the BAMPR which will allow the same spot size and profile as used on the BeAM. This is important to achieve the same powder mass capture rate across the machines. Furthermore, bespoke build plates have been purchased for the BeAM which match those seen on the BAMPR. This facilitates the next set of experiments to use like-for-like parameters on the same substrate with the same laser profile and spot size.

A collaboration with the Department of Automatic Control and Systems Engineering at the University of Sheffield is investigating non-greedy batch Bayesian DoE methodologies for DED.

New manufacturing processes require the understanding of variables and their interactions onto output variables in order to maintain desired performance. However, many factors can limit manufacturers' abilities to analyse the effects of process variables on output variation e.g. expensive evaluations (fiscal or time constraints), lack of effective models, multiple conflicting outputs. DoE methodologies are used to alleviate some of these issues allowing for in-depth knowledge to be gained whilst preventing exhaustive experimentation. As a result of this, we can now achieve desired component specifications using far fewer test builds than in comparison with a traditional DoE approach.



False-colour and heat map images of the melt pool captured *in-situ* during a build using the BeAM machine in Sheffield.

Closed loop process control in DED

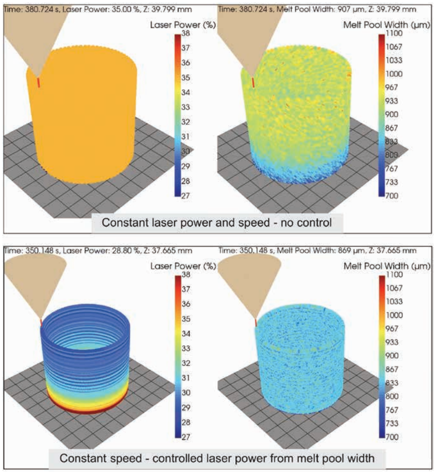
There is a drive in additive manufacturing (AM) to switch from constant processing parameters to variable parameters, controlled by sensor measurements of the live process acting on the material.

This means that AM processes can react to unknown changes in geometry, feedstock and environmental conditions to produce a reliable product.

In DED this control signal is primarily related to the melt pool, which is affected by the laser energy density, traverse speed and input rate of the feedstock powder or wire.

The University of Sheffield MAPP DED team has retrofitted a closed loop control system onto a BeAM Magic 800. The system involves analysing images of the melt pool taken from an optical camera positioned coaxial to the laser and powder feed nozzle. The melt pool dimensions are measured on-the-fly and used to determine the required change in laser power or traverse speed to maintain constant melt pool dimensions.

The figure below shows the differences in required laser power and melt pool width for builds of cylinders in a gas atomised stainless steel 316L powder. For the controlled build, the heat-sink effect from the build plate requires a higher laser power during the first 10-20% of the build. As the process moves further away from the baseplate the laser power reduces to maintain a constant melt pool geometry as the heat loss through conduction is also reduced.



Powder flow rate in DED systems

Numerous powder delivery methods in DED suffer from inconsistent feed rates or have insufficient controls to supply the required low flow rates with metal powders. It was noticed that delivering powder from a hopper and turntable system created a cyclical mass flow rate. This sinusoidal effect was detectable at multiple points, from the turntable itself through to the powder delivery nozzle.

MAPP used several techniques to characterise this flow variation to determine the best way to control for its resulting effects. The results of this work are published in Additive Manufacturing Letters (see p35 for more information) and are the subject of follow on work for closed-loop control development.

Henry Royce Institute - Materials 4.0 feasibility project

In December 2021, MAPP researchers Dr Ben Thomas, Dr Felicity Freeman and Dr Oliver Hatt were awarded feasibility funding for their project titled Digitisation of Powder Manufacturing.

This project will create a prototype Edge Computing platform, with modular networked sensors that can be retrofitted on industrial machinery. The platform is driven by the need to improve data management and data utilisation in materials science research, where data often has greater volume, velocity and variety than in industry.

The Edge Computing system will provide automated data acquisition and process control and will integrate with an in-house materials research data system. The combination of "computing at the Edge" and materials data "in the cloud" will combine characterisation and process data to feed machine learning activities across MAPP.

P2.2 SOLID STATE PROCESSING

P2.2a Field Assisted Sintering Technology/ Spark Plasma Sintering/Hot Isostatic Pressing

Investigators – Prof. Martin Jackson, University of Sheffield, Prof. John Francis, University of Manchester.

Collaborators – University College London (X1), Manchester (X2), Royce Translational Centre (University of Sheffield), Sir Henry Royce Institute (University of Manchester), Swansea University.

Continued research into the processing of metal powders via Field Assisted Sintering Technology (FAST) has led to several major developments in MAPP over the past year.

Following the opening of the Royce Discovery Centre (RDC) in Sheffield, researchers have begun to process both titanium powders and swarf using the new HP D 250 FAST machine from FCT Systeme GmbH. This equipment provides the capability for producing parts up to 250 mm in diameter and complements the pre-existing FCT HP D 25 FAST machine, which is still extensively used for smaller-scale R&D experiments up to 80 mm in diameter on an increasingly wider range of materials. One of the main benefits of producing larger FAST billets using the new equipment is the ability to extract a range of specimens for mechanical property testing with standard test dimensions. For example, for the tensile testing of a novel alloy produced by FAST consolidation of a blend of two commercial titanium alloys, with results demonstrating an excellent balance of strength and ductility.

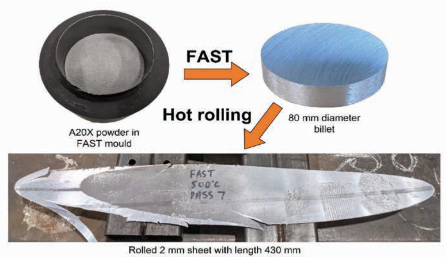
A key aspect of FAST research within MAPP is the processing of otherwise surplus metal powders which are out of size specification for common additive manufacturing (AM) techniques.

FAST is a promising alternative processing technique for these powders, especially when combined with subsequent thermomechanical processing steps. This has been reported using the Sheffield-developed FAST-*forge* route for titanium alloys.

More recently, rolling trials have been performed on billets of FAST processed A20X powder, an aerospace approved high strength aluminium alloy developed by Aluminium Materials Technologies Ltd (ECKART GmbH). The FAST material was successfully rolled from a 15 mm thick billet to a 2 mm thick sheet. Initial mechanical property data is encouraging, with FAST processed material exhibiting properties exceeding those of conventional cast alloy.

This work demonstrates that FAST can provide an effective processing route to convert surplus aluminium powders into useful sheet product, which has potential for use in the aerospace industry.

A collaboration between MAPP researchers at Manchester and Sheffield has investigated the use of FAST for the solid state processing of Dissimilar Metal Welds (DMW) joints. DMW joints are widely used to connect stainless-steel (316L) safe-ends to low-alloy-steel (SA508) nozzles of pressure vessels in primary loops of nuclear power plants (PWRs). These joints are traditionally made by arc welding, using a complicated



Processing of FAST consolidation combined with hot rolling to convert aluminum alloy powders into sheet product.

sequence of operations, which leaves high levels of residual stress. The fusion boundary region has a higher susceptibility to stress corrosion cracking than the bulk weld metal due to the change of microstructure as a result of dilution of weld metal during welding and migration of carbon and also due to presence of tensile stresses. A nickel based insulator layer is used in between dissimilar regions to prevent diffusion of carbon. Also, a post-weld heat treatment is required to relieve residual stresses after the welding process.

Recently there has been an interest in developing transition joints using solid state powder methods such as Hot Isostatic Pressing (HIP) and FAST. These processing techniques result in a dense component with uniform microstructure, thereby having superior properties compared to cast and forged components. The short processing time in FAST minimises diffusion across the dissimilar joint and prevents the formation of undesirable phases that affect the structural integrity.

Researchers at the University of Manchester and the University of Sheffield have produced dissimilar joints using FAST, with diffusion across the interface of less than 50 µm (Note: The diffusion in a conventional weld spans across a few millimetres).

Future work is planned on developing FAST transition pieces with a nickel insulator layer to further minimise diffusion. MAPP researchers are also in collaboration with Swansea University to develop dissimilar joints with a nickel insulator layer using powder interlayer bonding (PIB).

P2.2b Fundamentals of Solid State Processing

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

Collaborators – University College London (X1), University of Manchester (X2, P2.2).

This year the MAPP team at Oxford focused on two projects.

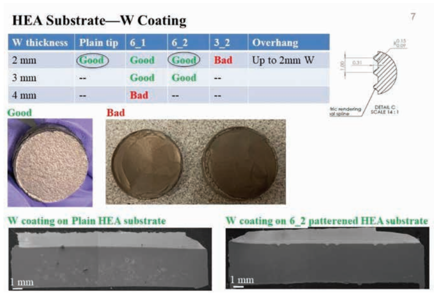
The first is to join tungsten (W) with a more irradiation resistant high entropy alloy (HEA) using a dual step FAST technique. It is based on the findings of a previous project.

By adding surface sculptures to the steel substrate, detrimental horizontal cracks can be modified into advantageous vertical cracks, which segments the tungsten coating and releases stress during thermal cycling.

However, the understanding of the cracking behaviour by introducing surface sculptures is still missing, and the possibility of expanding this technology to other alloy systems is unexplored. We focused on these questions.

We are aiming to understand the cracking behaviour in W coating during the FAST process via finite element modelling (FEM) and expand the technology to other alloy systems, e.g., high entropy alloy. We can achieve a coat of 3 mm thick W onto the HEA substrate and analyse the cracking behaviour within the W coating.

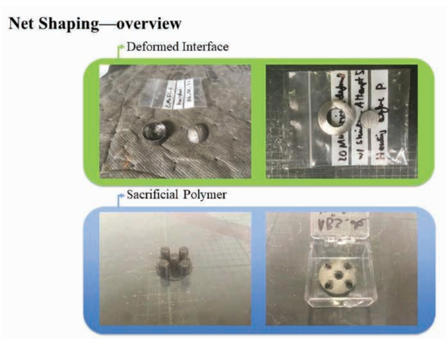
Within the project, we aim to understand and predict the W cracking behaviour under the different processing parameters and the complex stress field from surface sculptures, the different reaction of W coating with different alloy systems, and the effect of vertical cracks on the thermal cycling lifetime. We can use our understanding to manufacture thick W coating with a reasonable thermal cycling lifetime.



W thickness	Plain tip	6_1	6_2	3_2	Overhang
2 mm	Good	Good	Good	Bad	Up to 2mm W
3 mm	--	Good	Good	--	
4 mm	--	Bad	--	--	

Updates of the W coating project.

The second project aims to expand the versatility of FAST in the net shaping aspect. We are exploring the possibility of different sintering geometries within this project using the FAST technique. We have tried two methods by adding a deformed interface and a sacrificial polymer.



Updates of the net-shaping project.

P2.3 FUTURE MANUFACTURING PLATFORMS

P2.3a Diode Area Melting

Investigators – Dr Kamran Mumtaz and Dr Kristian Groom, University of Sheffield.

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

DAM uses an architectural array of low power, fibre coupled diode lasers to process pre-deposited powder.

The efficiently packed fibre arrays are integrated into a custom laser head (x50 lasers) designed to traverse across the powder bed.

Each laser diode is individually controllable, enabling selective laser processing of powder bed cross-sections and layered fabrication of 3D net-shape components. The operating wavelength of each of these lasers (450-808nm) are shorter than standard PBF systems, the laser energy is more efficiently absorbed by the feedstock material (e.g alloys of titanium, steel, copper etc.) allowing lower laser power to be used.

This process is inherently scalable, allowing hundreds if not thousands of lasers to simultaneously traverse and parallel scan across a build area, significantly increasing productivity compared to state-of-the-art PBF.

The most recent work has shown further efficiency gains with the use of low power blue laser sources (450nm) and the potential to control melt pool solidification, creating novel customisable microstructures.

P2.3b High Speed Sintering and Polymer AM

Investigator – Dr Candice Majewski, University of Sheffield.

Collaborators – University of Sheffield (X3), University of Manchester (X2).

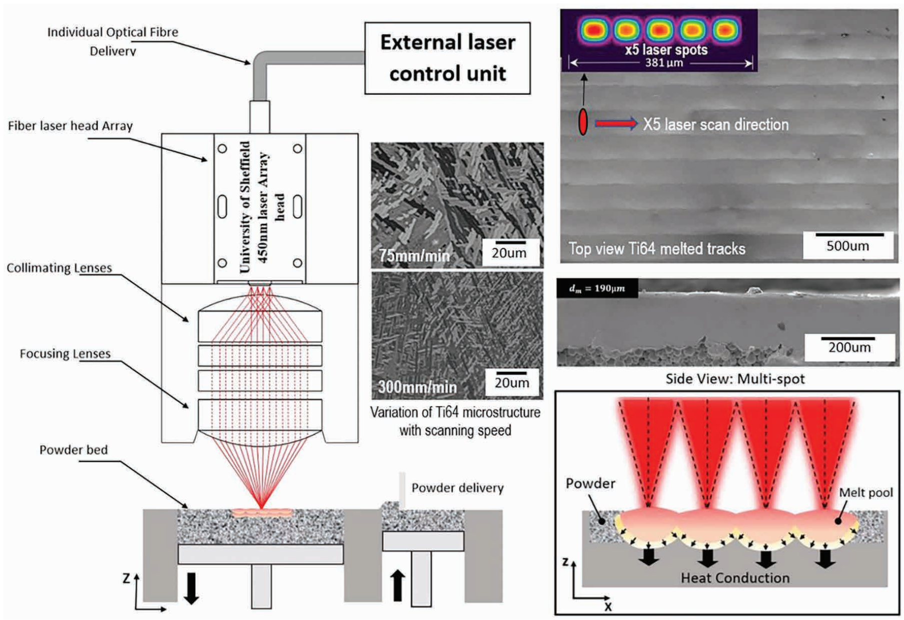
Our work in powdered-polymer additive manufacturing (AM) is focused on understanding the ways in which materials behave in our processes.

This in turn will allow us to maximise the quality and repeatability of the parts we produce - something that is particularly important to end-users of these techniques.

Through all of this research, we are supported by two excellent members of technical staff, Wendy Birtwistle and Kurt Bonser, and post-doctoral researcher Ryan Brown.

This year we have made progress in several areas. We've had some interesting results from work investigating the effects of different part manufacturing strategies for our processes in order to optimise part quality and post-processing behaviour, and PhD student Talal Al-Ghamdi has been investigating the effects of molecular weight on the behaviour of materials within the processes.

We have been working with Malvern Panalytical and Netzsch to investigate the use of advanced characterisation techniques for powdered-polymer AM, and have shown that we can use these techniques to identify variations in manufacturing behaviour between different material grades. This work highlights the increasing relevance of material characterisation in manufacturing, as well as the benefits to be gained through academia-industry collaboration.



Diode Area Melting.

Some of our efforts have been focused on understanding how parts produced using our techniques perform in real-life situations.

James Wingham has submitted his PhD thesis investigating antibacterial functionality for polymer AM, and Kieran Nar has recently published his first journal paper relating to characterisation of part surfaces. This work will underpin more detailed research into the tribological behaviour of polymer AM parts.

We've also been able to publish the first stage of our investigations into the long-term behaviour of parts, identifying the effects of ultra-violet weathering and beginning to understand the underlying causes of the changes we've observed.

Over the next year, we will be delving more deeply into these areas and working with our academic and industrial partners to see how our research findings, and the techniques we have been using to obtain them, can be applied to other areas of powder-based manufacturing.

We have also been working on non-experimental projects to further enhance our process understanding.

Oliver Leete is in the final stages of his PhD, producing a thermal model of one of our polymer processes; his work should provide us with greater insight into the effects of thermal variations (whether deliberate or not) and the approach he's taken should also be applicable across a range of powder-based AM processes.

Adam Gothorp's work applying Bayesian statistical methods to powder behaviour should also have an impact more broadly.

Of course we are always on the lookout for new problems to solve, so if anyone reading this has a powdered-polymer AM problem you would like to solve, please do get in touch.

High resolution image of the surface of a carbon-filled polyamide part produced using polymer Laser Sintering. Individual carbon fibres can be seen throughout the base polymer part. Image produced by PhD student Kieran Nar, whose PhD is focused around tribological characteristics of polymer additive manufactured parts.

P2.3c Ceramics

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

Collaborators – University of Oxford (P2.2), University of Manchester (X2), University of Leeds (P2.1), University College London (X1), University of Sheffield (X3, P2.2, P2.3), the Manufacturing Technology Centre, Photocentric.

We have continued our work on the development of new ceramic shaping and sintering technologies focusing on:

- The formulation of photocurable suspensions for the manufacturing of ceramics using digital light processing (DLP). Working in collaboration with the Manufacturing Technology Centre (MTC) and Photocentric, we have developed suspensions to build Al_2O_3 and SiC parts with a spatial resolution of ~100 microns. The work opens new opportunities for the extension of DLP to non-oxide ceramics, one of the current challenges in the field.
- The extension of robotic assisted deposition (robocasting) to the fabrication of ceramic composites and glasses. We developed technologies based on robocasting (core-shell printing, embedded printing) to print metal-ceramic and ceramic-ceramic composites with complex fibre arrangements or with bio-inspired structures using ceramic platelets. In collaboration with the University of Manchester, we are studying their fracture behaviour. The first results show how complex, auxetic structures embedded in ceramics guide crack propagation and enhance fracture resistance. We are currently extending the embedded printing technology to the introduction of complex microchannel arrays in ceramic bodies.
- The application of selected laser sintering and melting to ceramics. We previously showed how graphene enhances laser adsorption, opening new possibilities in the selective laser sintering and selective laser melting of laser transparent or reflective materials. Preliminary results obtained in collaboration with the University of Sheffield show how the strategy can be used in diode area melting to promote laser adsorption in ceramic powder beds.

In addition to our research on processing, we have developed a series of tools for the *in-situ* characterisation of mechanical properties at the micro to macroscopic scales.

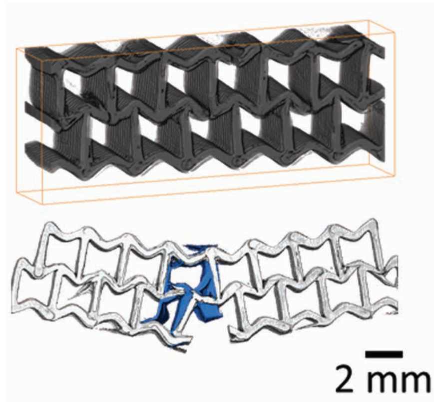
In collaboration with SECO, we are using these tools to quantify the fracture energy of specific grain boundaries in cemented carbides (WC-Co).

The goal is to guide the microstructural design of materials with improved fracture energy leading to better performance.

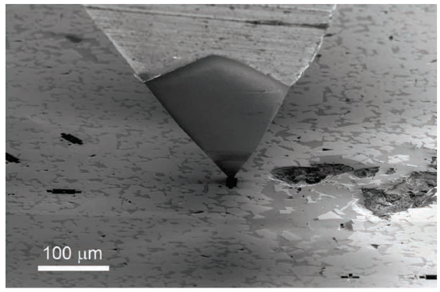
We are also using the techniques to measure the strength of ceramic granules used in processing and relate it to their performance.

At a more fundamental level, we have quantified the fracture energy of specific crystallographic planes in MAX phases.

This work helps us to understand the mechanisms leading to the enhanced fracture resistance of this important family of materials that exhibit an unusual combination of mechanical and thermal properties.

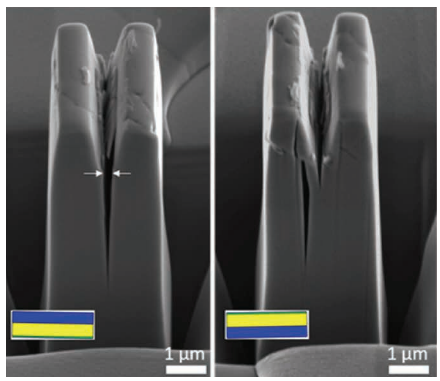


X-ray tomography of a steel auxetic structure embedded in a ceramic (Al_2O_3 in the top) and crack propagation inside the composite (bottom). In collaboration with the University of Manchester.



DCB testing of grain boundaries in WC cutting tool. Collaboration SECO tools.

SiC bars prepared by Digital Light Processing: effect of warping.



Microscopic Crack propagation in MAX phases.

CROSS-CUTTING X THEMES

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

X1 *In-Situ* Process Monitoring

Investigator – Prof. Peter Lee, University College London.

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

X1 has two main streams of research – Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition Additive Manufacturing (DED-AM).

Correlative imaging of the AM process has been achieved. With machine learning, better prediction and understanding of the weld pool dynamics in DED, and keyhole dynamics in LPBF, have been possible.

LPBF

The team has made significant advances, developing the world's first Quad laser *In-situ* and Operando Process Replicator (Quad-ISOPR), combining Renishaw's RenAM500Q scanning head with UCL's in house ISOPR printing chamber, enabling concurrent high-speed x-ray, optical and, soon, infra-red (IR) and chemical imaging too.

The Quad-ISOPR is capable of applying multi-beam strategies to better control the thermal gradient within the part, allowing us to instantaneously quantify the impact of altering processing parameters on build quality, with a goal of printing previously "unprintable" alloys.

Initial beamtime experiments are being conducted at the European Synchrotron Radiation Facility (ESRF). These experiments will provide a better understanding of the process dynamics during multi-laser LPBF to avoid the formation of features while printing and improve the part production process.

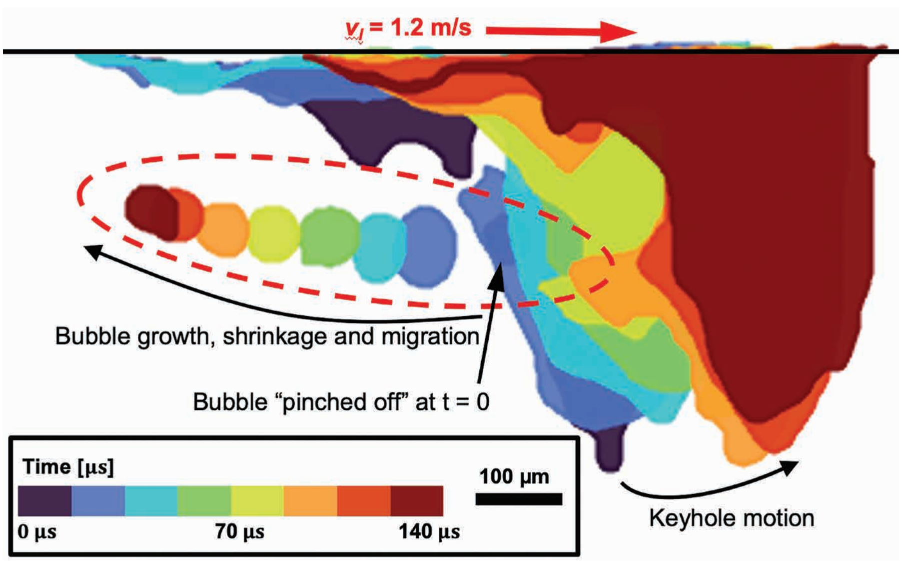
In addition to Quad-ISOPR, we are developing a chemical imaging system to monitor the vapour plume generation process, this may enable users to dynamically control and minimise the plume generation during LPBF.

DED-AM

The team has employed an in-house Blown Additive Manufacturing Process Replicator Second Generation (BAMPR II) in different beamtime experiments at both ESRF and Diamond Light Source (DLS).

Diffraction and tomography results revealed the impact of various process parameters on build quality, mapping the optimum processing parameters for a range of materials including high-temperature capable titanium and nickel alloys. These studies also revealed many previously unobserved phenomena, for example, the mechanisms by which oxidation affects titanium alloy builds, and how pores can be pushed along in the DED weld pool.

Additional rigs were developed to include magnetic field as a novel parameter to control the build microstructure.



The synchrotron captured the ultra-fast dynamics of keyhole pore formation. Courtesy Yuze Huang.

X2 Advanced Characterisation

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

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

X2 working with P2.2a

Useful insights have been gained into the Hot Isostatic Pressing (HIPing) process of a novel Ti-Fe binary alloy via *in-situ* mimic HIPing experiments under synchrotron X-ray.

For the first time, the whole densification process from elementary Ti and Fe powders to a fully dense Ti-Fe composite has been recorded by X-ray imaging.

The consolidation of the powders and the deformation of the powders into each other has been successfully captured.

The outcomes will serve as a good starting point to understanding the effect of powder characters on their HIPing response. Moreover, these results will be a solid reference to validate the processing models against.

In-situ diffusion of the fully-dense Ti-Fe composites has been investigated using synchrotron X-ray. The progressive 'dissolution' of the Fe particles into the Ti matrix was recorded. The outcomes underpin the understanding of the inter-diffusion process that is generally essential during the homogenisation of an alloy produced by HIPing elementary powders. This coupled with phase composition determined by X-ray diffraction will help tailor the design of alloy composition and microstructure for improved alloy properties.

Informed by the direct observation of the key processes in HIPing, the Manchester team is aiming to develop image-based models to simulate the actual HIPing process. Such models, when calibrated against the experimental observations, will produce a valuable guide on HIPing parameter optimisation and understanding the role of material properties on their HIPing response.

X2

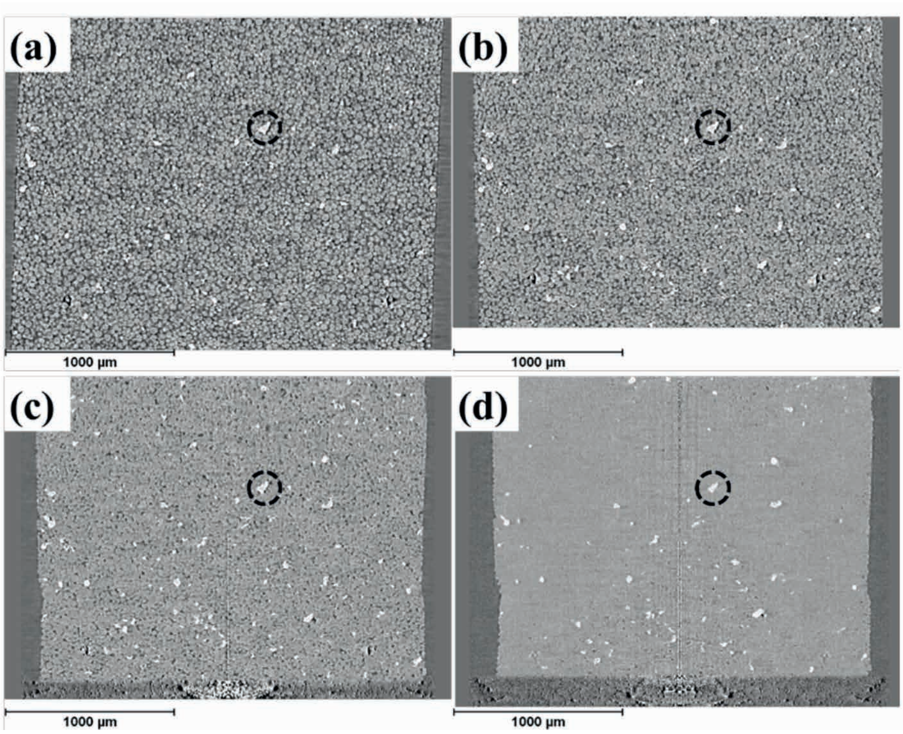
This joint project between Imperial College London and the University of Manchester focuses on understanding the fracture characters of an additively manufactured steel reinforced ceramic (Al_2O_3) matrix composite. Unlike monolithic ceramics, this composite shows a significant improvement in fracture toughness thanks to the auxetic steel reinforcement, making it a promising structural material in applications under a harsh environment. Through an *in-situ* four-point bending test within an X-ray Computed Tomography (XCT) scanner, the detailed crack initiation and propagation has been recorded. More importantly, how the propagating crack interacts with the auxetic steel reinforcement has been elucidated. An image-based FE model was also developed from the XCT images, enabling a parametric study of the effect of the matrix property, reinforcement property and interface property on the overall mechanical response.

X2/REINSTATE

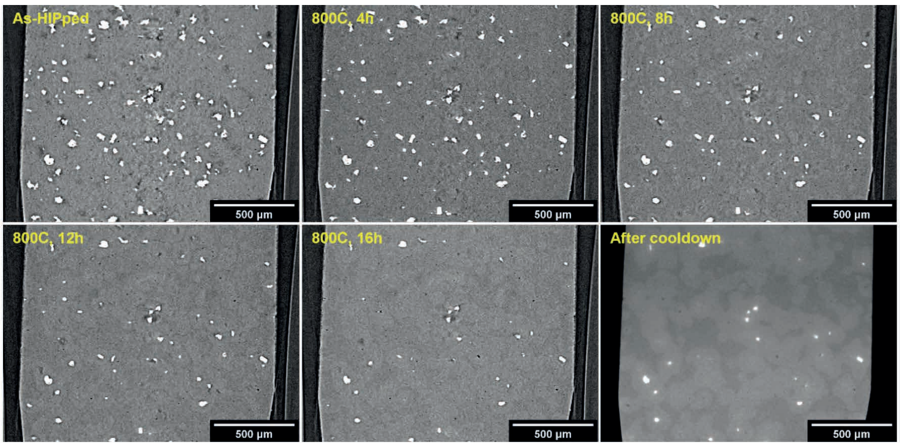
The MAPP team at Manchester has developed an automated workflow to analyse powders for AM using X-ray micro-CT (μCT).

This workflow has been applied to a range of powders supplied for Rolls-Royce Plc as part of the ATI programme REINSTATE (Repair, Enhanced Inspection and Novel Sensing Techniques for increased Availability and reduced Through life Expense).

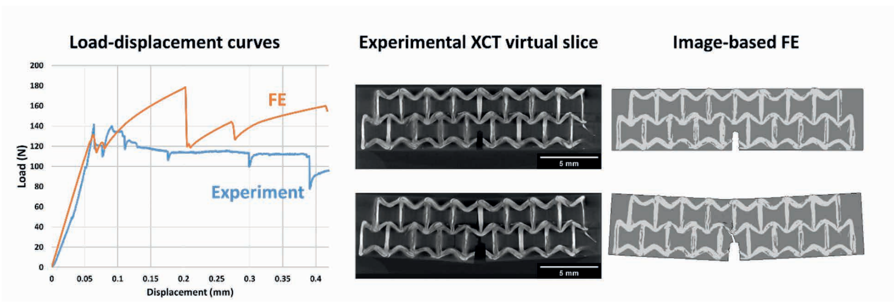
This work allows for databases for each powder to be established, which will then be linked with the characters/performances of the additively manufactured components.



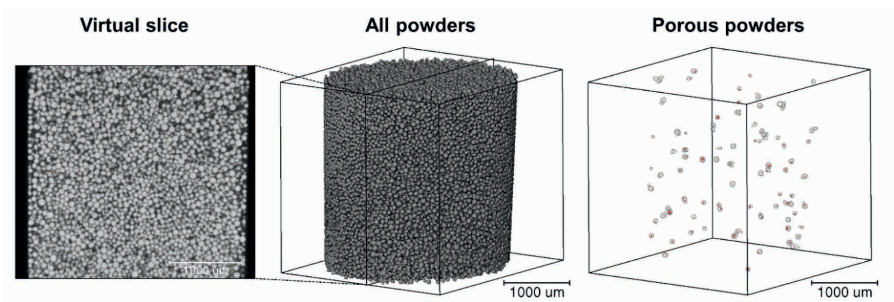
Synchrotron XCT virtual slice showing the same cross-section of a Ti-2 weight %Fe powder mixture (a) as-filled; (b) under pressure at room temperature; (c) after heating and (d) when the powder becomes fully-dense.



XCT virtual slices showing the same cross-section of an as-HIPed Ti-5 weight %Fe composite during the post-HIPing homogenisation process.



In-situ study and modelling on the fracture property of an AM steel-reinforced Al_2O_3 matrix composite.



An example showing the XCT image of one powder and individual particles analysed by the automatic workflow. Porous powders are also picked out and highlighted.

X3 Modelling, Optimisation & Control

Investigators - Prof. Visakan Kadirkamanathan and Prof. George Panoutsos, University of Sheffield, Assoc. Prof. Phillip Stanley-Marbell, University of Cambridge.

Collaborators – University of Sheffield (P2.1), University College London (X1), Imperial College London (P2.3).

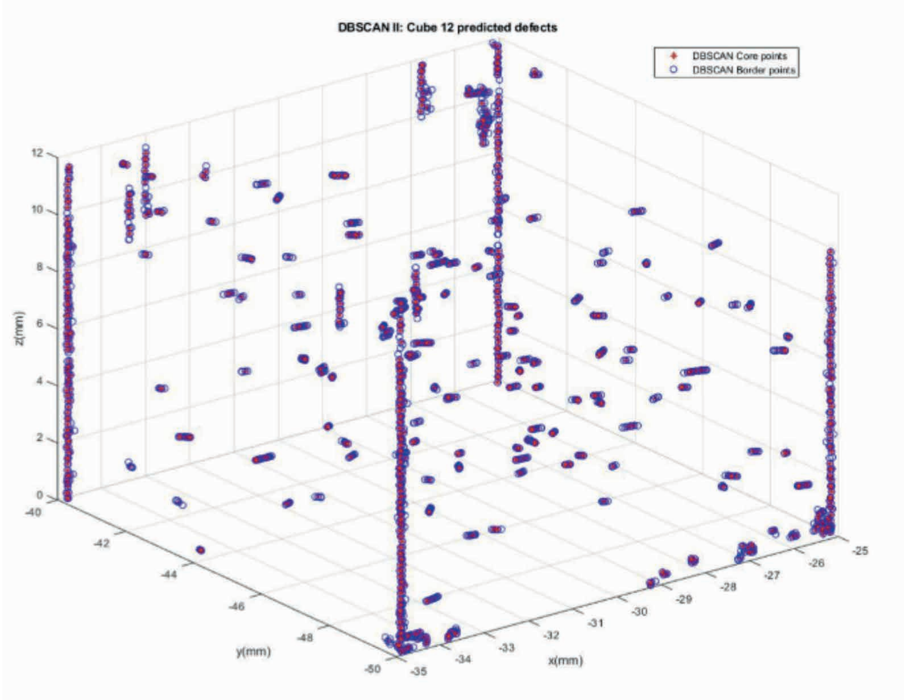
A number of underpinning research themes are now maturing in the programme, hence we see fundamental publications in process modelling, optimisation and control. We expect these to translate into specific additive manufacture (AM) case studies via wider engagement in the MAPP hub. Seven publications have been submitted. There have been four workshops/conference talks, three new partnerships and four new research awards.

Additional external and internal funding has given us the opportunity to engage more with external partners while bringing in additional capability (e.g. a funded studentship in AI-based control in Electron Beam Melting).

In powder-bed systems, and in process control, in particular, we have developed a 'control-ready' model for a Laser Powder Bed Fusion (LPBF) process (Al-Saadi, Panoutsos), as well as conducted a survey paper on advanced control in LPBF (Al-Saadi). In addition, we demonstrated how we can predict *in-situ* outlier performance (based on spectral emissions) and correlate these results with porosity defects (Panoutsos).

We submitted two publications on how to build physics-guided neural-based learning structures, capable of efficient data-driven learning, as well as accurate representation of underlying physics (Atwya, Panoutsos).

Separately, we published work on many-objective evolutionary optimisation strategies for part design simultaneously with minimising part defects (Wu, Panoutsos).



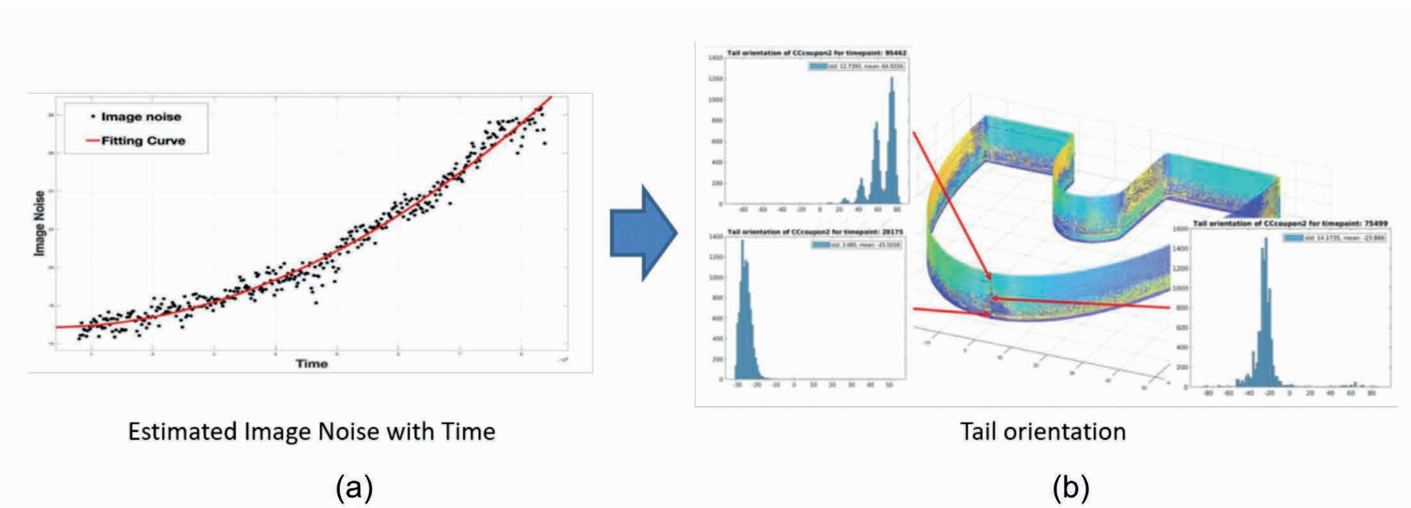
In-situ predicted (and XCT validated) part defects (aluminium, LPBF spectral emissions).

In Direct Energy Deposition (DED) and in process control specifically, we have developed a multivariate control strategy with computational efficiency, and a simulation/demonstrator software showcasing feedback controlled beam manipulation, on-the-fly (Aftab, Panoutsos).

We created a demonstrator system for *in-situ* outlier detection based on statistical process control, and we are now in the process of integrating this work with a digital twin of the process (Sahin, Panoutsos).

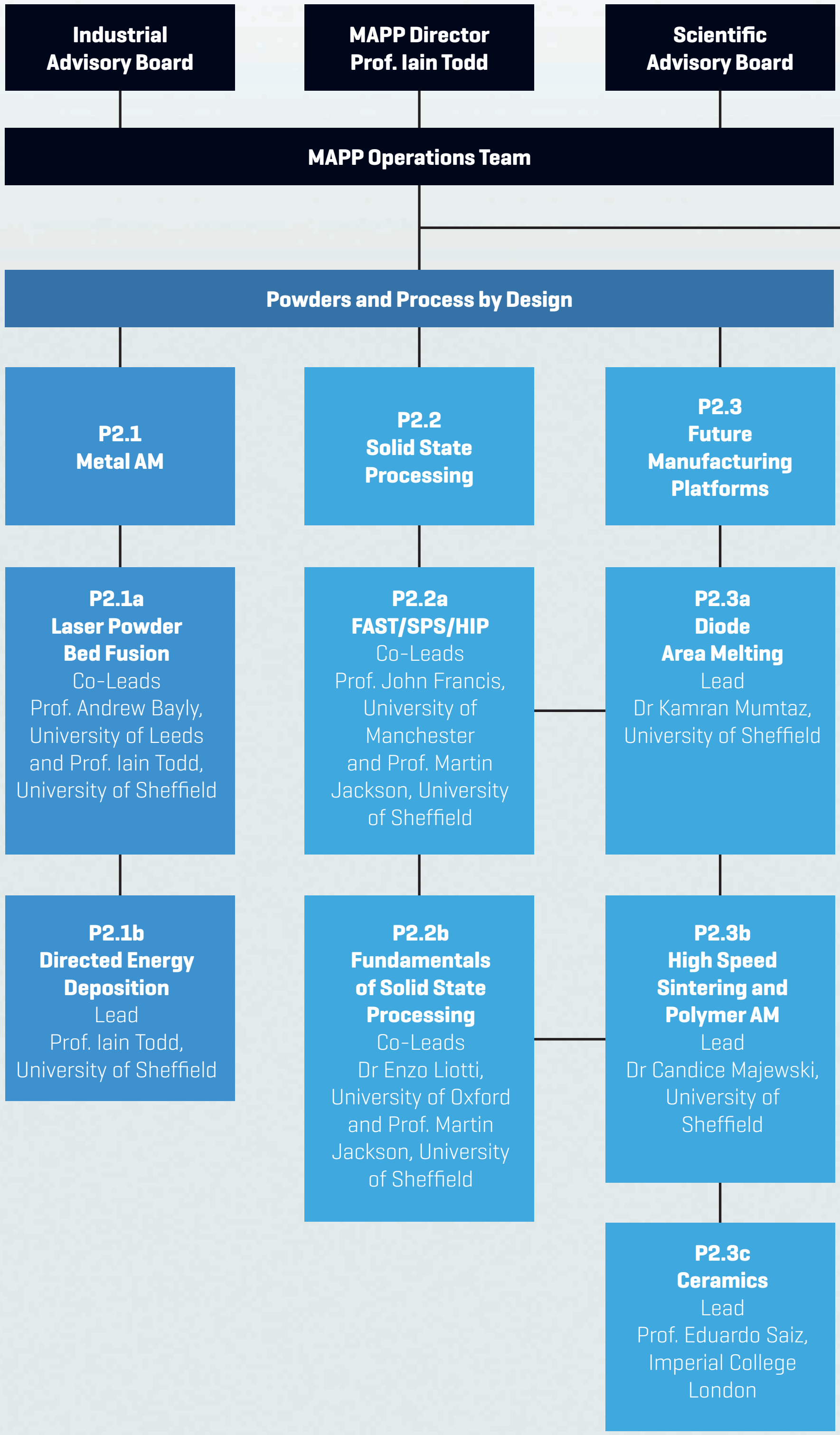
Under the same theme, of process monitoring in DED, we estimate image noise, on an image by image basis, using high pass filtering and outlier detection (Notley, Panoutsos). Distributions on the meltpool features, derived from the thermal image, are subsequently estimated using Monte Carlo simulation (based on the estimated noise level). The method shows increasing levels of image noise, with build time, leading to increased levels of uncertainty on derived meltpool features. Furthermore, a signal processing of consecutive melt pool images to create spatio-temporal features for part quality assessment (Aflyatunova, Kadirkamanathan).

Finally, a Bayesian design of experiments optimisation was applied to identify process conditions to optimise microstructure of built parts (Harding, Kadirkamanathan).



Uncertainty distributions for meltpool tail orientation estimated using Monte Carlo simulations;
(a) Image noise estimated as a function of build time and (b) tail orientation distributions for three geometrically similar points with increasing build time.

MAPP PROJECT
ORGANISATION CHART



Co-Investigators in Powders and Process by Design

Dr Finn Giuliani, Imperial College London

Prof. Patrick Grant, University of Oxford

Dr Kristian Groom, University of Sheffield

Assoc. Prof. Ali Hassanpour, University of Leeds

Prof. Andrew Mullis, University of Leeds

Prof. Philip Prangnell, University of Manchester

Prof. Luc Vandeperre, Imperial College London

Dr Jon Willmott, University of Sheffield

University Partners

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

Co-Investigators

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

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

Co-Investigators

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

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

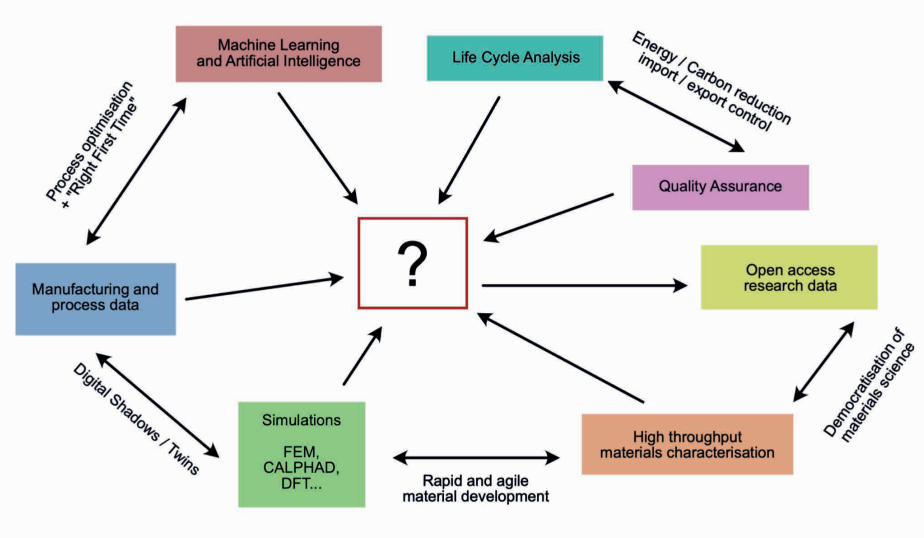
Co-Investigators

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

DEVELOPMENT OF A FRAMEWORK

CORE FOR MATERIALS 4.0 IN ACADEMIA

Dr Ben Thomas, Research Associate, the University of Sheffield, explains how we are adopting digital tools and technologies in manufacturing and developing a materials data framework.



Hub and spoke links between the systems that currently benefit from the digitisation of materials science. Links around the rim of the 'wheel' show some of the areas of "Materials 4.0" under active investigation. The 'hub' that binds all of these systems together, enabling data interchange, still doesn't exist.

Materials science is a data-heavy field.

All of this data has an intrinsic value, which for materials science is based on factors such as the manufacture of novel materials, sample preparations and time expensive experiments.

The same can be said for industry, where profit margins can be eaten up by lengthy development cycles, extensive sample testing and quality control procedures.

Research data can also have a tremendous latent value when we consider how the use of machine learning algorithms can leverage extra knowledge and understanding.

Further value is embedded when data is used for quality assurance and tracing materials throughout their life cycle; tracking energy/ carbon input and environmental impact at each process stage.

It has long been recognised that effective data management can be the key to improving efficiency in materials research and opening up its added value.

By making sure that data is appropriately labelled and archived, future researchers can build on previous results and prevent unnecessary replication of experiments.

Industry avoids this through centralised IT systems, quality control frameworks and resource management systems. The inherent value in a company's product development data is seen as a critical asset with a tangible monetary value.

Despite these good practices, industrial materials knowledge is often restricted to the domain of their products. Companies don't have access to sufficient data or knowledge to be truly agile in their development of new materials or applications.

Academia's model for materials data management has several major flaws. Academia is heavily biased towards a model of written publications for the communication of experimental data. This means that complex raw data is hidden within charts in PDF documents and heavily manipulated to normalise graph axes or by using poorly reported data analysis techniques. This makes data reproduction incredibly difficult and prevents the scientific community from effectively appraising research outputs or data analysis steps.

Thankfully there has been a shift in recent years with the introduction of journals dedicated to the publication of methods and datasets.

There is also now a push by funding bodies to require research teams to share the data behind their publications in raw, open-access formats; a requirement that is also mirrored by some publishers.

Open access data archives are now beginning to spring up everywhere, enabling researchers to share their datasets with others around the world.

These systems, however, have to accommodate a wide range of data types and working practices, which results in the most viable archival format consisting of a 'dump' of zip files with a readme or spreadsheet file to describe what is in the folders and files.

People wanting to access this data find themselves in a position of having to manually curate all this data into their own formats or to abandon access attempts altogether.

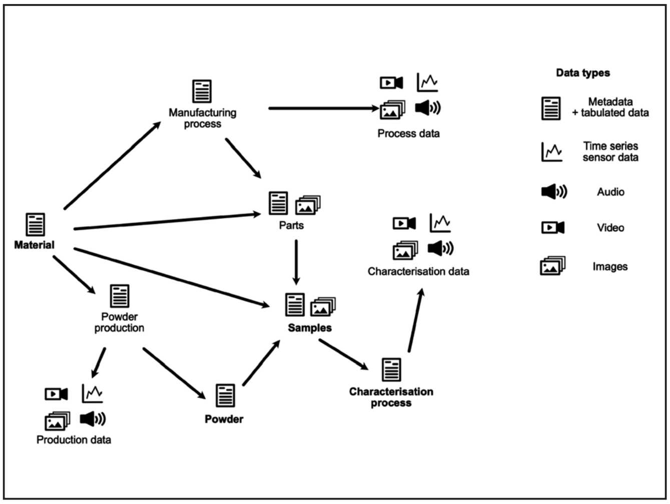
There is a general consensus that about 80 per cent of a data analyst's time is spent identifying, cleaning and transforming data to fit into their algorithms.

If computing hardware is becoming ever more powerful and easier to access, data curation tasks will continue to be a limiting factor that stifles rapid innovation.

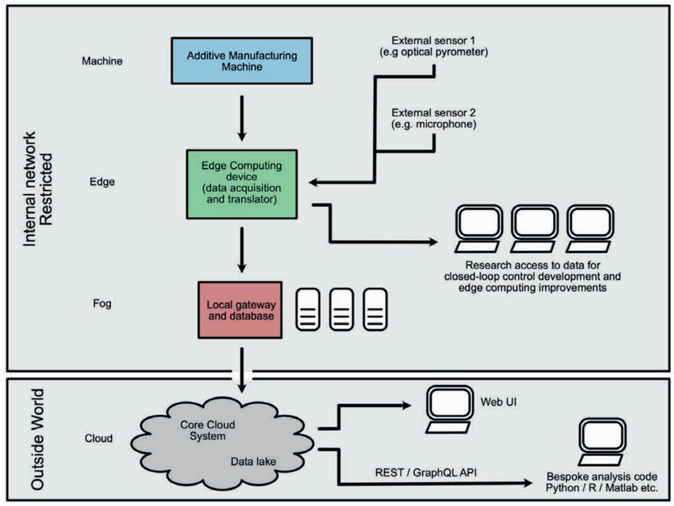
The assertions in the previous paragraphs are, in some cases, over-generalisations and many areas of science, such as physics, biochemistry and pharmacology, are already dealing with these issues very effectively.

However, I am sure that many academics who read this can relate to the feeling of despair when knowledge is lost through factors such as poor experimental design, sparse data logging, hardware failures and high turnover of research or technical staff.

Within MAPP, these issues have been brought to the fore with researchers coming together to feed their expertise into solving common issues within powder metallurgy and polymer sciences.



Pseudo data flow chart for a portion of the 'Materials Curation System.' Types of data are shown for each node in the chart.



Schematic of the hardware infrastructure to automate complex research data acquisition and management for additive manufacturing.

The problems being addressed range from fundamental powder flow behaviour to complex thermo-mechanical powder processing. When you add in the development of machine learning algorithms to expedite knowledge generation, process optimisation and control of the powder process, you can see how important data generation, acquisition and dissemination is to the project.

Working in conjunction with the Henry Royce Institute at the University of Sheffield, MAPP is prototyping its own materials data framework as a way to solve these complex issues.

The aim is to provide a platform to enable researchers to easily input, curate, query and analyse the multitude of complex data that is being generated across the wide breadth of materials science.

Another major part of the development is the integration of live process data from new equipment brought by the Henry Royce Institute as well as legacy equipment.

We are currently in the design and prototyping phase and are testing several sub-systems within the University of Sheffield.

These sub-systems cover materials data across the full research workflow from material creation, alloy design and manufacture to process window investigations and final part characterisation.

The backbone is a common language based on JavaScript Object Notation (JSON). We hope to be able to provide interlinks between our own and existing systems at a later date.

A major distinguishing feature is the integration of raw experimental data. The easiest way to do this would be to create a range of data 'ingesters'; peripheral code functions that take an input of text files from equipment and translate them into the predefined format for the core system to store.

This relies on users manually inputting the data and provides several opportunities for the 'human-factor' to degrade data quality.

Because we have physical access to all the equipment that we intend to integrate, it is possible to automate a large portion of this data transfer, ensuring data integrity and compliance.

A good example is the process data from a Laser Powder Bed Fusion (LBPF) additive manufacturing machine.

The machine operator will typically fill in a list of build parameters on a spreadsheet and prepare the build-in specialist CAD software.

Once complete, the parts are removed, cleaned and sent for post-processing. At all stages of this process, it is possible to haemorrhage data, through poor recording of build parameters, not tracking powder usage, not acquiring peripheral data from extra sensors and not characterising/debugging failed parts.

By linking the machine use logs, automating data acquisition of external sensors, flagging failed parts and ensuring data input from users into an easy-to-use common system it is possible to ensure a minimum data standard for all LPBF builds.

This in turn leads to good quality datasets that subsequent users can build on.

Maximising automation in this environment frees up researcher time, maximises data acquisition and quality, and breaks through resistance to workflow changes by minimising changes to the users' regular routines.

In December 2021, Dr Ben Thomas was awarded a pilot study grant from the Henry Royce Institute to create a proof of concept data platform for Materials 4.0. The work will produce an edge computing framework that takes live process data from numerous bespoke sensors, stores it in a prototype Materials 4.0 database and creates data streams to external control scripts and digital twins. It will provide the foundations for a research-driven Digital Innovation Factory in engineering materials at the University of Sheffield.

EVENTS

2021–2022

MAPP has attended and hosted hybrid, in-person and online events in 2021 and 2022.

The MAPP Lecture series has continued online, a hybrid workshop was hosted in partnership with CAM² (see page 23 for more details) and MAPP's Quarterly Meetings were held as online and hybrid events.

Our researchers have been involved in many conferences, as both delegates and presenters, as well as public engagement events.

This has included:

Exploring STEM for Girls
(March 2022)

MAPP researchers attended this annual event that saw about 180 13 to 16-year-old girls explore their options in STEM (Science, Technology, Engineering, and Mathematics), related careers and pathways.

Additive Insight podcast
(January 2022)

MAPP Investigator Dr Candice Majewski took part in the podcast's Innovators on Innovators series. During the episode, she discussed with Alex Kingsbury, an AM Industry Fellow at RMIT University, how they came to work in the 3D printing space, the importance of standards being developed to allow industrialists and academics to better understand each other, and their wishes for the future of AM.

Image-Based Simulation for Industry 2021
Institute of Physics
(October 2021)

Dr Chu Lun Alex Leung was a keynote speaker. His talk was titled Seeing inside powder bed fusion with X-ray imaging and image-based modelling.

1st Conference on FAST/SPS from Research to Industry
(October 2021)

Cameron Barrie, Dr Oliver Levano Blanch, Dr Simon Graham, and James Pepper spoke at the conference.

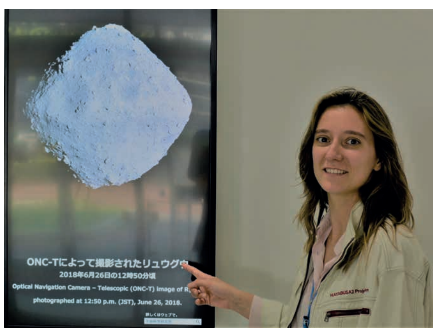
TMS 2021
(March 2021)

The Materials Structure & Manufacturing group at Harwell presented 13 talks and some posters. MAPP speakers included Alisha Bhat, Dr Yunhui Chen, Xianqiang Fan, Prof. Peter Lee, Dr Chu Lun Alex Leung, Seb Marussi, David Rees and Dr Lorna Sinclair.

Skype a Scientist
(March 2021)

Dr Rob Snell spoke online to children at schools in Brooklyn, Chicago and Ohio, giving them an opportunity to find out more about his work. Topics included 3D printing, what it is like being a scientist, the size of the Arcam Q20plus and career options. Some pupils got to watch a live build in the Henry Royce Institute at the University of Sheffield's Royce Discovery Centre, based in the Harry Brearley Building at the University of Sheffield.

Dr Chu Lun Alex Leung speaking at MAPP's 2019 Industry Partner Briefing event.



Dr Stefania Soldini, Lecturer in Space Engineering at the University of Liverpool.

MAPP LECTURE SERIES

The MAPP Lecture Series has gone from strength to strength since its launch in 2017 with a wide range of thought-provoking topics.

In 2020, 2021 and for some of 2022, the lectures were held online due to Covid-19 restrictions.

Each of the one-hour online lectures attracted more than 50 attendees from industry and academia.

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

Dr Catrin Mair Davies a Reader in Structural Integrity of Alloys at Imperial College London, gave her lecture, Residual Stress Prediction, Mitigation and Model Validation in Laser Powder Bed Fusion of 316H Stainless Steel in February 2021.

Professor Nick Lavery, Director of the Materials Advanced Characterisation Centre and lead academic of the Swansea Manufacturing Research group spoke about Developing High Entropy Alloys for Additive Manufacturing in March 2021.

In June 2021 Professor Adam T. Clare, University of Nottingham, gave the lecture Metal Additive Manufacturing: What Next? It was followed by a short talk, titled Towards Perfect Powders: New Methods for Powder Modification and Re-Use in AM, given by Dr James Murray, University of Nottingham.

In December 2021 Dr Stefania Soldini, Lecturer in Space Engineering at the University of Liverpool, spoke about the Connected Everything Feasibility Study on Manufacturing of 3D-printed morphing origami solar sails for the next generation of CubeSats.

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

SUCCESSFUL WORKSHOP ON ARTIFICIAL INTELLIGENCE IN ADDITIVE MANUFACTURE

A joint Centre for Additive Manufacture – Metal (CAM^2) and MAPP hybrid event

Prof. Iain Todd (front left) and Prof. George Panoutsos (middle left) during a networking session at the workshop on Artificial Intelligence in Additive Manufacture.

A workshop on **Artificial Intelligence in Additive Manufacture (AM)** provided an opportunity for MAPP to connect with more than 180 colleagues and address some AM monitoring, control, and data challenges.

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

To enable this requires an extremely high degree of control over the process.

To achieve this needs advances in machine control and sensor technologies and in the application of modelling and machine learning in understanding process planning and its direct control.

Researchers at CAM^2 and MAPP have been deeply involved in the development of new methods and strategies and their application to the control of the AM processes and components manufactured by AM.

The joint workshop, on Wednesday 20 October 2021, focused on this research, the opportunities the digitalisation of the AM process offers and the continuing research challenges it presents.

The workshop covered the following topics:

- Quality Assurance and Sensors for AM – including thermal, hyperspectral, audio.
- Artificial Intelligence/Machine Learning and physically-based modelling for AM.
- Ground Truth in AM processes.
- Digital qualification of processes and materials.

The programme included MAPP Director Professor Iain Todd, Professor Eduard Hryha, director of CAM^2, and speakers from Chalmers University of Technology, the University of Sheffield, the University of Cambridge, Siemens Energy, Linde, Wayland Additive, and Alloyed.

The workshop ran as a hybrid event, with the opportunity to attend in person or access the event virtually.

More than 130 colleagues connected online, 30 colleagues attended the in-person venue in Sheffield, UK, and 20 colleagues attended the in-person venue in Göteborg, Sweden.

Delegates during a talk at the workshop on Artificial Intelligence in Additive Manufacture.

Dr Ben Thomas presenting at the workshop on Artificial Intelligence in Additive Manufacture.

Networking session at the workshop on Artificial Intelligence in Additive Manufacture.

CELEBRATING COLLEAGUES' ACHIEVEMENTS

Professor Eduardo Saiz

The Institute of Materials, Minerals and Mining (IOM3) has awarded two highly esteemed prizes to members of MAPP's Executive team.

MAPP Executive member and P2.3c Ceramics theme lead Professor Eduardo Saiz, Imperial College London, has been awarded the Verulam Medal and Prize which is presented in recognition of distinguished contributions to ceramics.

Prof. Saiz said: "This is not just an award for me but also for all the people who have helped me over the years. I have been lucky to work with great colleagues, students, technical and administrative staff throughout my career."

MAPP Executive member and X1 *In-Situ* Process Monitoring theme lead Professor Peter Lee, University College London, has been awarded the John Hunt Medal which is presented for outstanding contribution to the science and/or technology of casting and solidification of metals. The award recognises the lifetime contribution of Professor John Hunt FRS and is supported through the General Research Institute of Non-ferrous Metals (GRINM) in Beijing.

Prof. Lee said: "It is an honour to be awarded the John Hunt Medal. John was not only a world-leading solidification expert but also a mentor of dozens of researchers during their early career, including myself, always challenging our theories and by doing so improving them."

Professor Peter Lee

A MAPP scientist's work on the additive manufacture of magnetically graded steels has won a prestigious prize in the European Powder Metallurgy Association's 2021 Thesis Competition.

Post-Doctoral Research Associate Dr Felicity Freeman, the Department of Materials Science and Engineering, University of Sheffield, won the first prize in the Diploma/PhD category for her thesis on: 'Structuring Difference: The Additive Manufacture of Spatially and Functionally Differentiated Microstructures'.

The thesis covers the development of an *in-situ* magnetically and microstructurally graded material, built by selective laser melting from a single composition of 17-4PH stainless steel.

Dr Freeman said: "Winning this prize has been a wonderful bit of good news, after a rather unusual year. It's always nice to get acknowledgement and recognition of something you've spent a lot of time and effort on, particularly from people outside your day-to-day network."

Dr Felicity Freeman

MAPP Investigator and P2.3b High Speed Sintering and Polymer AM theme lead Dr Candice Majewski has been shortlisted as one of five finalists for the TCT Women in 3D Printing Innovator Award 2022.

It is the second year TCT has collaborated with Women in 3D Printing to present the TCT Women in 3D Printing Innovator Award.

The award recognises the fantastic work that women are undertaking in the additive space.

Women in 3D Printing is a global organisation dedicated to promoting, supporting and inspiring women who are using additive manufacturing (AM) technologies.

The ultimate winner will be decided by a public vote which closed in February 2022, with the winner announced at the TCT Awards ceremony on 8th June 2022.

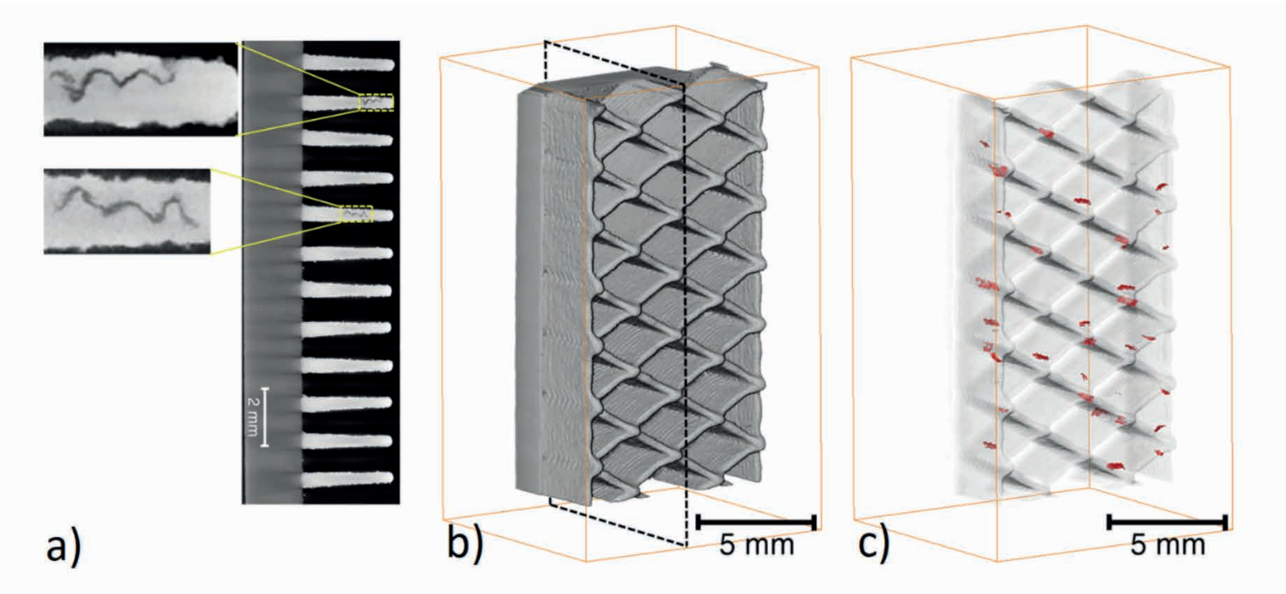
Dr Majewski said: "'I'm excited and honoured to be short-listed for this award, and to be nominated alongside some other incredible women working in 3D Printing. Regardless of who 'wins' the award, this is a great chance to celebrate the amazing work being done by women around the world to keep pushing the boundaries of 3D Printing."

Dr Candice Majewski

ABRADABLE TURBINE SEAL

SEGMENT REPAIR

MAPP researchers at the University of Manchester are closely collaborating with Swansea University and Rolls-Royce Plc to gain a detailed understanding of Turbine Seal Segments using advanced X-ray Computed Tomography (XCT) techniques.



XCT images of a seal segment repair imaged by MAPP researchers at the University of Manchester. The detail of two sub-surface cracks has been highlighted in a cross-sectional slice (a) taken through the 3D solid reconstruction of the seal segment (b). The internal crack locations are mapped in the transparent 3D visualisation of the seal segment (c).

Abradable seals used in Rolls-Royce turbine engine applications are worn down in service and can be subsequently repaired using the blown powder or Directed Energy Deposition (DED) processes.

To increase the lifespan of abradable seals, new deposit geometries have been designed and manufactured using the powder-based process.

To simulate the failure of the new geometries, a new mechanical test method based on four-point bend testing is being trialled by Rolls-Royce supported PhD student, Zac Nye, studying at the Institute of Structural Materials (ISM), Swansea University.

Bend tests to date have been run on varying seal segment geometries that have received different prior-test heat treatments to simulate *in-situ* thermal stresses.

Being able to determine the extent of any cracking present, without destructively sectioning the components, allows the four-point bend testing to be carried out sequentially with incrementally higher bending stresses. This requirement has led to a research collaboration between Swansea University and MAPP at the University of Manchester with oversight from the Materials experts at Rolls-Royce.

The Manchester team have studied the internal structure of seal segment repairs using XCT. The extent of any internal cracking in the repair has been revealed in 3D.

More importantly, the locations of the cracks with respect to the supporting structure have been determined and are being tracked after sequential bend-testing.

The outcomes are enabling the researchers to better understand the crack formation mechanisms, levels of bending stresses that can be applied and which geometries are most resistant to cracking.

The research conducted by the University of Manchester has highlighted a number of additional aspects in which XCT can be used for insightful, non-destructive evaluation of components repaired using DED.

IN-SITU IMAGING OF ADDITIVE MANUFACTURING PROCESSES

Dr Lorna Sinclair passed her PhD viva in 2021. She was a PhD student in Professor Peter Lee's group at UCL, based at the Research Complex at Harwell.

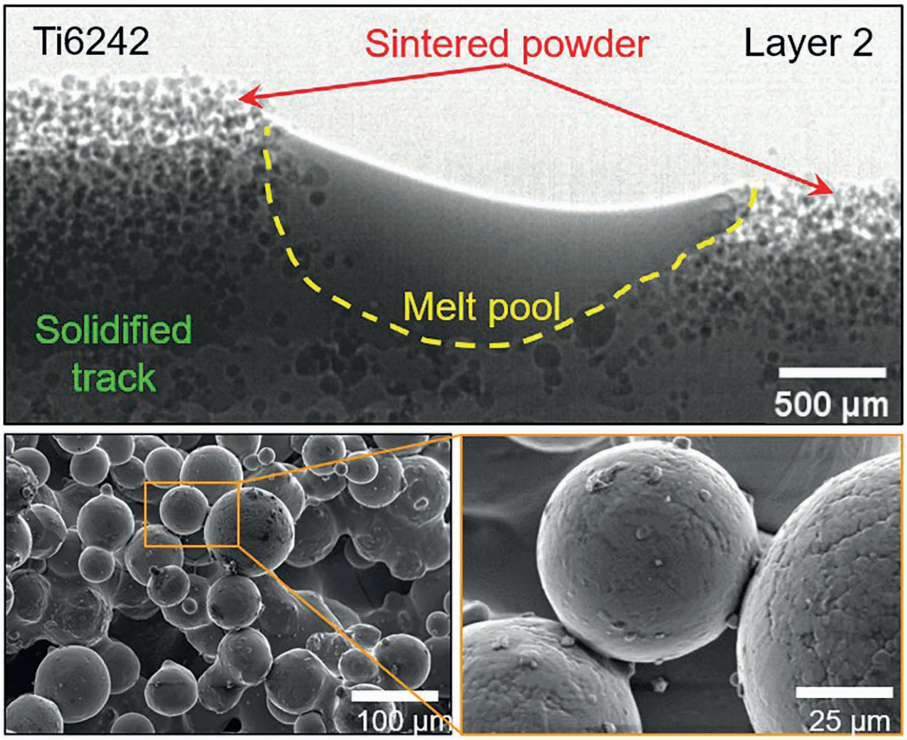
She has helped to design and build an *in-situ* process replicator for the blown powder additive manufacturing process, which is used for synchrotron X-ray experiments that have led to greater understanding of the process.

Her work's main focus was to study the molten pool dynamics and solidification characteristics of metallic powders during AM. She also studied the interactions between the laser and powder particles, and the formation of defects such as porosity during processing.

She gives an overview of her PhD's three main areas:

"I worked on Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition (DED), using our AM process replicators on the synchrotron to capture x-ray images of the processes *in-situ* which shed new light on what is happening during AM builds. The *in-situ* process replicators replicate commercial systems and are custom-built for use on synchrotron beamlines.

"Initially my main focus was on DED but I looked at LPBF too while the DED *in-situ* process replicator was being built.



X-ray radiograph image of the melt pool in DED using Ti-6Al-2Sn-4Zr-2Mo alloy, showing a build-up of sintered powder on the track, and SEM images of the powder showing classic sintering necks between particles.

"My main goal was to better understand the DED process, focussing on melt pool dynamics, laser-matter interactions, defect formation, and manufacturing using Ti-alloys alongside other commercial and novel alloys.

"The main AM process variables I looked at were laser power, laser scanning speed, gas flow rates, and powder feed rate.

"Synchrotron X-ray imaging was the primary experimental technique used. Others included X-ray Computed Tomography, Schlieren imaging, metallography, and optical microscopy.

"My first study looked at LPBF and used a process replicator to study laser and pore interactions in multilayer LPBF tracks under a range of process parameters.

"I then moved on to look at sintering phenomenon in DED when manufacturing Ti-alloys using our DED *in-situ* process replicator (BAMPR) and this work is going to be published in a paper in Additive Manufacturing soon.

"My third study looked at the effects of gas flowrates in DED using BAMPR with comparison to industrial samples produced on a BeAM DED machine in Sheffield.

"It has been a great experience working with the team, industrial collaborators, and sponsors, and conducting research at the Diamond Light Source."

ANALYSIS OF PACKING AND BULK FLOW BEHAVIOURS OF POWDERS

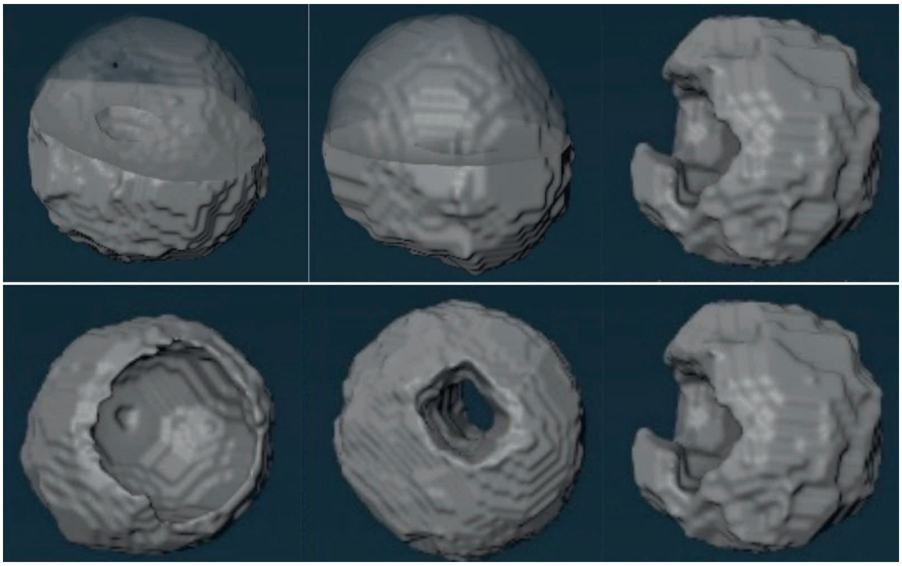


Illustration of hollow and concave particles (gas atomized Ti6) by using X-ray technique.

Ball indentation.

Dr Mozhdeh Mehrabi passed her PhD viva at the University of Leeds in 2021, she gives an overview of her work:

"My PhD, Analysis of Packing and Bulk Flow Behaviours of Powders, has been a great journey working with very supportive supervisors and colleagues in the School of Chemical and Process Engineering, the University of Leeds.

"In additive manufacturing, flowability which could be related to spreading is an important factor since it can affect the final product qualification or product development rate.

"Powders are complex and variable. Powder behaviours can be affected by factors such as size and distribution, shape, surface texture, density, cohesion, adhesion, the environment they are kept in and the properties of specific equipment. You have to take all of these into consideration when characterising a powder.

"The PhD's aims were to experimentally characterise powder properties, single and bulk, of two samples of Ti6Al4V powders in regard to the spreading process. One of the samples was produced using gas atomisation (GA) and the other via the hydride/dehydride (HDH) process which is based on the reversible interaction of titanium and hydrogen.

"There is not a universal test to quantify flowability, leading to some suggesting that all possible test values be considered.

"The work included:

Single particle properties

Determination of the powder's physical properties of size and size distribution, particle shape and density. The X-ray micro tomography has revealed some GA particles could have internal pores which may not be detected by other techniques.

Powder flowability characterisation

A range of different powder flowability techniques were studied and compared, including tapped density, angle of repose, powder flowmeter, Schulze Shear cell, avalanche angle, and FT4. Flow performance was evaluated by using an in-house spreading rig to reveal any possible correlation between specific flowability techniques and the packing quality of the powder layer. It indicated the GA sample had excellent flowability and the HDA sample had good flowability, which led to a better spreadability behaviour for the GA powders.

An X-ray microtomography study of ball indentation processes

A detailed study of the ball indentation technique was presented by using the X-ray microtomography technique for a better understanding of the packing behaviour of metal powders during filling, compaction and ball indentation stages. It was observed that for loose or very low compaction stages, the indentation position can have a significant influence on the value of hardness for both powders."

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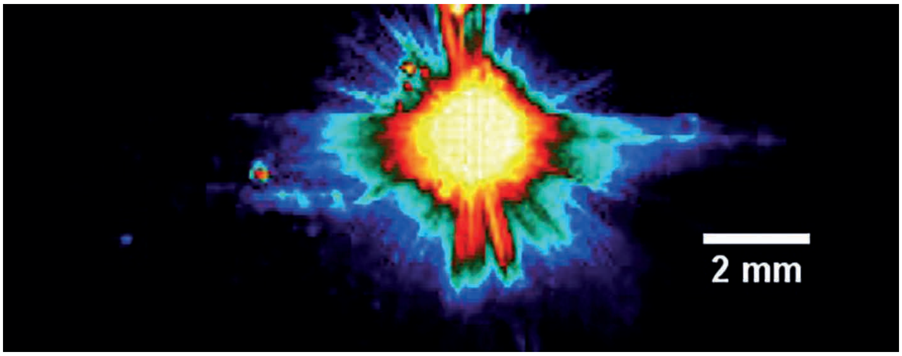
Dr Felicity Freeman at the BeAM Magic 2.0 at the Henry Royce Institute at the University of Sheffield.



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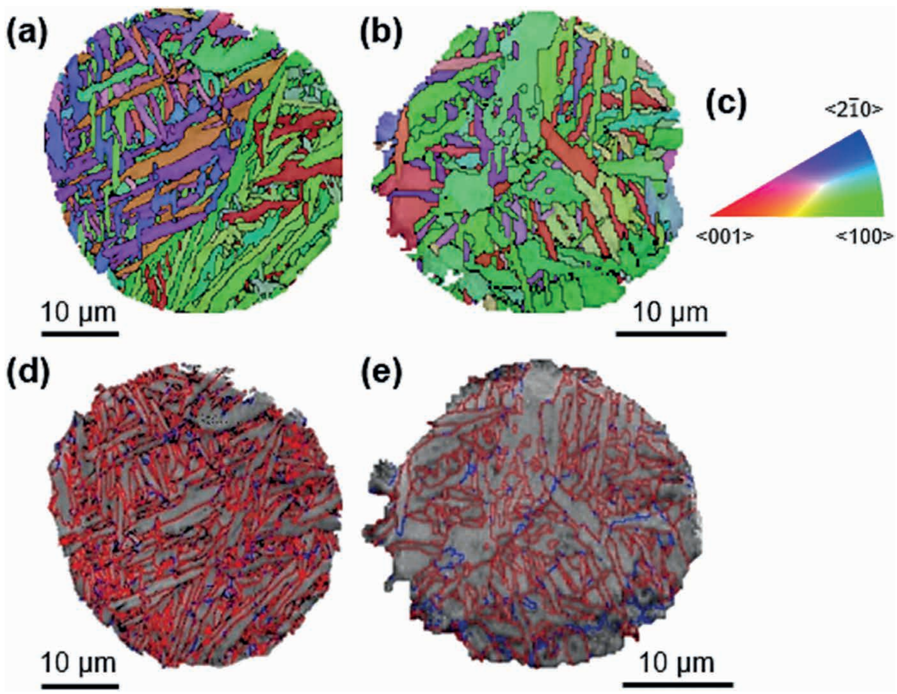

"Orientation maps of virgin (a) and near-melt zone (b) powder particles based on the IPF (c). Band contrast map of the same virgin (d) and near-melt zone (e) powder particle with HAGB (red, θ > 15°) and LAGB (blue, 1.5°< θ < 15°)." Reprinted from *Additive Manufacturing*, **46**, Soundarapandiyan, G., *et al.*, The effects of powder reuse on the mechanical response of electron beam additively manufactured Ti6Al4V parts, 102101., Copyright (2021), with permission from Elsevier.

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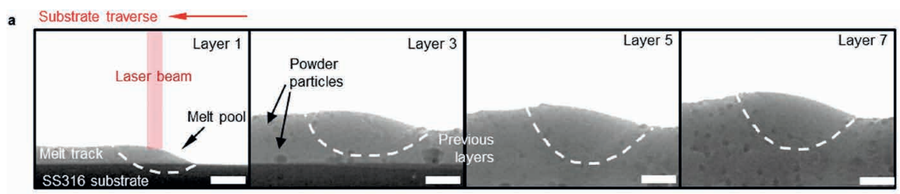

"*In situ* and operando X-ray imaging of DED-AM. Laser power 200 W, scan speed 1.67 mm s^{-1}, powder feed rate 2 g/min, captured at 200 fps. Laser beam diameter is 200 µm. (a) Still radiographs from the time-series during DED-AM showing the change in pool shape in subsequent layers during DED-AM of a SS316 multi-layer build. Scale bar = 500 µm." Reprinted from *Materials Letters*, **286**, Chen, Y., *et al. In-situ* X-ray quantification of melt pool behaviour during directed energy deposition additive manufacturing of stainless steel, 129205., Copyright (2021), with permission from Elsevier.

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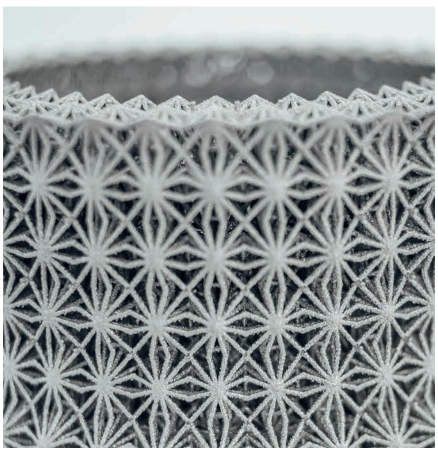

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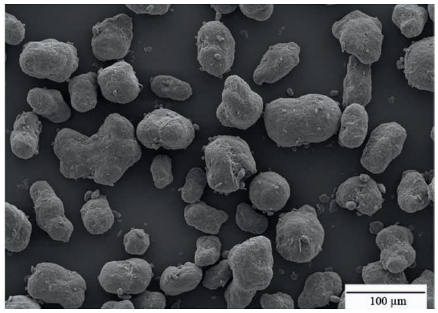

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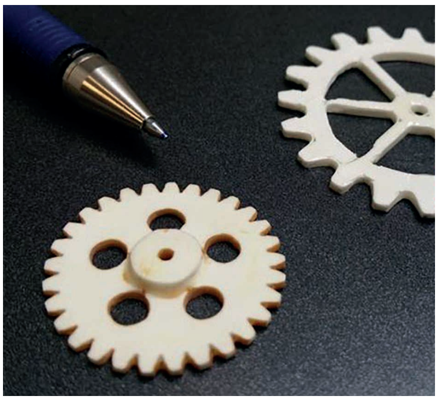

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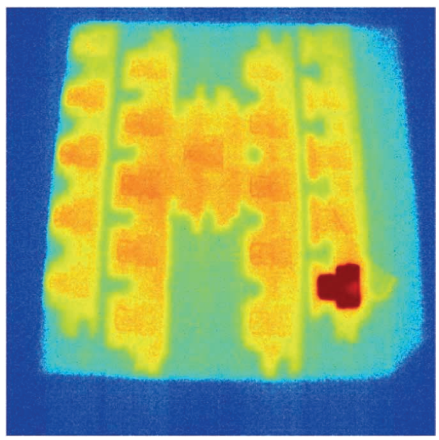

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Photograph of a selection of parts made from PA2200 (left) alongside the 1% B65003 composite material (right). Turner, R.D., *et al.* (2019). Use of silver-based additives for the development of antibacterial functionality in Laser Sintered polyamide 12 parts. *Scientific Reports*. **10**, 892. Creative Commons Attribution 4.0 International License. https://creativecommons.org/licenses/by/4.0/legalcode

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FEATURED PUBLICATIONS

PAPER:

Synchrotron X-ray imaging of directed energy deposition additive manufacturing of titanium alloy Ti-6242

PUBLICATION:
Additive Manufacturing

AUTHORS:
Chen, Y., Clark, S.J., Sinclair, L., Leung, C.L.A., Marussi, S., Connolley, T., Atwood, R.C., Baxter, G.J., Jones, M.A., Todd, I., Lee, P.D.

MAPP researchers have published a paper that enhances the fundamental understanding of the Directed Energy Deposition additive manufacturing (DED-AM) process.

In-situ and operando synchrotron X-ray imaging was used to reveal key information about DED-AM of Ti-6242 that can be used as a guide for optimising industrial additive manufacturing (AM) processes.

To replicate a commercial laser DED-AM system for use on synchrotron beamlines a custom-built blown powder additive manufacturing process replicator (BAMPR) was used.

Using different build strategies, the authors observed single track deposit evolution, melt pool morphology and multilayer build phenomena.

They also gained an increased understanding of gas pore formation and dynamics.

Analysis of the process conditions revealed that laser power is dominant for build efficiency while higher traverse speed can effectively reduce lack of fusion regions.

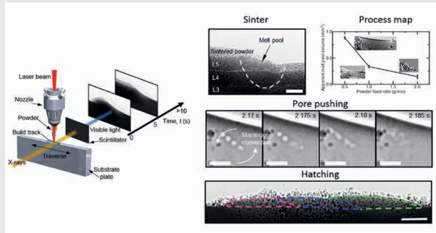


Image reprinted from *Additive Manufacturing*, **41**, Chen,Y., *et al.*, Synchrotron X-ray imaging of directed energy deposition additive manufacturing of titanium alloy Ti-6242, 101969., Copyright (2021), with permission from Elsevier.

PAPER:

Enhanced near-infrared absorption for Laser Powder Bed Fusion using reduced graphene oxide

PUBLICATION:
Applied Materials Today

AUTHORS:
Leung, C.L.A., Elizarova, I., Isaacs, M., Marathe, S., Saiz, E., Lee, P.D.

Laser Powder Bed Fusion (LPBF) is an additive manufacturing (AM) process that uses a laser to create 3D objects from built-up layers of powder.

It allows unparalleled complexity and the fabrication of parts in a single step but there are limited choices of commercial powders for LPBF.

The laser absorbance, an area that is not well investigated, is one of the factors limiting powder choice.

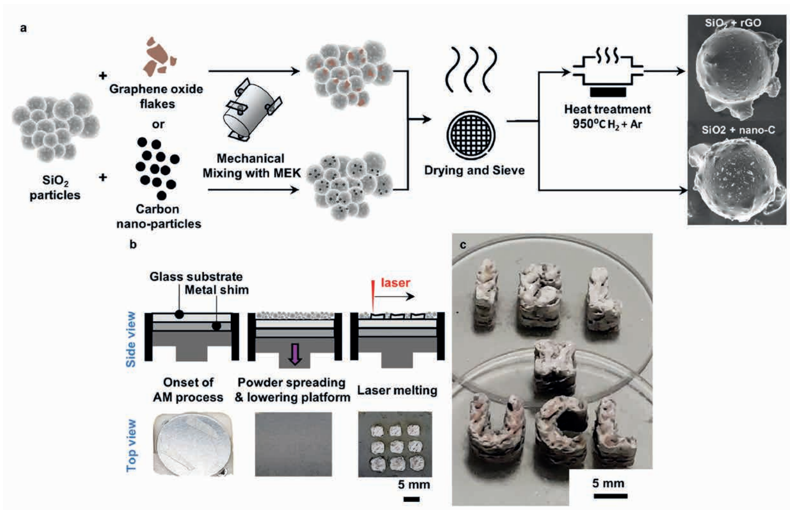
Carbon additives are commonly used to promote near infra-red (NIR) absorbance of the powders but their efficiency is limited.

The paper authors combined the use of a custom-built *In-Situ* and Operando Process Replicator machine while performing synchrotron X-ray imaging with chemical characterisation techniques to explain the role of additives on NIR absorption, melt track and defect evolution mechanisms during LPBF.

The paper details the first successful demonstration of reduced graphene oxide (rGO) as a NIR absorber for AM powder feedstock and the first *in-situ* quantification of AM fused silica, revealing laser-matter interaction and powder consolidation mechanisms.

The authors used an rGO additive to enable LPBF of low NIR absorbance powder, SiO 2, resulting in glass tracks with overhang features without pre or post heat treatment.

Their approach will dramatically widen the palette of materials available and enable existing LPBF machines to process low absorbance powder, such as SiO 2, using a NIR beam.



Laser Powder Bed Fusion (LPBF) of fused silica, SiO_2, powder mixtures using a near-infrared laser beam. Image shows: "**a**, Schematic of the powder production process where powder mixtures undergo mechanical mixing, drying, and sieving, resulting in SiO_2 + nano carbon or SiO_2 + reduced graphene oxide (after heat treatment) - insets show the typical powder morphology; **b**, glass mixtures are then processed by an *In-Situ* and *Operando* Process Replicator (ISOPR) to produce large-scale sample coupons and c. glass structures of Imperial College London crossover with University College London (ICL x UCL)." Reprinted from *Applied Materials Today*, **23**, Leung, C.L.A., *et al.*, Enhanced near-infrared absorption for laser powder bed fusion using reduced graphene oxide. Copyright (2021), with permission from Elsevier.

PAPER:

Multi-faceted monitoring of powder flow rate variability in directed energy deposition

PUBLICATION:

Additive Manufacturing Letters

AUTHORS:

Freeman, F.S.H.B., Thomas, B., Chechik, L., Todd, I.

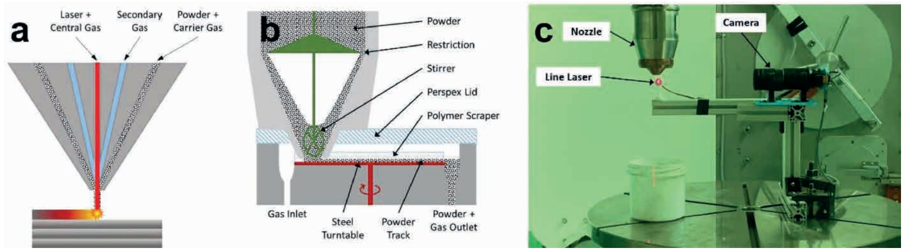
This paper deepens the understanding of powder flow rate, which is a key parameter in Directed Energy Deposition (DED) processes.

DED systems use nozzles to focus a mixed stream of metal powder and gas onto a substrate simultaneously with a laser directed onto the substrate which melts the powder to form a build. As the laser moves back and forth the deposit is built up in 3-D.

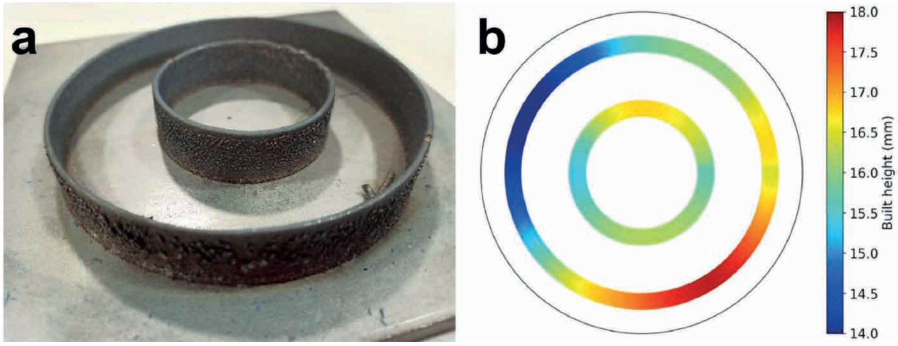
The team have measured a periodic fluctuation in the powder delivery rate which is coincidental with the time of rotation of a disc used to deliver the powder from the hopper.

This work “confirmed that DED systems can experience variations in powder flow rate at a magnitude that can affect build quality and that this effect is observable in melt pool imaging.”

It highlights the need for closed-loop control of powder flow rate. This would “eliminate the need for offline measurement before a build, minimise the risk to build quality from flow rate variation, mitigate against fill level effects as the hopper gradually empties, and ensure that melt pool imaging for temperature monitoring was unaffected by flow rate effects.”



a) BeAM Magic 2.0 nozzle schematic; b) Medicoat AG disc hopper schematic; c) Set-up for side-view flow imaging using line laser.



Cylinders built to test whether turntable-frequency flow variation was observable in the physical build. a) Physical appearance of built cylinders; b) Colour map of cylinder height.

Images and quotes from Freeman, F.S.H.B. *et al.* Multi-faceted monitoring of powder flow rate variability in directed energy deposition. *Additive Manufacturing Letters* **2**, 100024 (2022).

As a result of this investigation, the team is now working to determine whether process parameters can be altered dynamically to counteract the variation in powder flow rate which will enable this approach to be used on multiple different deposition platforms and with different hopper designs.

The DED machine used in this work was a BeAM Magic 2.0. The authors quantified the powder flow stability for different types of 316 L steel powders.

A combination of methodologies including offline weight measurements, flow imaging, *in-situ* build data and coaxial melt pool imaging were used.

PAPER:

Making our parts work harder – getting started with functional materials for 3D printing

PUBLICATION:

Journal of 3D Printing in Medicine

AUTHOR:

Majewski, C.

New materials provide the potential for major improvements in polymer 3D printing but can be complex to develop and optimise.

The use of functional additives incorporated into ‘standard’ polymers can provide an effective method of achieving new or improved part properties; this is particularly attractive for medical uses.

This editorial article explains a general process for developing new material combinations, the benefits and potential stumbling blocks.

Using the polymer laser-sintering process as an example, the article highlights the main steps toward the early-stage testing and development of novel material combinations.

In the example, the focus is the incorporation of a specific concentration of additive into a base polymer to provide antibacterial functionality.

The discussion includes the importance of understanding the 3D-printing process being used, testing the materials to see if there is any potential to harm human cells, and the preference for material to be homogeneous throughout parts. Micro-computed tomography, depending on the additive used, can be used to identify the dispersion of additive throughout the parts.

“There is no doubt that new and varied material combinations will play an important role in increasing the usefulness of 3D-printing techniques, both in medicine and more broadly.

“As the processes themselves develop further, we are likely to see increasing numbers of applications taking advantage of a combination of both the geometric capabilities of 3D printing and novel materials – the outlook is exciting!” (Majewski, C., (2022) Making our parts work harder – getting started with functional materials for 3D printing. *Journal of 3D Printing in Medicine. Creative Commons Attribution 4.0 License*, http://creativecommons.org/licenses/by/4.0/).

MAPP

EXECUTIVE TEAM

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

Iain, Professor of Metallurgy, University of Sheffield, 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 is actively supported by 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 previously led the Mercury Centre at Sheffield, an ERDF supported activity that helped regional SMEs secure contracts worth >£7m and safeguarded/created 150 jobs.

Iain is a Fellow of the Institute of Materials, Minerals and Mining and is Director of the Materials Made Smarter Research Centre.

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

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

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

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

Associate Professor Ali Hassanpour

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

INDUSTRIAL ADVISORY BOARD (IAB)

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

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

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

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

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

Marko Bosman, Chief Technologist Additive Manufacturing, GKN Aerospace

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

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

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

Dr Gael Guetard, Rapid Alloy Research Centre Director, Alloyed (formerly OxMet Technologies)

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

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

In 2018, he moved back to the UK to join OxMet Technologies (now part of Alloyed), a spin-off company of the University of Oxford, specialised in the computational development of new alloys. There, he leads the Rapid Alloy Research Centre, a laboratory focused on accelerating Alloyed's technologies in the field of alloys and additive manufacturing.

Dr Hugh Hamilton, Scientific Consultant, Johnson Matthey

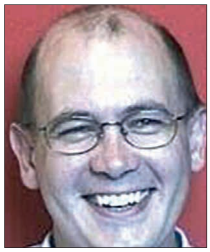
Hugh has been with the Johnson Matthey Technology Centre since 1988, during which time he has worked in a variety of technical areas including catalysts for automotive applications, modified atmosphere packaging, PEM fuel cell membrane electrode assembly design and manufacture, hydrogen storage alloys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

Professor Neil Hopkinson, Stratasys

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

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

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



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

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

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

Ian Laidler, Chief Technology Officer, Wayland Additive

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

THE SCIENTIFIC ADVISORY BOARD (SAB)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

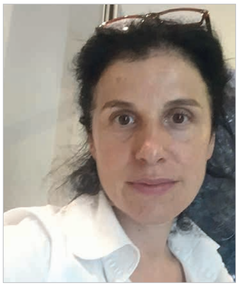
Professor Jin Ooi,
University of Edinburgh

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

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

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

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



Professor Barbara Previtali,
Politecnico di Milano

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

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

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

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

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

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

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

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

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

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

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

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

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

MAPP INVESTIGATORS

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

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

Professor Patrick Grant, 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. It uses variants of industrial manufacturing techniques like vacuum plasma spraying and field assisted sintering alongside in-house developed novel processes like spray deposition of multi-suspensions and 3D printing of dielectric materials. 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. A Fellow of the Royal Academy of Engineering his research has been published in more than 200 research papers and eight patents.

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

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

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

Dr Candice Majewski, University of Sheffield. P2.3b High Speed Sintering & Polymer AM Theme Lead. Candice is a senior lecturer with almost 20 years of experience in the field of AM. She manages the University's Advanced Polymer Sintering Laboratory and has built up a large network of academic and industrial collaborators, focusing much of her research towards improving powdered polymer AM materials and processes to increase their potential for widespread industrial usage. In 2011 she received the International Outstanding Young Researcher in Freeform and Additive Manufacturing Award. She is an advocate for Equality, Diversity, Inclusion and Accessibility, leading the MAPP EDI committee, and is deputy head of her Departmental Well-being and EDI committee. Externally she is a member of The Inclusion Group for Equity in Research in STEMM.

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

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

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

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

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

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

Professor Luc Vandeperre, Imperial College London, Deputy Director of the Centre for Advanced Structural Ceramics (CASC) at Imperial College London. 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 European Ceramics Society and of the Institute of Materials, Minerals and Mining (IOM3). He received the IOM3 Verulam Medal & Prize in 2019.

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

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

MAPP PDRAs:

Dr Daliya Aflyatunova
Dr Ryan Brown
Dr Yunhui Chen
Dr Wen Cui
Dr Yun Deng
Dr Iuliia Elizarova
Dr Emad Girgis
Dr Simon Graham
Dr Oliver Hatt
Dr Yi He
Dr Samy Hocine
Dr Yuze Huang
Dr Ashfaq Khan
Dr Mozhdeh Mehrabi
Dr Scott Notley
Dr Rob Snell
Dr Ben Thomas
Dr Rahul Unnikrishnan
Dr Kai Zhang
Dr Xun Zhang

MAPP-aligned PDRAs

Dr Oliver Levano Blanch
Dr Sheng Cao
Dr Felicity Freeman
Dr Oriol Gavalda Diaz
Dr Bo Luo
Dr Minh Phan
Dr Nicholas Weston

MAPP PhDs

Mohamed Atwya
Hugh Banes
Cameron Barrie
Alex Goodall
Guy Harding
Oliver Leete
Joseph Samuel
Dr Lorna Sinclair

MAPP-aligned PhDs

Hussam Abunar
Muhammad Aftab
Saad Syed Iqbal Ahmed
Talal M Al-Ghamdi
Abdullah Alharbi
Mohammed Alsaddah
Josh Berry
Alisha Bhatt
Matthew Boreham
Florian Buschek
Louise Chan
Lova Chechik
Max Chester Jude Emmanuel
Imogen Cowley
Ben Evans
Xianqiang Fan
Lucy Farquhar
Cameron Favell Gallifant
Maureen Fitzpatrick
Kubra Genc
Anna Getley
Adam Gothorp
Abdul Haque
Caterina Iantaffi
Addhithya Ashok Kumar
Ruben Lamber-Garcia
Sam Lister
Elaine Livera
Frances Livera
Alistair Lyle
George Maddison
Guillame Matthews
David McArthur
Kieran Nar
Maha T Omran
Ollie Osborn
Sourabh Paul
James Pepper
David Rees
Tom Robb
Elena Ruckh
Beatriz Fernandez Silva
Alex Sloane
Leigh Stanger
Pawel Stuglik
Sarath Veetil
Dr James Wingham
Kai Wu
Kylee Yingwei Wu
Zhen Xi
Jiaqi Xu
Miguel Zavala-Arredondo
Zhouran Zhang
Shitong Zhou

MAPP

OPERATIONS TEAM

Jessica Bamonte, Project Administrator, Jess joined MAPP in March 2017 and works alongside Clare Faulkner. As well as providing executive support to Prof. Iain Todd and Dr Gavin Baxter she leads on events and Researchfish.

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

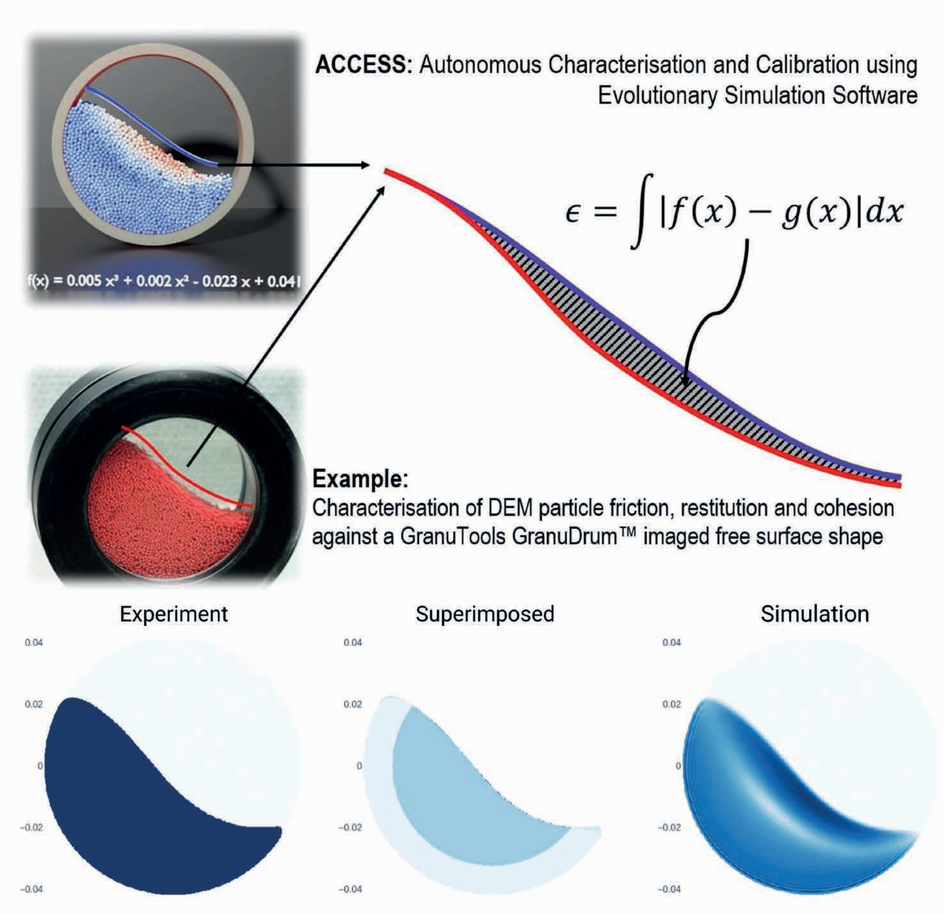
Clare Faulkner, Project Administrator, Clare joined MAPP in April 2019 and works alongside Jess Bamonte. As well as providing executive support to Prof. Iain Todd and Dr Gavin Baxter she leads on project plans and reporting.

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

Karen Wood, Project Manager, Karen has been with MAPP since 2017, joining us from managing another research programme in the Faculty of Engineering at the University of Sheffield. Initially qualifying in biological sciences, Karen has a wealth of experience, not only in project management and business development but also in entrepreneurship and business start-up, commercialisation and facilitating academic-industry networks and many other areas such as bid-writing and skills development. Within MAPP she has oversight of the programme, managing all aspects of MAPP operations on a day-to-day basis and acting as the central contact point for our academic partners. During 2021/2, Karen has been on secondment to another EPSRC future manufacturing hub also led out of Sheffield (FEMM Hub) and has the opportunity to share best practices between them.

SPOTLIGHT ON COEXSIST: COUPLED EXPERIMENTAL-SIMULATIONAL STUDY TECHNIQUE

Principal Investigator (PI) Dr Kit Windows-Yule, School of Chemical Engineering, the University of Birmingham.
PhD students: Leonard Nicusan and Dominik Werner, School of Chemical Engineering, the University of Birmingham.



This project has developed new tools, methods and algorithms intended to revolutionise the characterisation of particulate media and the calibration of numerical models for industrial systems.

The study uses the hybridisation of experimental imaging, numerical particle simulation and machine learning.

It was conceived because current characterisation methods are not sufficient as the traditional descriptors for powders, such as internal friction angle, yield stress, compressibility and flowability fail to adequately describe powders' complexity as a system.

To put it more precisely, these quantities describe bulk (macroscopic) properties of a powder as a whole as opposed to the microscopic properties of individual particles which underpin their fundamental dynamics, and are crucial to the accurate numerical modelling thereof.

The modern particle-handling industry is increasingly moving away from traditional empirical models towards numerical simulation, which can offer greater precision and more information, making it a vital next step in the industry's evolution.

PI Dr Kit Windows-Yule, from the School of Chemical Engineering at the University of Birmingham, has first-hand experience of the shift from empirical to numerical through his work leading a project for the International Fine Particle Research Institute (IFPRI).

The IFPRI project brings together a consortium of 16 companies from diverse powder manufacturing industries with the aim of studying the current use of Discrete Element Method (DEM) in industry.

The project has a particular focus on characterisation and calibration methods and assessing the success of these methods in producing accurate simulations of industrial systems.

The IFPRI work performed so far shows the lack of a standardised approach to characterisation, calibration and simulation, and that the processes involved are inefficient, time-consuming and labour-intensive.

This highlighted the need for new solutions such as those proposed in the CoExSiST feasibility study which also addresses key issues within MAPP's research themes.

A key feature of CoExSiST is the ACCES: Autonomous Characterisation and Calibration using Evolutionary Simulation tool, which was developed with MAPP funding.

DEM is a very powerful tool used in both industry and academia but it has some drawbacks, including the need for detailed calibration and that it is computationally expensive.

The goal of ACCES is to address these limitations by making the process simpler and less labour intensive using the ACCES algorithm.

ACCES uses evolutionary algorithms to solve an inverse problem, computing the microscopic (particle-level) properties of arbitrary particulate media from measurements of their macroscopic (bulk) properties and thus allowing the calibration of virtually any simulation parameters.

It does so by comparing simulated (DEM) and experimental data against a user-defined cost function, quantifying and then minimising the disparity between the simulated system and the experimental reality using state-of-the-art evolutionary strategies.

It is autonomously 'learning' the physical properties of the simulated system, without the need for human input.

The next steps include using ACCES on real and complex projects with industrial partners, and using it to improve particle characterisation for additive manufacture – working towards "designer particles" and a "printability standard".

ACCES is available open-source as a valuable new tool for researchers in the field (https://github.com/uob-positron-imaging-centre/Coexist),

Impact of MAPP feasibility funding for CoExSiST

- £50,000 follow-on funding from EPSRC Impact Acceleration Account to pursue collaboration with chemical giant FMC, further developing the algorithm and directly applying it to real-world problems.
- £50,000 industry funding from Granutools to integrate ACCES with their widely-used characterisation tools.
- £57,000 from the Henry Royce Institute to develop a "sister algorithm" to ACCES, Multiphase Materials Exploration via Evolutionary Equation Discovery (M^2E-D) which uses the same evolutionary framework as ACCES to autonomously determine the *equations governing the motions* of particles and complex fluids.
- Helped leverage $40,000 funding for a two-year project with the IFPRI to further develop the Best Practice for DEM simulation.
- Multiple grants building on ACCES, including two EPSRC standard mode applications, are currently under development.

MAPP's Feasibility Studies have led to journal papers, a new MAPP partner in Physical Computation, and follow-on funding.

In 2018 MAPP opened its first round of feasibility funding. The successful applications (alphabetically) and their outcomes were:

- Prof. Jawwad Darr, University College London – 'Cold press sintering of solid-state electrolyte powders.' Outcomes include follow-on funding.
- 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.' Outcomes include the paper Pham, M-S., Dovgyy, B., Hooper, P.A. *et al* (2020). The role of side-branching in microstructure development in laser powder-bed fusion. *Nature Communications* **11**, 749.
- Prof. Cornelia Rodenburg, The University of Sheffield – 'Feasibility of polymer powder based SMART parts.' Outcomes include three journal papers and a new project SEE MORE MAKE MORE: Secondary Electron Energy Measurement Optimisation for Reliable Manufacturing of Key Materials. The other SEE MORE MAKE MORE investigators include MAPP's Prof. Iain Todd, Dr Candice Majewski and Dr Jon Willmott.
- Dr Phillip Stanley-Marbell, The University of Cambridge – 'Programmable in-powder sensors (PIPS) for real-time metrology and data-analysis in powder processes.' Outcomes include the University of Cambridge becoming a new MAPP partner in Physical Computation.

MAPP's second round of feasibility funding, closed in November 2019. The successful applications (alphabetically) were:

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

MATERIALS MADE SMARTER RESEARCH CENTRE

MAPP's Director is leading the new £5 million **Materials Made Smarter Centre** set to revolutionise the way we manufacture and value materials in the UK.

In partnership with UCL and the Universities of Cambridge, Brunel, Nottingham, Sheffield and Swansea, the MMSC will bring together leading researchers in materials, advanced manufacturing, modelling, physical computing, psychology and management across the whole materials manufacturing value chain.

Led by the University of Sheffield, the MMSC will work with High Value Manufacturing Catapult Centres, including the University of Sheffield Advanced Manufacturing Research Centre (AMRC), and the Manufacturing Technology Centre (MTC), as well as The Materials Processing Institute and industrial partners including Rolls-Royce, Tata and Constellium.

It will bring together the Future Composites Manufacturing Hub, the Future Liquid Metal Engineering Hub, the Institute of Work Psychology, MAPP and the SUSTAIN Future Manufacturing Research Hub.

Professor Iain Todd said:

"Our aim is to put the UK's materials intensive processing industries at the forefront of the UK's technological advancement and green recovery from the dual impacts of the Covid-19 pandemic and rapid environmental change."

The new centre has been co-created by academia and industry as a response to the pressing need to revolutionise the way we manufacture and value materials in our economy.

It will work on overcoming technological challenges preventing the adoption of new materials and manufacturing processes needed to become more sustainable and help achieve net-zero emissions.

Prof. Todd continued:

"We will develop the advanced digital technologies and tools to enable the verification, validation, certification and traceability of materials manufacturing and will work with partners to address the challenges of digital adoption.

"Digitalisation of the materials thread will drive productivity improvements, realise new business models and change the way we value and use materials."

The MMSC is one of five new digital manufacturing research centres to focus on helping the UK's manufacturing industry become more productive and competitive through innovation and the adoption of digital technologies.

The funding was awarded through the Made Smarter Innovation programme at UK Research and Innovation, a collaboration between the UK government and industry designed to support the development and increase the use of these emerging technologies.

Nearly £25 million is being invested in the five industry-sponsored research centres set up to accelerate the development of cutting-edge digital solutions that can transform manufacturing businesses across many sectors.

Based in universities throughout the UK, they will help to make supply chains faster, more efficient, and more resilient.

Each centre will focus on a different area of manufacturing and the other centres are:

- **Made Smarter Innovation Research Centre for Connected Factories** led by the University of Nottingham, aims to deliver a platform for next-generation resilient connected manufacturing services. It will allow future manufacturing operations to be delivered by universal production units that can be easily repurposed, relocated and redeployed in response to changing market demand.
- **Made Smarter Innovation Digital Medicines Manufacturing Research Centre** led by the University of Strathclyde, will accelerate the adoption of IDTs in the pharma sector to transform medicines development and manufacturing productivity and drive patient-centric supply.
- **Made Smarter Innovation People-Led Digitalisation Centre** led by the University of Bath, will create a step-by-step cross-sectorial process for manufacturers to map their current digitalisation position and from the findings plan their future state map to realise the potential of digitalisation.
- **Made Smarter Innovation Research Centre for Smart, Collaborative Industrial Robotics** led by the University of Loughborough, aims to advance smart manufacturing by eliminating barriers and accelerating widespread use of smart collaborative robotics technology to unlock the full potential of the UK industry in productivity, quality, and adaptability.

Materials MADE SMARTER Centre

MAPP

PROJECT PARTNERS

MAPP is led by the University of Sheffield and brings together leading research teams from the Universities of Cambridge, Leeds, Manchester and Oxford, Imperial College London and University College London, together with 20 industry partners and the UK's High Value Manufacturing Catapult.

HIGH VALUE MANUFACTURING CATAPULT CENTRES

INDUSTRY PARTNERS

SPOTLIGHT ON

PHOENIX SCIENTIFIC INDUSTRIES

MAPP industry partner, Phoenix Scientific Industries Ltd (PSI) is a well-known supplier of specialist rapid solidification technology to produce high quality materials for demanding applications.

Highlighted below are three areas of technological innovation that PSI is driving through research programmes and system development:

1. Continuous VIGA powder production
2. Post-atomisation modification of powders
3. Magnetic materials

CONTIPOUR® Powder Production

Vacuum-inert gas atomisation (VIGA) is recognised as the leading technology for the mass production of high quality, inclusion free and low oxygen-content spherical powders for a broad range of applications including near net shape manufacturing. Despite the increasing size, melt capacity and therefore the productivity of these systems, conventional batch operation is a limiting factor. To address this PSI is now offering continuous operation atomisers to the market to achieve the lowest process cost per kilogram for high quality VIGA powders. For reactive materials such as titanium, PSI continues to develop cold crucible technology and is part of the joint UK-Sweden aerospace sector Demand Repair project.

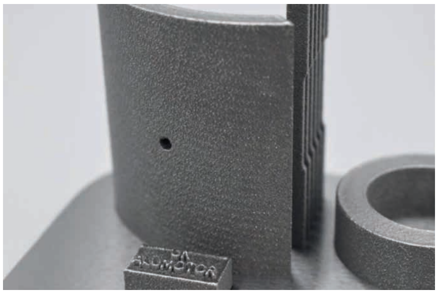
Production scale PSI HERMIGA atomiser.

VIGA melt stream atomisation by close coupled die.

Powder Modification

PSI has recently focused efforts on post-atomisation modification of powders in bulk form to enable and enhance advanced applications. Examples include heat treatments, coatings and chemical reactions using PSI's in-house fluidised bed reactor. As part of the ENGPOW project, PSI solution heat treated and quenched aluminium powders to increase deposition efficiency during cold spray repair of in-theatre aircraft components. As a partner in the SPICE project, PSI CVD coated fine composite silicon-graphite powders, used to manufacture battery cell anodes, to enhance the performance of electric vehicles. These processes are scalable and demonstrate the commercial potential to add value through powder modification.

PSI in-house pilot scale Fluidised Bed Reactor for the modification of powders.



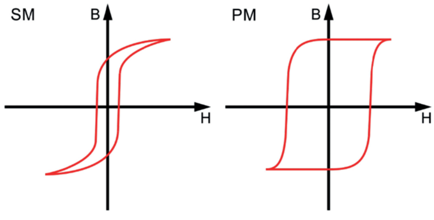
Additively manufactured parts from the Alumotor Project made from a soft magnetic powder developed and manufactured at PSI.

Magnetic Materials

The drive towards decarbonisation is increasing demand on magnetic materials that are critical in many applications including Power Electronics, Machines and Drives (PEMD). PSI together with Ricardo (lead), Warwick Manufacturing Group, Aspire Engineering, Brandauer and Global Technologies Racing form the UK-ALUMOTOR consortium, which has recently been awarded a further phase of funding. The objective of the project is to increase the manufacturing readiness level of a high-performance synchro reluctance motor utilising aluminium windings and soft magnetic components to avoid the global supply chain concerns associated with copper and permanent magnets. In parallel to this work PSI offers systems, such as melt spinners, for the production of permanent magnetic materials, either from virgin or recycled feedstock.

Please contact PSI Research and Development Manager Mikael Olsson Robbie if you would like to learn more about the company's research, technology and services: info@psiltd.co.uk

PSI LTD



Characteristic magnetic hysteresis loops from a "soft" ferromagnetic material (left) and a "hard" ferromagnetic material (right).

ALIGNED PROJECTS

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

LIVE PROJECTS

AIRLIFT (Additive Industrialisation for Future Technology)

Funder: Innovate UK

Funded Value: £6,138,691

Funding period:
December 2018 - November 2023

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

AMITIE (Additive Manufacturing Initiative for Transnational Innovation in Europe)

Funder: European Commission - Horizon 2020

Value of award to the consortium: £774,147

Funding period:
March 2017 - 2021

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

DAM (Developing Design for Additive Manufacturing)

Funder: Innovate UK

Funded Value: £7,212,148

Funding period:
December 2018 - November 2022

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

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

Funder: EPSRC

Funded value: £2,608,542

Funding period:
November 2020 - October 2024

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

ALIGNED PROJECTS

LIVE PROJECTS

Development of MgWOxB Ceramic Neutron Shielding Material

Funder: UKAEA (UK Atomic Energy Authority)

Funded value: £20,000

Funding period: July 2021 - March 2022

Organisations: CASC Imperial.

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

Funder: Horizon 2020

Funded value: £672,915

Funding period: January 2019 - December 2022

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

LIVING MATERIALS

Funder: ONRG

Value of award to the consortium: £400,000

Funding period: July 2018 - January 2022

Organisations: Cidetec, Imperial College London.

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

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

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

Funding period: April 2019 - March 2029

Organisations: University College London.

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

Funder: Rolls-Royce

Funded value: £100,000

Funding period: July 2021 - December 2022

Organisations: CASC Imperial.

COMPLETED PROJECTS

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

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

Project costs: EUR 3 439 420

Funded value: EUR 3 439 420

Funding period:
January 2015 - December 2017

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

DARE (Designing Alloys for Resource Efficiency)

Funder: EPSRC

Project costs: £4,033,113

Funded value: £3,226,490

Funding period:
September 2014 – September 2019

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

FACTUM

Funder: Innovate UK

Project costs: £1,427,215

Funded value: £725,001

Funding period:
November 2013 - October 2016

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

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

Funder: Innovate UK

Funded value: £507,551

Funding period:
March 2018 - 2021

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

Horizon (AM)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £13,304,769

Funded value: £7,042,370

Funding period:
March 2015 – November 2017

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

JewelPrint (Innovative Jewellery Manufacturing Process using 3D Printing)

Funder: Innovate UK

Funded value: £401,528

Funding period:
June 2019 - May 2020

Organisations: Diamond Centre Wales Ltd, University of Sheffield.

Large Volume, Multi-material High Speed Sintering Machine

Funder: EPSRC

Project costs: £1,115,283

Funded value: £892,226

Funding period:
April 2015 – September 2017

Organisations: University of Sheffield.

ALIGNED PROJECTS

COMPLETED PROJECTS

LATEST2 (Light Alloys Towards Environmentally Sustainable Transport)

Funder: EPSRC

Project costs: £7,202,651

Funded value: £5,762,121

Funding period:
July 2010 - July 2016

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

MIAMI (Improving the productivity of industrial additive manufacturing)

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

Project costs: £552,732

Funded value: £200,000

Funding period:
July 2017 – March 2020

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

MIRIAM (Machine Intelligence for Radically Improved Additive Manufacturing)

Funder: Innovate UK

Funded value: £666,383

Funding period:
October 2017 - March 2019

Organisations: Reliance Precision Ltd, University of Sheffield.

OPTICON (Optical Infrared Coordination Network for Astronomy)

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

Funded value: £166,605

Funding period:
January 2017 - June 2021

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

REMASTER (Repair Methods for Aerospace Structures using Novel Processes)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £3,484,901

Funded value: £1,742,390

Funding Period:
January 2016 – December 2018

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

SHAPE (Self Healing Alloys for Precision Engineering)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £2,127,805

Funded value: £1,071,094

Funding period:
September 2015 – August 2018

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

TACDAM (Tailorable and Adaptive Connected Digital Additive Manufacturing)

Project funder: Innovate UK and EPSRC

Project costs: £1,482,626

Funded value: £1,071,094

Funding period:
January 2017 - December 2018

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

TiPOW (Titanium Powder for Net-shape Component Manufacture)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £3,129,835

Funding period:
March 2015 – February 2020

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

VULCAN

Funder: Innovate UK

Funded value: £267,650

Funding period:
January 2020 - December 2021

Organisations: The University of Sheffield, Wayland Additive.

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

Project funder: EPSRC

Funded value: £149,031

Funding period:
March 2018- March 2019

Organisations: University of Sheffield.

MAPP
Manufacture using Advanced
Powder Processes
EPSRC Future Manufacturing Hub

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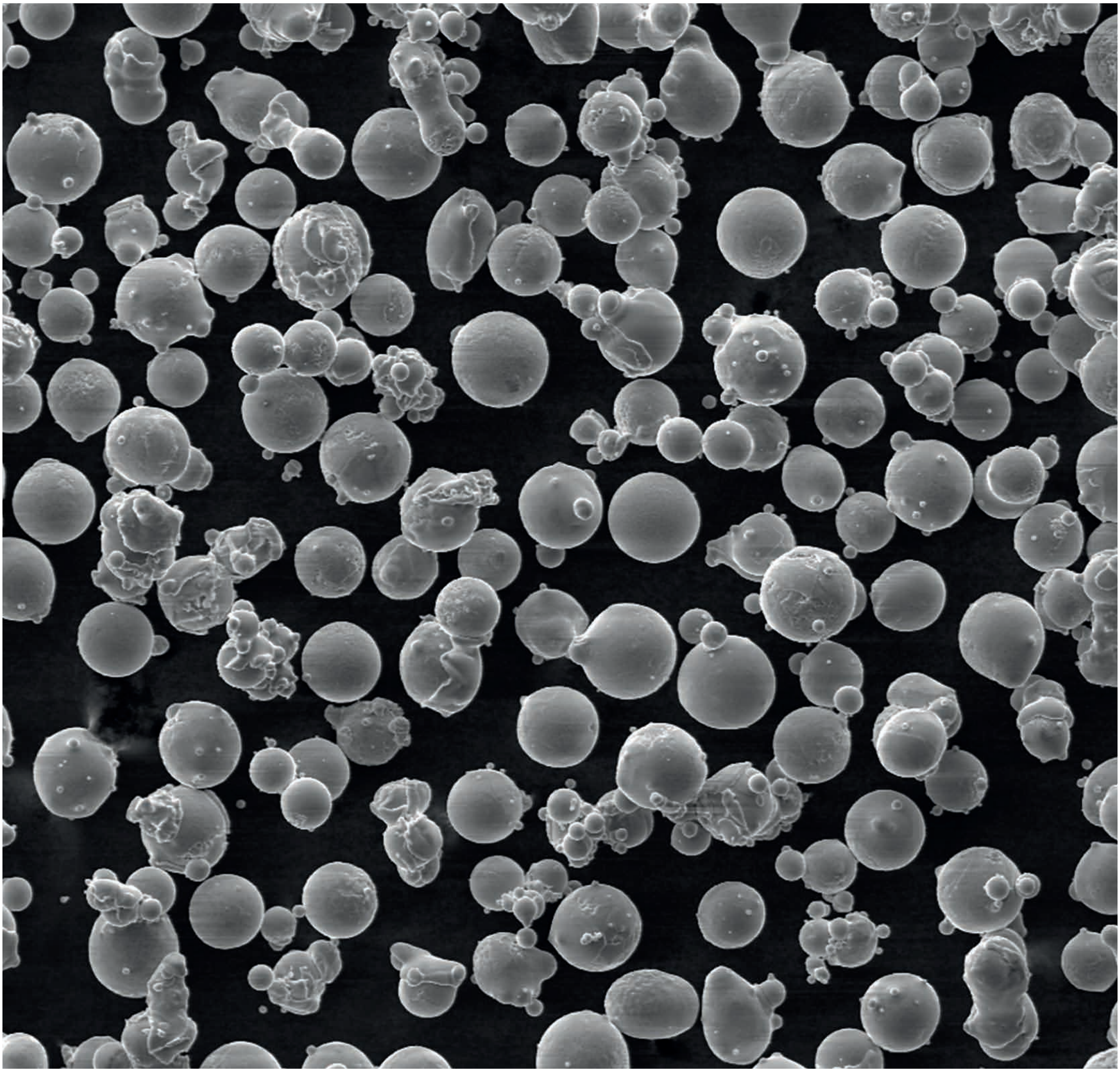

SEM image showing the morphologies and size of AlCu powder used in LPBF. Image by **Xianqiang Fan.**

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