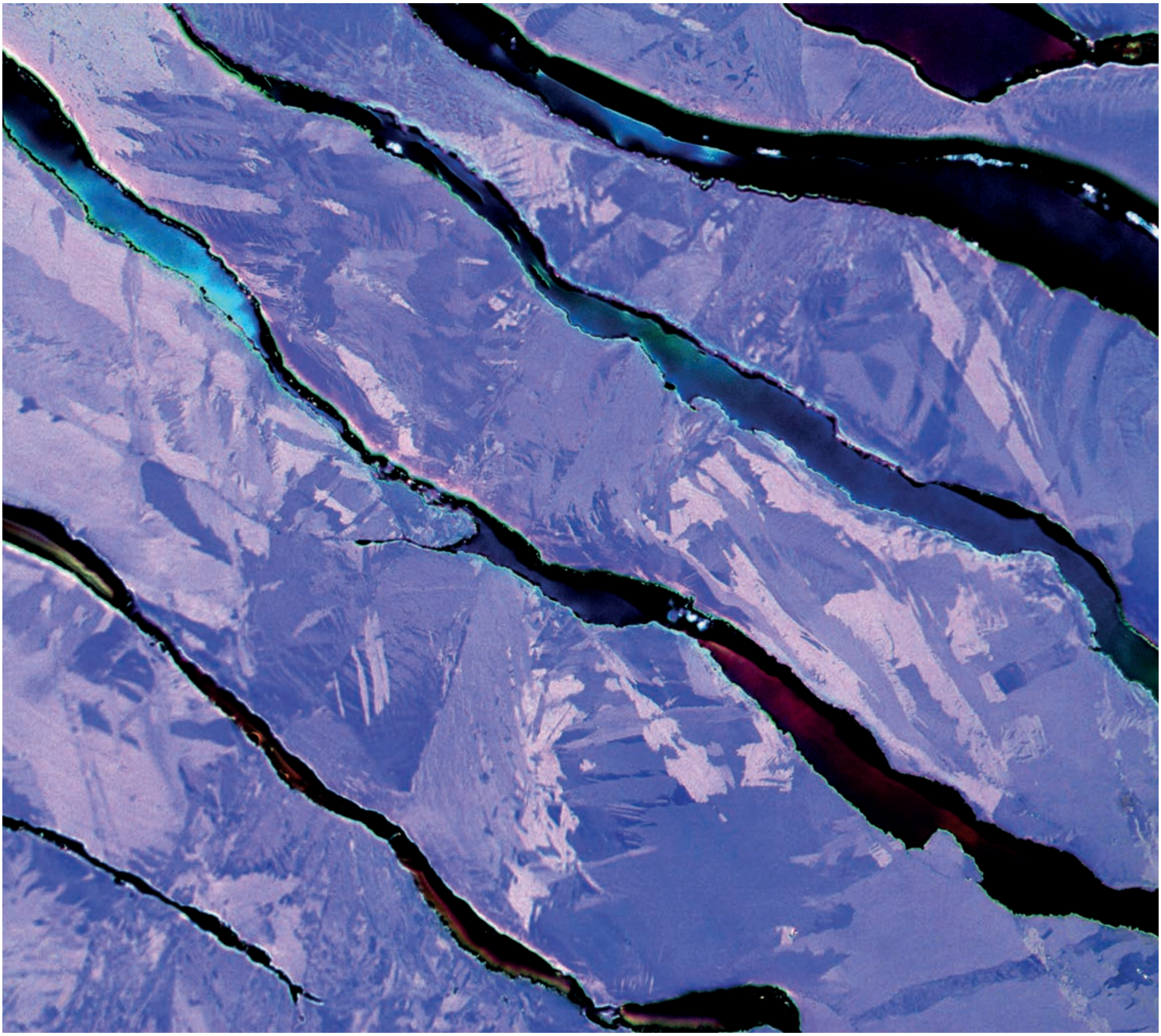
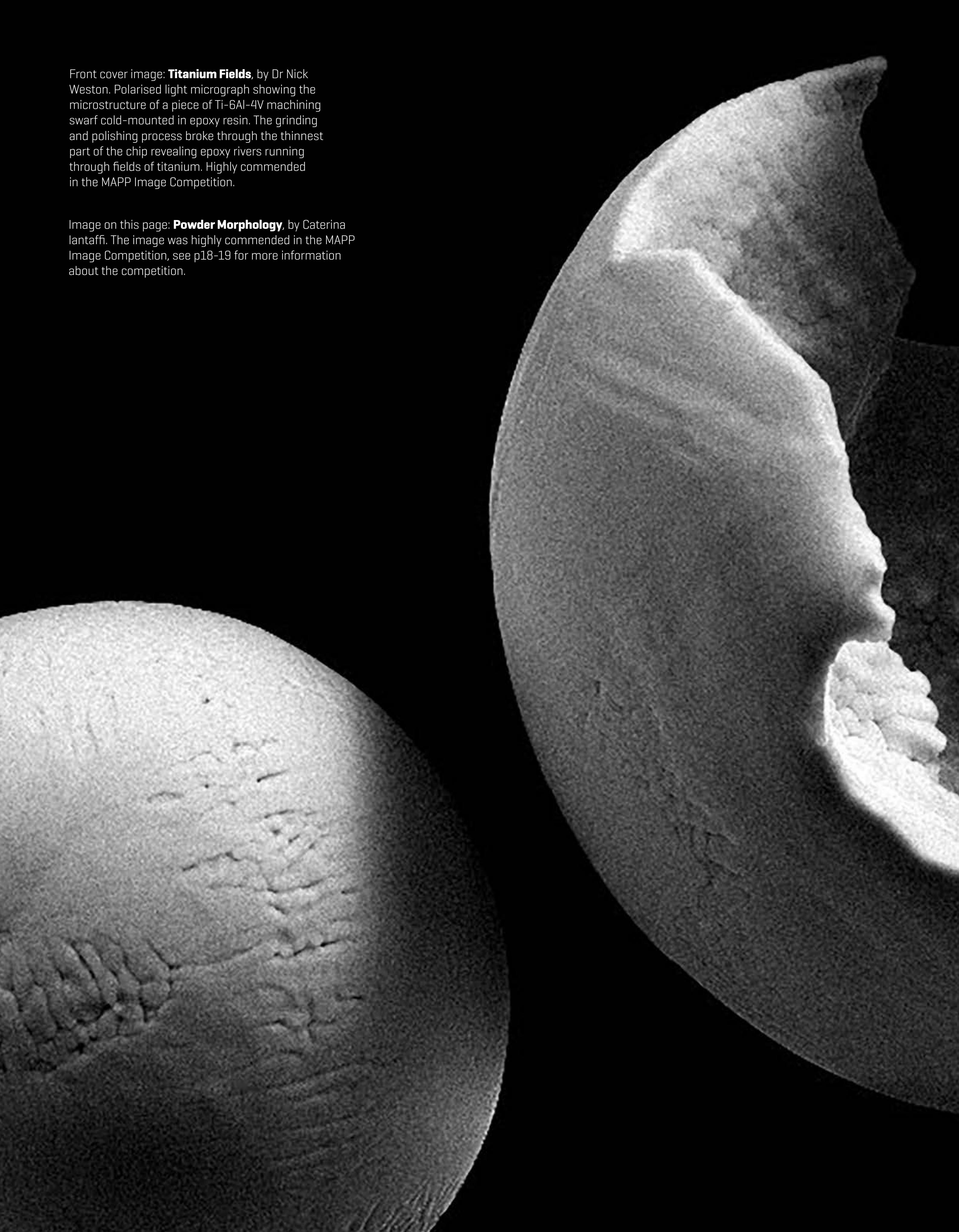
MAPP

Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

Annual Report 2021

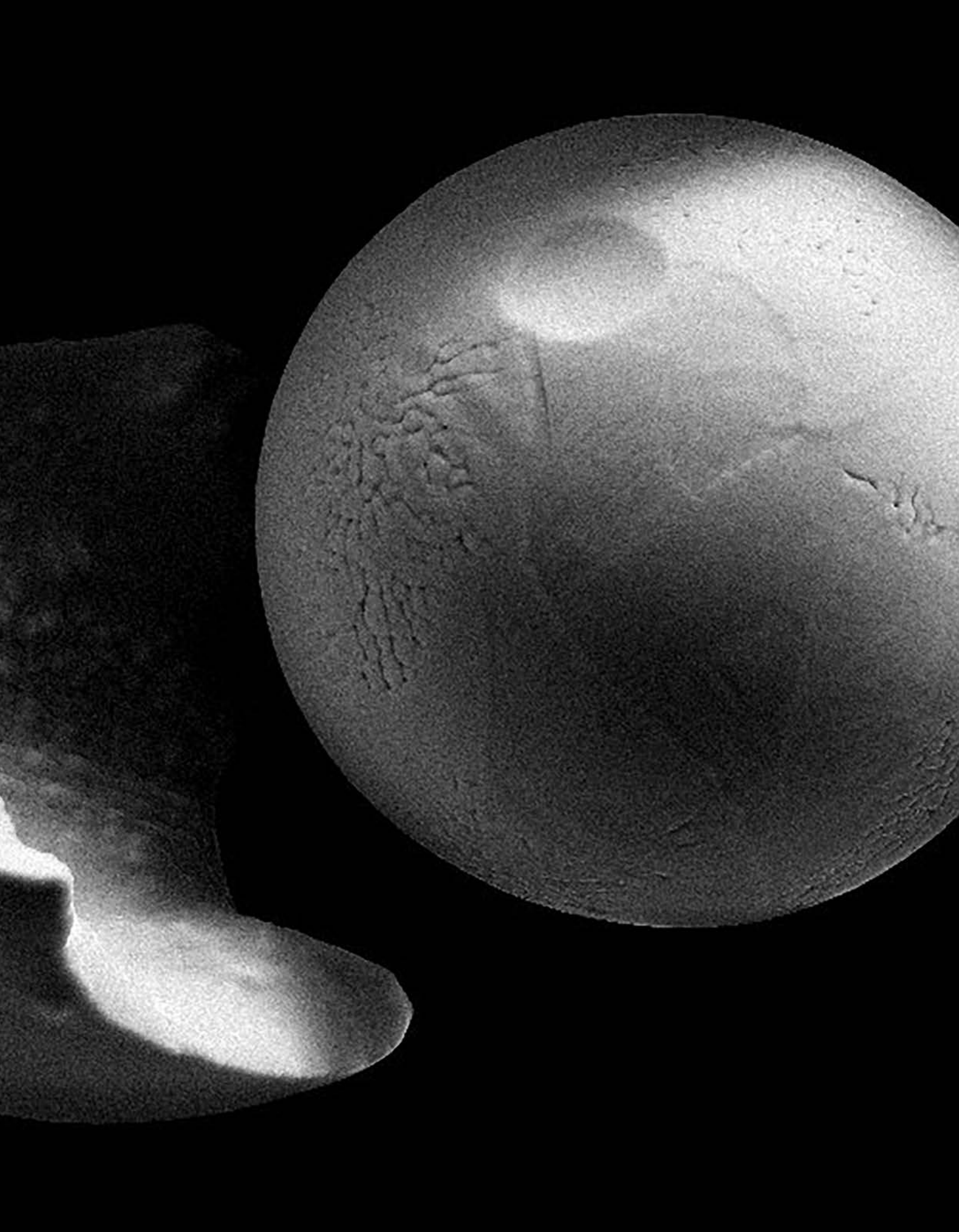


The University Of Sheffield. | University of Cambridge | Imperial College London | University of Leeds | Manchester 1824 The University of Manchester | University of Oxford | UCL | UKRI Engineering and Physical Sciences Research Council



Front cover image: **Titanium Fields**, by Dr Nick Weston. Polarised light micrograph showing the microstructure of a piece of Ti-6Al-4V machining swarf cold-mounted in epoxy resin. The grinding and polishing process broke through the thinnest part of the chip revealing epoxy rivers running through fields of titanium. Highly commended in the MAPP Image Competition.

Image on this page: **Powder Morphology**, by Caterina Iantaffi. The image was highly commended in the MAPP Image Competition, see p18-19 for more information about the competition.



CONTENTS

WELCOME

Welcome to the fourth MAPP Annual Report.

2020 was a year like no other and I am proud of everyone at MAPP who pulled together to continue our work, despite the challenges.

After MAPP's midway point in 2019, we refreshed some of our core research to ensure we continue to deliver world-class knowledge and understanding against our Grand Challenge themes.

Our research is also benefiting from the University of Cambridge becoming a new MAPP partner in physical computation (see p21 for more details) following our successful feasibility funding project with Dr Phillip Stanley-Marbell.

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

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

Our focus, going forwards, will be on ensuring that research done in the first half of the programme can be 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.

It is an exciting time for us here - I hope you enjoy reading about some of our highlights of 2020 and we look forward to continuing to work with you in the future.

Prof. Iain Todd. MAPP Director

Professor Iain Todd
MAPP Director

ACHIEVEMENTS

2017–2021

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

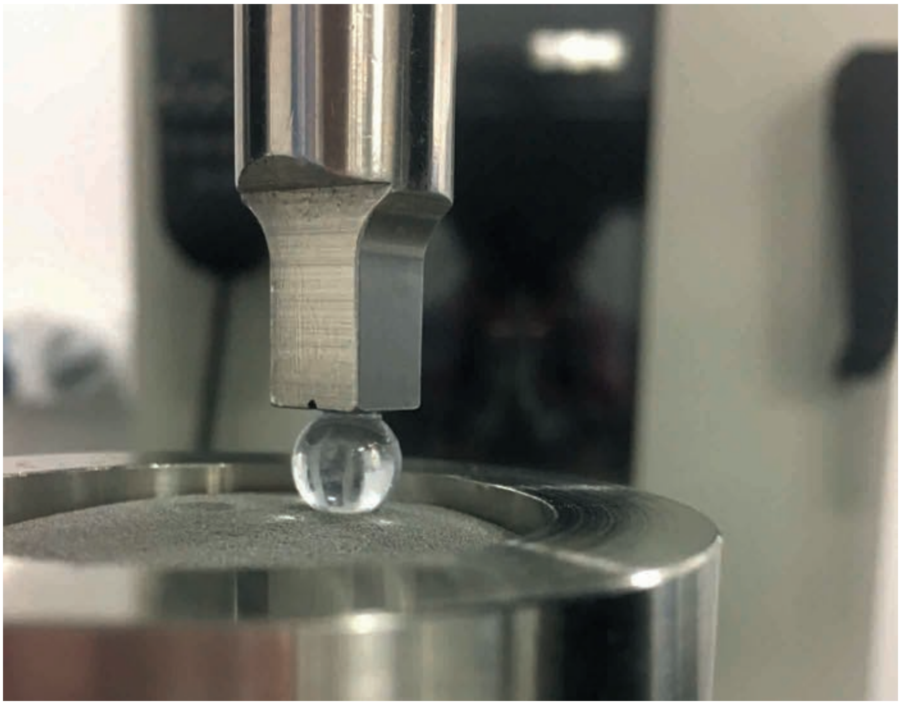
Our research programme has defined the scientific and engineering challenges that were set in conjunction with all partners at the outset.

As part of our commitment to being forward-facing and responsive to change we underwent a strategy review and programme refresh in 2019 which was approved by the MAPP Executive and endorsed by our Industry Advisory Board and Scientific Advisory Board at the start of 2020.

A number of key outputs have been achieved including:

- **Characterising a library of powders at the individual and bulk level.**
- **Developing ceramic inks based on robocasting.**
- **Methods to coat stainless steel powders to prevent oxidation.**
- **Using Field Assisted Sintering Technology (FAST) to optimise and improve process control.**
- **Developing deep learning algorithms to enable rapid process parameter development, monitoring components as they are manufactured to enable 'right first time' manufacturing.**
- **Development of a new additive manufacturing (AM) technology - Diode Area Melting (DAM).**
- **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.**
- **Machine learning used to develop data driven approaches to predict printability in AM.**

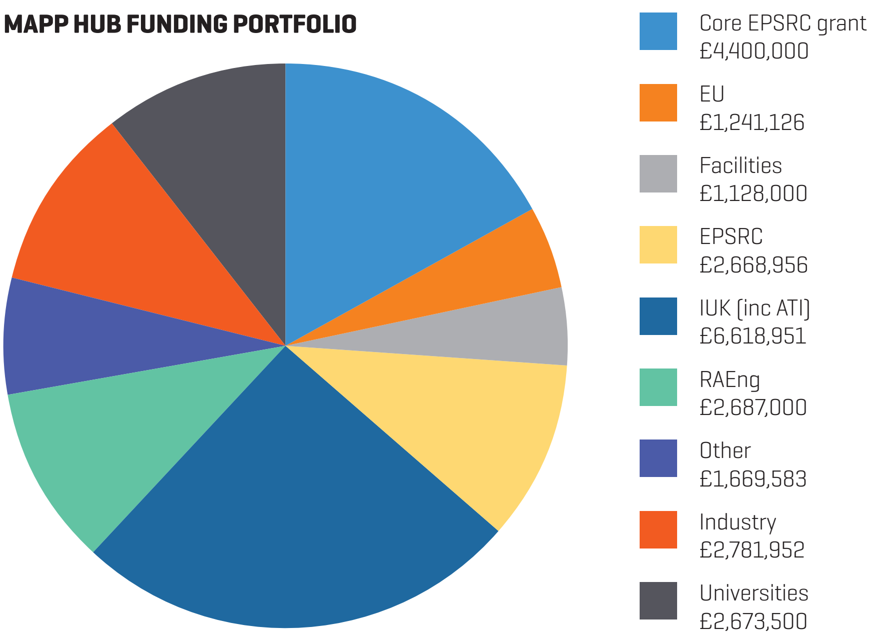
Some of our research has progressed more quickly thanks to additional linkages with our aligned projects (you can find out more about these on pages 47-51) and we have successfully leveraged funding to enable us to build a wider team and retain key skills.



A close up image of the ball indentation process, by Mozhdeh Mehrabi. The image was highly commended in the MAPP Image Competition, see p18-19 for more information.

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

MAPP HUB FUNDING PORTFOLIO



93
publications

>900
delegates at MAPP events

A set of automotive valve retainers for an engine, re-manufactured from waste titanium alloy machining swarf. The swarf was cleaned, consolidated using Field Assisted Sintering Technology (FAST), then machined into the final component. A titanium nitride coating improves wear performance and gives an appealing gold colour. This is work from the Innovate UK FAST-STEP3 project, which aims to produce titanium alloy components at 20 percent of their current cost. The image, by Dr Nick Weston, was highly commended in the MAPP Image Competition, see p18-19 for more information.

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:

- Our partnerships with catapults.
- Our partnerships with UKRI Critical Mass Activities.
- Setting the Henry Royce Institute agenda in Materials 4.0.

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, of which four are now complete (you can read more about our feasibility funding on page 28).

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

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

Our colleagues took part in our first Image Competition, see page 18 for more information, which has resulted in a range of fantastic images. Two of the images are featured on these pages.

Researchers have also been taking the lead in the running of MAPP's Training Committee, Research and Research Stakeholder Management Committee, and Equality, Diversity and Inclusion Committee.

Former MAPP PDRA Dr Samuel Clark, now of the Advanced Photon Source at Argonne National Laboratory.

Former MAPP PDRA Dr Zicheng Zhu, now of the National Manufacturing Institute Scotland.

RESEARCH PROGRAMME OVERVIEW

CORE RESEARCH THEMES

PLATFORM RESEARCH: POWDERS AND PROCESS BY DESIGN

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

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

GRAND CHALLENGE (GC) THEMES

GC1: Right First Time Manufacturing

Ensuring we can deliver defect free and fit for purpose components. Being able to predict porosity and microstructure evolution through multiphysics modelling. Accommodating variability through real time process control. Achieving pre-defined performance in components and reducing waste. Working towards zero waste manufacture – processes which are cleaner, more efficient and generate less waste.

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

In-situ microstructural control, i.e. components which can be made with specific and controlled microstructures and properties, which will allow us to move from 'form on demand' (right first time) to 'performance on demand'. Prediction of component performance in subsequent manufacturing steps and service conditions from the original starting material and processing conditions.

GC3: Enhanced Product Performance

Enhanced component performance through careful control of process and materials. Structural manipulation to enhance component performance and functionality – controlled hierarchical structures and components. Development of starting materials which are tuned for process (e.g. 'alloys by design'). Development of processes for materials which are challenging to process or cannot be currently processed via existing powder processes. Manufacturing of products with properties that are currently impossible.

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.

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, UCL, Cambridge University and industry.

Several projects are in progress as part of final year undergraduate research. Limited access to the labs has allowed students to gain useful experience in coding and machine learning.

One project is looking to use laser parameters and derived geometric factors to predict the measured thermal output on a pyrometer. Once the model has been developed the plan is to use it in reverse, to calculate what laser parameters are needed to maintain a stable processing temperature in any geometry. Another project is attempting to build a similar model using DED AM.

The biggest change in P2.1 is a new collaboration with Dr Phillip Stanley-Marbell's group at the University of Cambridge. The physical computing approaches they have developed offer a different way to process data from AM. This new approach could uncover previously hidden physical details and help to enhance our understanding of the physics in AM processes.

The physical computing approach also provides a route for ultra-fast processing of data. Presently the main obstacle to real-time monitoring and defect-fixing is the processing speed required. Current project work is looking to directly address this with dimensionless numbers capturing an efficient data-set and making parameter changes on a layer-by-layer basis.

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, UCL, Cambridge University and industry.

Research is centred around optimisation of the material addition process window using a range of important alloys including Ti-6Al-4V and IN718.

The process parameters selected for depositions have been optimised in order to achieve target microstructures defined by Rolls-Royce.

The research is now working towards incorporating *in-situ* process monitoring of builds and repairs.

Complex geometries observed in DED result in different temperature gradients across the component. This gives rise to different cooling rates which dictate the final microstructure and therefore mechanical properties. It is these properties which ultimately determines the in-service performance of the component.

P2.1 is now allowing us to monitor the melt pool geometry in real-time during builds. This has been achieved using both thermal and optical camera technology.

The ability to monitor the melt pool coaxially will allow us to achieve closed-loop control of the process in order to influence the microstructure across different geometries in the same build.

Research into the DED process has produced a number of successful collaborations across MAPP.

Prof. Peter Lee's team have conducted a synchrotron investigation of the DED process at the Diamond Light Source, at the Harwell Science and Innovation Campus in Oxfordshire, UK.

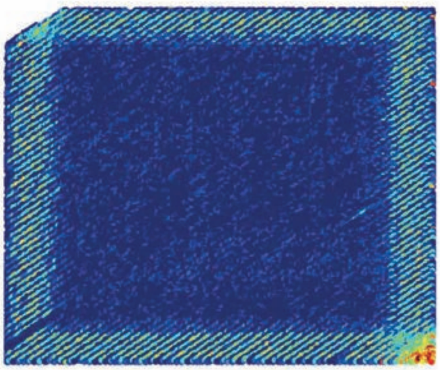
This work has produced high-resolution imaging of laser-matter interaction and defect formation.

The synchrotron research is also being used as an alloy design platform which investigates thermodynamic behaviour, phase transformation quantification and micromechanical behaviour.

MAPP's work in this area is enabling translation to industrial applications. Current experimental work on the BeAM DED machine, at the Royce Discovery Centre, University of Sheffield, is attempting the industrial scale-up of the trials observed by Prof. Lee's team.

Intra-institutional MAPP collaboration has brought together the departments of Automatic Control and Systems Engineering and Materials Science, at the University of Sheffield. We are currently looking at streamlining our design of experiments (DoE) approach by utilising greedy batch Bayesian optimisation. This algorithm takes data from small DoE batches and helps guide and instruct the next DoE experimental trials. This approach helps to avoid large and approximate DoEs by reducing the range of parameters on trial.

Increasing our understanding of *in-situ* process monitoring is driving us towards the goal of achieving closed-loop control. The impact this will have is huge. It will allow us to build and repair in 5-axis with confidence in the final microstructure as well as increasing right-first-time throughput of components. The current reactive approach to DED research gives slow turnaround times and can be costly. The impact of this research will allow for a much more proactive approach to DED with the aims of rapid, cost-effective and right-first-time repairs.



A diagram of the thermal effects of laser history. Heat accumulation can be seen where the laser turns around in the hatch pattern and in the final corner.

P2.2 SOLID STATE PROCESSING

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

Field Assisted Sintering Technology/Spark Plasma Sintering

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

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

Our understanding of Field Assisted Sintering Technology (FAST) has continued to develop in 2020; the range of materials and shape possibilities is expanding as our knowledge of the process matures.

While primarily used as a resource efficient powder metallurgy process the need for ever higher performing parts has increasingly edged into the research agenda.

In-situ FAST-DB (Diffusion Bonding) of powders has extended from similar alloys to mixtures of titanium alloys, nickel superalloys, ferritic and austenitic steels, tungsten and high entropy alloys. Chemical grading is rapidly becoming a dominate driving force in FAST research due to its unique ability to bond loose powders *in-situ* with incredibly short sintering times.

The MAPP team at Manchester has extended FAST-DB even further using it as a technique to rapidly investigate the bonding of steels for nuclear pressure vessels; as a low cost analogue for conventional Hot Isostatic Pressing (HIPing). This is coupled with the ability to coat steel powders with nanoscale oxidation resistant layers, further reinforcing the potential impact for HIPing technology in the nuclear sector.

Expanding on from last year's work, data acquisition of FAST process data has now been streamlined; automatically logging experiments to the cloud and linking with powder characterisation data. This system allows the datasets to always include the most recent experiments and for researchers to interrogate the provided REST APIs to obtain their desired data. This is linked automatically with results from characterisation tests of both process feedstocks and final parts. Over the next year it is expected to be integrated with modelling techniques to create Digital Shadows and Twins of the FAST process as an important part of the EPSRC grant Doing More With Less: A Digital Twin of state-of-the-art and emerging high value manufacturing routes for high integrity titanium alloy components.

Despite lockdowns during 2020, the Henry Royce Institute at Sheffield was able to receive and install the new, industrial scale, semi-continuous FAST furnace from FCT Systeme GmbH. It is capable of sintering parts up to 250 mm in diameter and will be a key part of MAPP and the FAST-STEP3 Innovate UK project. This project is seeking to use FAST to manufacture automotive prototype engine parts directly from recycled titanium swarf.

Hot Isostatic Pressing - Functionalization of metallic powders for performance enhancement

Investigator: Dr John Francis, University of Manchester

Collaborators: TU Vienna, University of Leeds, University of Sheffield, Royce Translational Centre (UoS), Sir Henry Royce Institute (UoM), The Open University, MTC Coventry

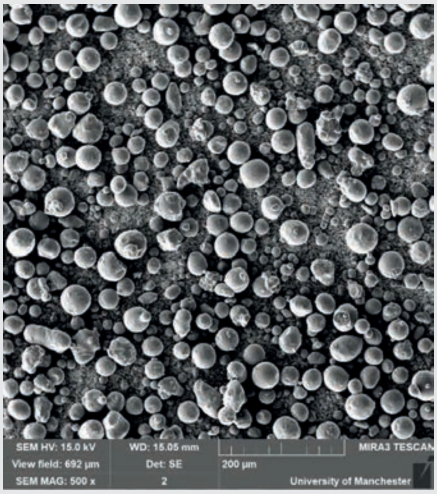
Hot Isostatic Pressing (HIPing) is a near net shape manufacturing technique, where powders are densified under high temperature and pressure in a canister that represents the final geometry of the component.

HIPing results in a highly dense component with a uniform microstructure that has superior mechanical properties to that of castings. Recently, there has been some interest in manufacturing stainless and low alloy steel nuclear structural components by HIPing.

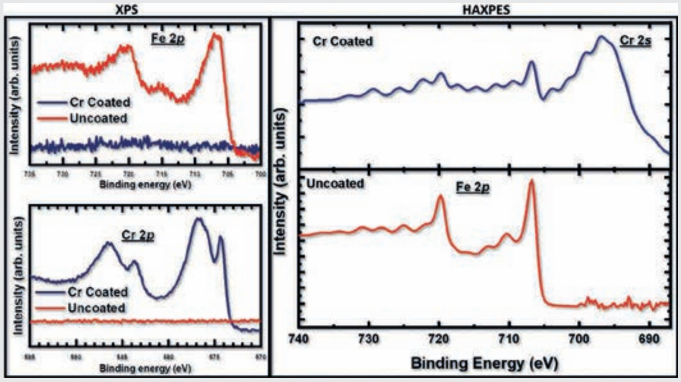
The major challenge in HIPing of low alloy steels like SA508 alloy is the oxidation on the surface of powders which will affect the fracture toughness of components.

MAPP researchers at The University of Manchester, in collaboration with TU Vienna, Austria have been working on developing chromium coatings for oxidation protection of powders such as SA508 low alloy steel. The powders were coated with a chromium layer approximately 7.5 nm thick using custom built magnetron sputtering equipment based at TU Vienna. The chromium coated powders were studied using scanning electron microscopy, X-ray photoelectron spectroscopy (XPS) and novel lab based high energy x-ray photoelectron spectroscopy (HAXPES). Typically, HAXPES at 9 keV results in sampling depths of up to 50 nm, compared to 3-10 nm using surface sensitive XPS and standard lab sources such as Al Kα (1.486 keV). Hence, HAXPES can provide information on possible oxidation of the powder beneath the chromium coating. It was found that the chromium coating significantly reduces the oxygen content in powders. It was also found that chromium completely diffuses into the bulk material during HIPing.

Apart from the oxidation resistance, a chromium coating was also found to reduce electrostatic charging on the surface of powders. This may have significant applications in improving the surface properties of powders. The coating may also help to manufacture components with powders that are difficult to electron beam melt due to surface charging issues.

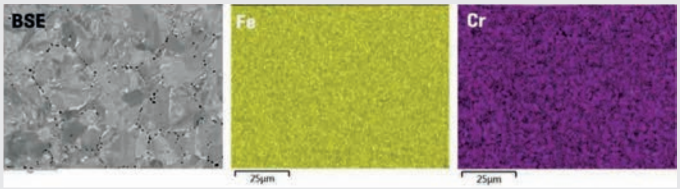


Above: SEM SE image of SA508 steel powder used in the study



XPS and HAXPES spectrum of Iron and Chromium on uncoated and chromium coated SA508 steel powder. No Iron was detected in XPS spectrum of coated sample whereas HAXPES picked Iron signals on a coated sample.

Right: SEM BSE Image and EDS map of fully HIPed chromium coated SA508 steel powder. The chromium is fully diffused in to bulk material.



P2.2b Fundamentals of Solid State Processing

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

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

An understanding of process maps in sintering processes is key to optimising both the density and microstructure of the final parts.

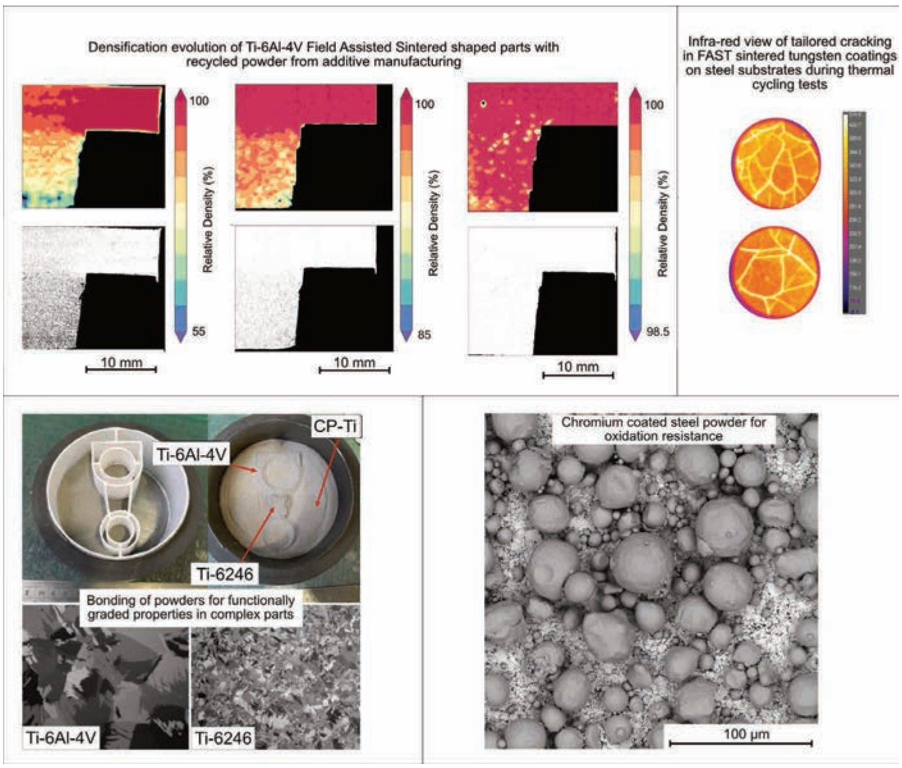
The rapid nature of Field Assisted Sintering means that experiments can be conducted in a high-throughput environment.

MAPP researchers have been able to fully define sintering process windows for key powders allowing highly reproducible results. This is now being extended to understand the complex interlinking of pressure and temperature histories within Field Assisted Sintering, with initial results suggesting the timing of these parameters can have an effect on the final part's microstructure and properties.

Modelling of the sintering process has further improved this year; to include increased shape complexity, with experimental validations showing the importance of generating accurate material data.

Scaling up the models is of critical importance with the shift to ever larger part sizes as FAST is taken off into industrial projects. We can predict the thermal gradients in these larger parts that could have a detrimental effect on product yield and downstream performance.

The effects of electrical current have also been shown to have a phenomenally large effect on the rate of densification in powder parts within FAST. The exact mechanisms as to why this is the case are subject to debate but have become a key focus of research over the next year.



The MAPP team at Oxford have continued their work on tungsten coated steels, investigating the thermal stability of a range of coating designs with Culham Centre for Fusion Energy. Expanding on this, high entropy alloys are also now been added to the research agenda, as a way to improve the bonding and performance of tungsten for the extreme environments in nuclear fusion reactors.

P2.3 FUTURE MANUFACTURING PLATFORMS

P2.3a Diode Area Melting

Investigators – Dr Kamran Mumtaz and Dr Kristian Groom, Sheffield

The Diode Area Melting (DAM) process seeks to overcome the challenge of limited productivity within current Powder Bed Fusion (PBF) systems, for example, selective laser melting.

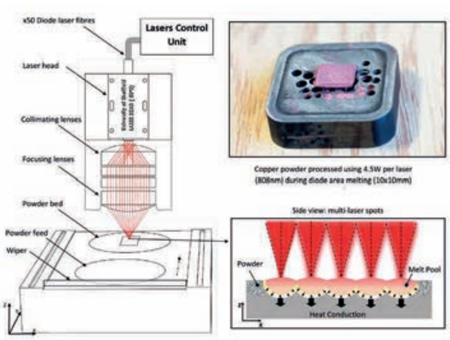
DAM uses an architectural array of low power, fibre coupled diode lasers to process pre-deposited powder.

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 (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 blue laser sources (450nm).

Blue lasers are now being integrated into a new x50 laser head that will be integrated into the DAM system.

Direct comparisons are being made between standard PBF and 450-808nm DAM processing, examining fabricated component properties (resolution, structural integrity, microstructure etc.) and productivity.



Diode Area Melting

P2.3b High Speed Sintering and Polymer AM

Investigator – Dr Candice Majewski, Sheffield

Collaborators – Sheffield (X3), Manchester (X2)

This project is developing our understanding of the processes, materials, and interaction between the two.

The overall aim is to develop an optimised manufacturing process for powdered-polymer AM.

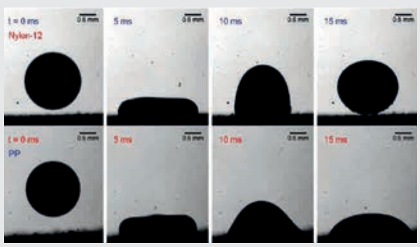
There is a growing need for increased repeatability of polymer AM parts as we move towards higher numbers of end-use applications, often in highly-demanding sectors.

A crucial part of achieving this is to obtain a better understanding of the effects of processing parameters and material characteristics on part performance.

As part of our efforts in this area, we have been using micro-CT techniques to examine porosity of our parts (and its relationship with processing parameters and final part performance), providing previously unseen information into the ways in which we can minimise and control porosity.

Investigations are underway into the use of Positron Annihilation Lifetime Spectroscopy (PALS) for non-destructive characterisation of polymer AM parts, with an expectation of applying these findings to further powder-based techniques.

Current work is investigating the potential to identify changes in parts at a material level (crystallinity and molecular weight) and a performance level (tensile properties). In this way, we aim to develop a much deeper understanding of the underlying science behind changes in part performance, which we can then apply to modelling and predicting the performance of our parts in real-life situations.



Droplets of identical ink on different polymer surfaces, showing substantial differences in spreading behaviour. Work performed in collaboration with the MAPP team at the University of Leeds.

P2.3c Ceramics

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

Collaborators – Oxford, Manchester (X2), Leeds, UCL (X1), Sheffield (P2.2, X3)

Work has continued on the development of key additive manufacturing processes – robocasting of technical ceramics and composites, selective laser sintering of ceramics and glasses and digital light processing of ceramics.

Some key advancements have been made in the fabrication of fibre-reinforced composites using two in-house designed techniques based on robocasting – embedded printing and core shell printing.

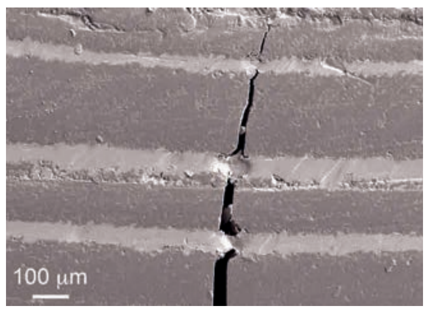
We have produced alumina-steel composites with fine internal auxetic reinforcement structures, and, through our collaborative work with The University of Manchester, progressed our understanding of drying of ceramic gel matrices used for embedded printing.

This work will be further directed at the production of ceramic composites with architectures designed to direct crack propagation, as well as deepening our understanding of the toughening mechanisms acting in these materials through *in-situ* mechanical testing.

We have made progress in the production of ceramic components using selective laser sintering. Employing a novel sintering additive, reduced graphene oxide, as well as advanced *in-situ* and in-operando characterisation (in collaboration with UCL), we have achieved direct laser processing of transparent silicon oxide powder. The process is now being patented, and we plan to apply our findings to expand the range of materials suitable for laser sintering technology.

In addition to powder processing and manufacturing research, we performed advanced microscopy-assisted *in-situ* mechanical testing of ceramic materials. Specifically, targeted micromechanical tests in cemented carbide (WC-Co) composites to measure tungsten carbide grain boundary fracture energy – an important step towards understanding fracture in WC-Co cutting tools. We have selected boundaries of interest by analysing EBSD data using custom Matlab scripts, with testing being done via wedge loading of FIB milled DCB geometries at boundary sites. This work has been submitted as a paper to The Journal of The Minerals, Metals & Materials Society for publication and is under review.

Finally, we intend to further test carbide boundaries and perform grain boundary statistical analysis in order to provide much-needed guidelines to design the microstructure of WC-Co cutting tools with improved performance.



Fracture of a alumina matrix/steel fibre composite fabricated by robocasting

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, UCL

Collaborators – Manchester, Sheffield, Leeds, Imperial, Oxford

There are two main streams of research – laser powder bed fusion (LPBF) and directed energy deposition additive manufacturing (DED-AM).

In 2020-21, the X1 team employed ultra-fast X-ray imaging *In-situ* and Operando Process Replicators (ISOPRs) to study process and defect dynamics in LPBF and DED-AM.

LPBF

Pore evolution and melt pool dynamics were followed during LPBF of aerospace grade alloys and ceramics. Using the data, we have developed a new analytical model to evaluate the thermal properties, surface roughness, and defect evolution on multi-layer melt tracks.

We have been developing the first multiphase and multi-physics simulation to predict and elucidate pore and hump formation during LPBF in collaboration with Rolls-Royce plc. and the European Space Agency. We have also worked with Access E.V to model and predict the metal vapor jet and spatter formation. The next step will be to develop synchrotron calibrated machine-learning models.

A new Quad-ISOPR setup capable of using up to four lasers is under development, in close collaboration with MAPP industry partner Renishaw.

The Quad-ISOPR aims at performing unique LPBF experiments using multiple lasers at the same time and novel scanning strategies not possible with a single laser. The setup will be compatible with synchrotron X-ray beamlines and will allow us to realise experiments in imaging and diffraction conditions.

Key experiments include the study of the spatter formation during LPBF using various hatching strategies. By performing multi-laser scanning and beam shaping, it is expected to better control the thermal gradient within the part and observe the impact on phase transformation, possibly affecting the accumulation of residual stresses *in-situ.*

The expected outcome will give a better understanding of the process dynamics during LPBF to avoid the formation of defects while printing and improve the part production process.

We will study the impact of multi-laser techniques on part production efficiency, reducing the time and cost needed during printing. This will be achieved through better control of energy input and thermal gradients during LBPF, leading to tailored macro and microstructures within the part. This promising method will also explore the printability of alloys that are currently difficult to process using AM, expanding the range of options available for industries.

DED-AM

Building on our first ISOPR that replicates a commercial DED-AM system, enabling both synchrotron x-ray imaging and diffraction, we have designed a second-generation system (BAMPRII) that has correlative infra-red and optical imaging, a greater capacity, and pre-heating substrate.

Recent results revealed how the laser-induced non-equilibrium solidification process drastically influences the resulting microstructure and residual stress in a variety of materials, and an applied magnetic field can significantly influence the resulting microstructures.

We explored the capability of BAMPRII on generating graded structures using different materials; and, working with the University of Sheffield, we explored the energy density of BAMPRII and how it matches with an industrial-scale machine.

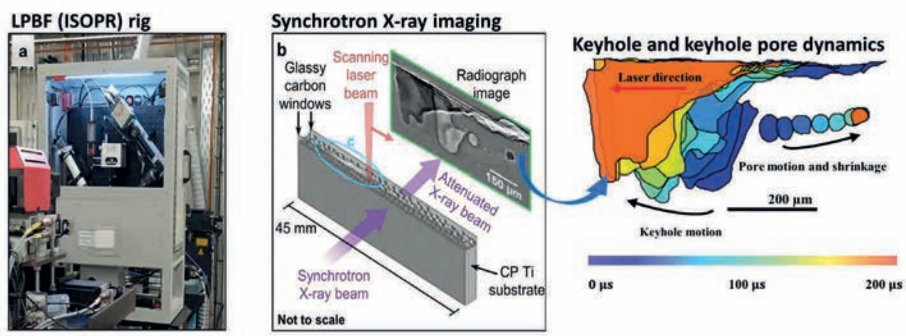
More experiments on BAMPRII will be performed on a variety of materials using synchrotron X-ray imaging and diffraction at European Synchrotron Radiation Facility (ESRF) and Diamond Light Source (DLS).

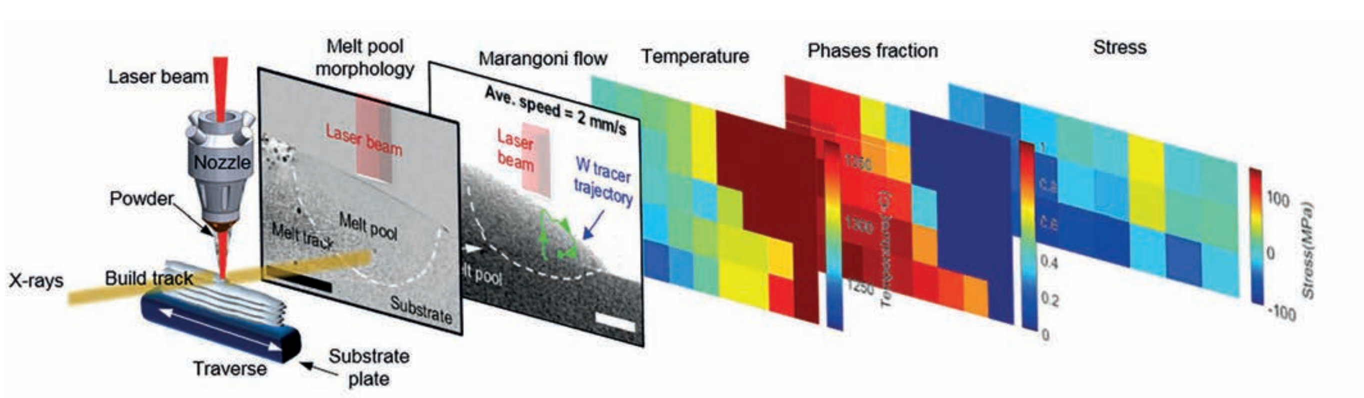
New projects such as magnetic control of microstructures, grading in laser additive manufacturing, and the development of new nickel-superalloy are progressing.

Our results provide an enhanced understanding of the underlying physics of the DED-AM process for a broad audience.

We provide a gold standard for experiments and computational model validation. Such advancements are critical for new alloy and process design.

The application of BAMPRII will initiate new research avenues, for example alloy development and technique development for quantifying secondary phases during ultrafast manufacturing processes.





X2 Advanced Characterisation

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

Collaborators – Manchester, Leeds, Sheffield, Imperial

X2 working with P2.2a

Utilising the Royce-funded HIPing facility based in the University of Sheffield, a novel Ti-Fe composite has been successfully produced.

A multi-scale XCT image-based finite element (FE) model frame has been developed in order to understand in detail the correlation between the process-variables, for example temperature, pressure, particle size and property, and the product property such as density and structure.

Specifically, the overall deformation of the canister during HIPing is recorded by low-resolution XCT.

High-resolution XCT scans provide the detailed information on individual particles.

A time-lapse high-resolution XCT study is ongoing to record the particle evolution at different stages of HIPing which will underpin the development of an image-based FE model on the particle scale for the densification process.

With numerical homogenisation, the effective properties of the powder agglomerate can be determined and input into the macroscopic model that is mapped directly onto the low-resolution XCT slice.

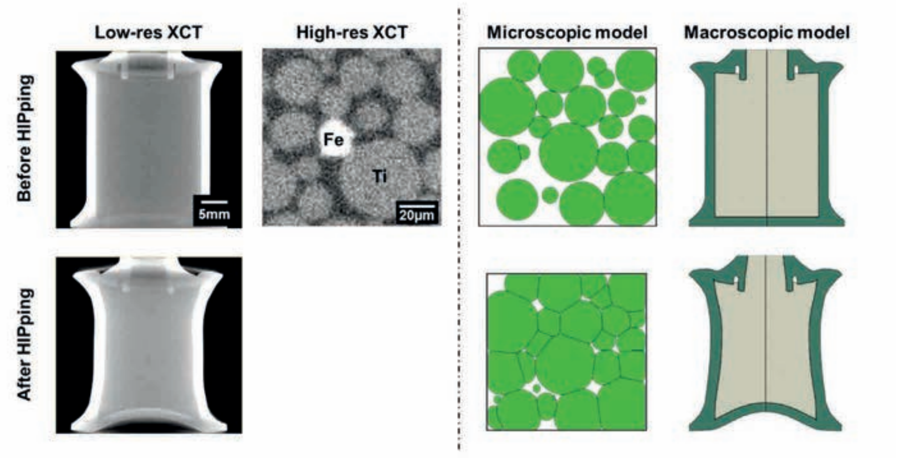
Future work will focus on exploring the factors to which the property of interest, for example shape change, is sensitive to. It will also focus on exploring the correlation among process-variables and the densification characteristics.

In-situ synchrotron experiments will be conducted to follow the homogenisation, via Fe diffusion, process in the HIPed composite and high-resolution electron microscopy (EM) will be used to explore the diffusion and reaction on the grain and subgrain scales.

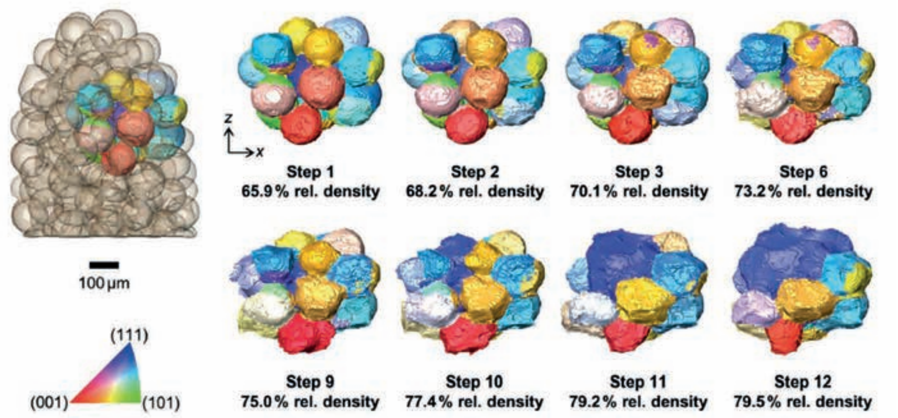
The multi-scale time-lapse XCT images and corresponding FE models will provide comprehensive insights into the densification process during HIPing and factors to which the densification is sensitive.

In-situ time-lapse laboratory diffraction contrast X-ray tomography (Lab-DCT) has been successfully used to follow the recrystallisation and competitive grain growth during sintering of Cu powders at the University of Manchester.

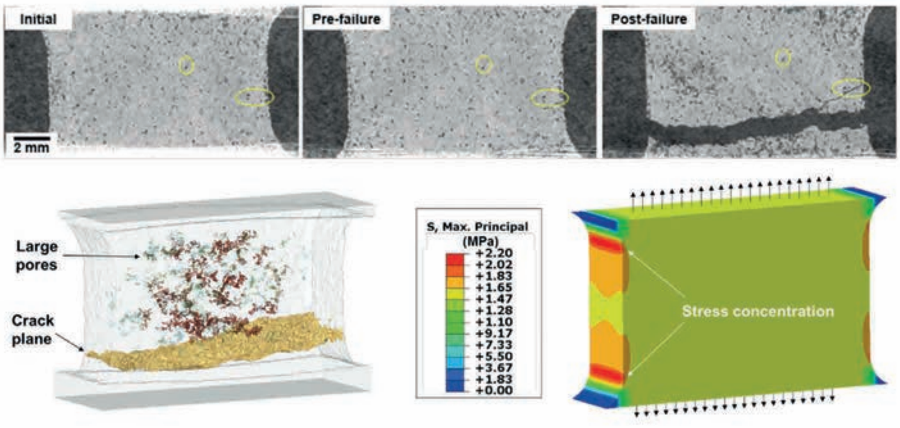
The shrinkage and dissolution of grains in the immediate vicinity of a fast-growing grain are recorded. The accuracy of the size, shape and location information for the grains has been validated by EBSD analysis. So far, the free sintering has been studied as a benchmark. This workflow can be extended into a more general powder processing routine such as HIPing, FAST and SPS. The outcomes will provide detailed information on the microstructural evolution during these powder-based processing routines and underpin a



XCT slices (LHS) and microstructurally cognisant models (RHS) showing the sample before and after HIPing on the component (macroscopic) and particle (microscopic) scales.



Time-lapse series of sintering steps during densification of the powder body showing a small RoI comprising the nearest neighbour particles, and thus nearest neighbour grains, to the particle containing a fast-growing grain. The location of the RoI with respect to the full sample is illustrated (left). The grains are colored by crystallographic orientation according to inverse pole figure.



XCT virtual slices showing the middle of an AM manufactured polyamide sample at different stages of loading (top row) together with the 3D view highlighting the larger defects together with the crack plane that are mapped onto the sample prior to failure and a companion FE results showing the stress concentration induced by sample geometry.

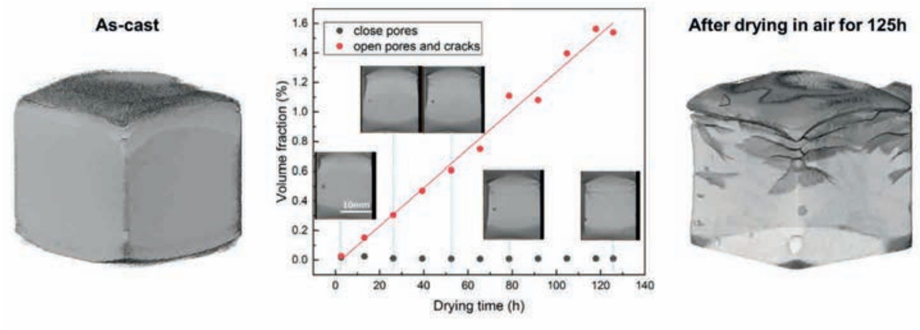
more comprehensive understanding of the kinematic processes and guide the optimisation of processing parameters in powder-based processes such as HIPing, FAST and SPS.

Other X2 work

In collaboration with the University of Sheffield, *in-situ* tension test combining has been performed with XCT on a polyamide AM sample to investigate the effects of porosity on its mechanical behaviour.

Micrographs through the middle of the specimen have been recorded at different stages of loading. Comparison of the sample images enables the crack plane to be tracked back to the as-manufactured sample. The large inter-connected pores are identified from the XCT virtual slices. A finite element (FE) model has been developed to reproduce the tension test.

The FE results show stress concentration where the crack has propagated due to the sample geometry. The stress can be intensified further by the surface roughness. Once nucleated, the crack can propagate by linking up with the pores, leading to fracture. As a step forward, the digital replica of the AM sample can be converted into FE meshes. This will provide a more detailed response of the sample under the applied load.



Development of pores/cracks during drying of gel-cast alumina followed by *in-situ* XCT.

Virtual mechanical tests can be conducted using the FE model, enabling microstructure engineering to achieve designed mechanical properties.

A joint project between Imperial College London and the University of Manchester focuses on exploring the development of defects including pores and cracks within an alumina gel-cast during drying.

The *in-situ* XCT results highlight the crack and pore density as well as their locations as the sample dries. This helps to understand the fundamental driving force for the crack and pore development and provides insights into potential solutions to minimise the crack and pore formation.

X3 Modelling, Optimisation & Control

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

Collaborators – Sheffield, UCL, Imperial

DED-AM

The research team in Sheffield, in collaboration with UCL, is focusing on machine learning frameworks to model laser-matter interaction towards fundamental understanding of process behaviour.

Via synchrotron *in-situ* x-ray imaging of the DED-AM process, a DED-AM process replicator is utilised, to capture IN718 DED behaviour.

Meltpool morphology (length, height and volume) is extracted from the data and a neural-network structure is used to model and map the full range of process parameters including laser power, traverse speed and powder feed rate.

A new mathematical framework, for training neural networks, that is based on the characterisation and stabilisation of measurement variations is introduced.

The mathematical framework results in a number of useful properties that maximises the use of data as well as aiding in the interpretation of results in a systematic and principled manner.

Separately, a new computational framework has been created for the creation of physics-informed learning algorithms for neural-network structures.

The new framework is designed to optimise network structure via embedding empirical errors (data-driven) in the learning process.

Demonstration of this work includes a number of simulations on benchmark functions, with the next step in research including the application of this new work on an AM process.

LPBF

Thermal process monitoring: this research aims to reconstruct true thermal profiles from images which have been captured during laser powder bed fusion. The readout method of the image sensor which the camera adopts is a rolling shutter, where the exposure and readout are done line by line. The goal was to implement Kalman filtering technique to estimate cooling profile over time from noisy data.

A discrete element approach has been developed to identify temperature variation parameters from a simplified PDE model and tested on a thermal imaging sequence. These are being adapted to the rolling shutter imaging process to identify a consistent temporal cooling profile.

DoE Optimisation: We implemented a Bayesian-Design of Experiments optimisation framework sequentially onto the multi-defect formation (lack of fusion and thermal strain) in Selective Laser Melting of a NI-Based Alloy in order to locate optimal parameters as well as understand the underlying interactions through the development of the Gaussian Process Regression (GPR) surrogate models. More recently we extended the Bayesian-DoE method in order to select batches of experiments simultaneously rather than filling a batch sequentially. Based on a demonstrator LPBF conceptual study, its deployment for DED-AM is being explored.

Software Demonstrator

Our software graphical interface and learning routines based on machine learning to optimise AM processes under multiple performance objectives (part quality, process speed, design options) and process constraints (scanning strategy, process limits) is under industrial trials and evaluation, with preliminary results demonstrating efficient exploration of the process parameter space.

MAPP PROJECT
ORGANISATION CHART

- **Industrial Advisory Board**
- **MAPP Director Prof. Iain Todd**
- **Scientific Advisory Board**

MAPP Operations Team

Powders and Process by Design

- **P2.1 Metal AM**
  - **P2.1a Laser Powder Bed Fusion**
    Co-Leads
    Prof. Andrew Bayly, University of Leeds and Prof. Iain Todd, University of Sheffield
  - **P2.1b Directed Energy Deposition**
    Lead
    Prof. Iain Todd, University of Sheffield
- **P2.2 Solid State Processing**
  - **P2.2a FAST/SPS/HIP**
    Co-Leads
    Dr John Francis, University of Manchester and Prof. Martin Jackson, University of Sheffield
  - **P2.2b Fundamentals of Solid State Processing**
    Co-Leads
    Dr Enzo Liotti, University of Oxford and Prof. Martin Jackson, University of Sheffield
- **P2.3 Future Manufacturing Platforms**
  - **P2.3a Diode Area Melting**
    Lead
    Dr Kamran Mumtaz, University of Sheffield
  - **P2.3b High Speed Sintering and Polymer AM**
    Lead
    Dr Candice Majewski, University of Sheffield
  - **P2.3c Ceramics**
    Lead
    Prof. Eduardo Saiz, Imperial College London

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
- Dr 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 — X2 Advanced Characterisation — X3 Modelling, Optimisation and Control

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

Co-Investigators

Dr 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

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University of Leeds

Dr 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

Dr Ali Hassanpour,
University of Leeds

Prof. Andrew Mullis,
University of Leeds

Prof. Philip Prangnell,
University of Manchester

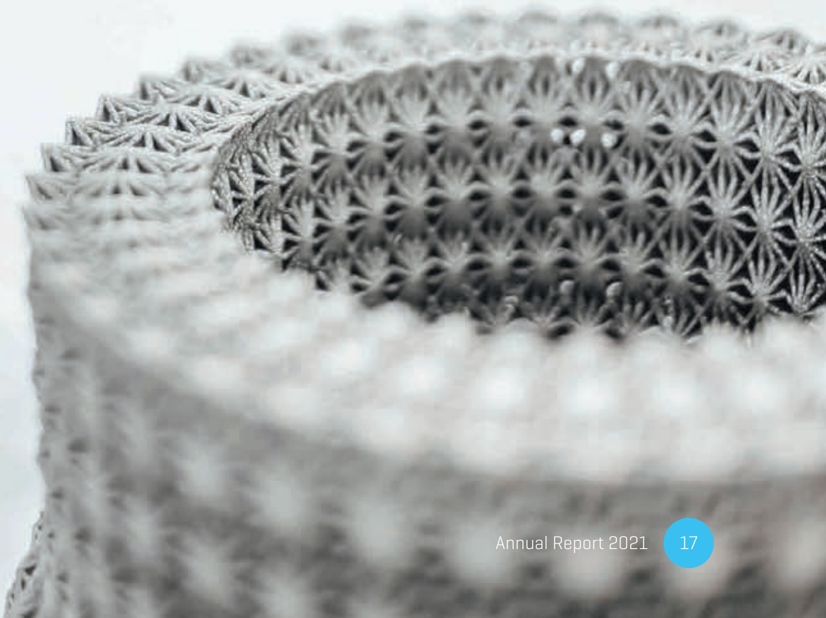


IMAGE COMPETITION

MAPP's first Image Competition attracted a high calibre of entries.

The competition, which was open to the wide network of MAPP researchers at all levels, showcased some of the fantastic photographs captured during the powder and processing studies taking place across partner sites.

Researchers from across the MAPP programme submitted more than 40 entries ranging from microscopic images, heat map and artefacts to equipment shots and structures.

Judging the entries was a tough job for the panel, MAPP Director Professor Iain Todd, professional photographer Mark Harvey, Jamie Clayton from Freeman Technology and Robert Prior from Verder Scientific, as the standard was so high.

Chair of the panel, Prof. Todd said:

"We've always known the research talents of our MAPP network and it's been great to see that they also have an eye for a striking shot.

"We are especially grateful to the sponsors of the competition Freeman Technology and Verder Scientific as it means that we have been able to award prize money to the winners."

There were two categories:

MATERIALS UP CLOSE

Sponsored by Freeman Technology

Freeman Technology, a Micromeritics company, specialises in systems for measuring the flow properties of powders and has over 20 years' experience in powder flow and powder characterisation. The company invests significantly in R&D and applications development, and provides comprehensive support alongside its range of products. Expert teams guide and support users around the world in addressing their individual powder challenges, focusing on delivering the most relevant information for the process. The result is world-leading solutions that underpin process and product understanding, accelerate R&D and formulation towards successful commercialisation, and support the long term optimisation of powder processes.

ARTEFACTS AND THEIR MANUFACTURE

Sponsored by Verder Scientific

Carbolite Gero, Retsch & Microtrac MRB are part of the Verder Scientific Group. With over 1,000 employees in 22 offices around the world, Verder Scientific sets the gold-standard for high-tech quality control and R&D solutions in research institutions, analytical laboratories and cutting-edge manufacturing organisations. Whether you are looking for particle characterisation, milling and sieving products or a new laboratory or industrial oven or furnace – Verder Scientific's high-quality portfolio delivers significant returns on investment. Find out more today at www.verder-scientific.com.

MATERIALS UP CLOSE

Winner:
Max Emmanuel

Runner up:
Lorna Sinclair

Five highly commended prizes were also awarded to: Alex Goodall, Caterina Iantaffi, Mozhdeh Mehrabi, and Dr Nick Weston for two of his images.

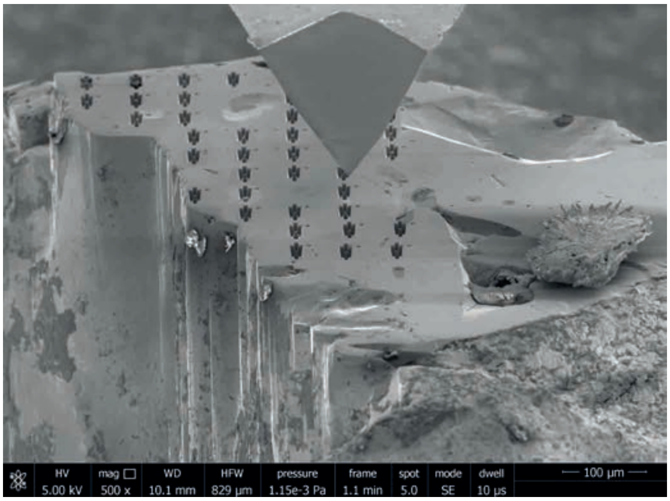
ARTEFACTS AND THEIR MANUFACTURE

Winner:
Dr Nick Weston

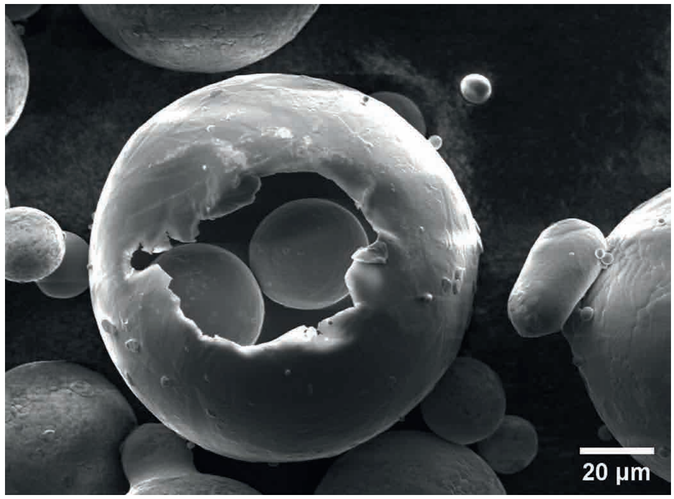
Runner up:
Dr Oliver Levano Blanch / Dr Daniel Suárez Fernández

Five highly commended prizes were also awarded to Dr Oliver Levano Blanch / Dr Daniel Suárez Fernández, Dr Yunhui Chen, Xianqiang Fan, Mozhdeh Mehrabi, and Dr Nick Weston.

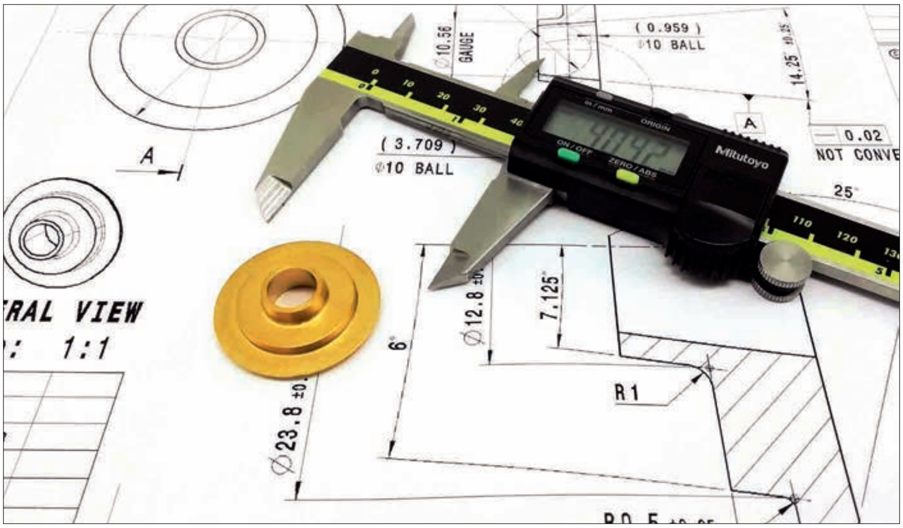
Winners were announced at a virtual awards ceremony where the sponsoring companies presented the prizes. Some of the winning images are featured opposite and throughout this annual report.



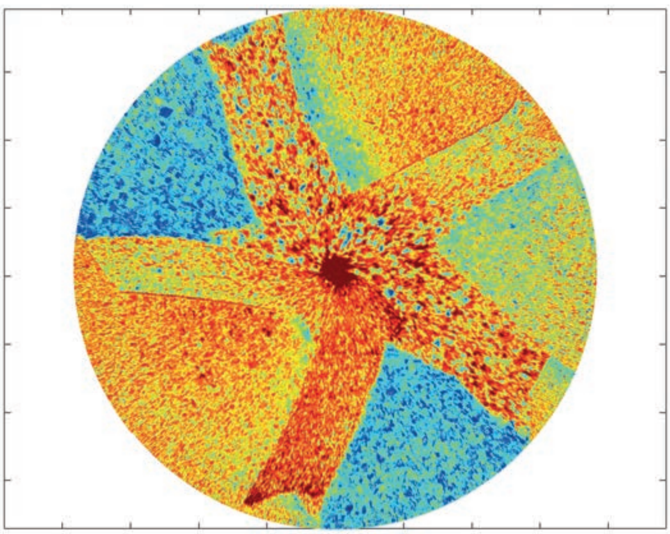
Materials up close winner Max Emmanuel's image showing double cantilever beams (DCB) on the surface of a WC single crystal.



Materials up close runner up Lorna Sinclair. Although usually solid, this Ti-6Al-2Sn-4Zr-2Mo gas atomised powder particle is hollow, and a fractured surface reveals two smaller powder particles hidden inside, likely trapped during atomisation.



Artefacts and their manufacture winner Dr Nick Weston. Photograph of an automotive valve retainer for an engine having dimensions verified against tolerances on its technical drawing. The valve retainer was re-manufactured from waste titanium alloy machining swarf. The swarf was cleaned, consolidated using Field Assisted Sintering Technology (FAST), machined into the final component, and a titanium nitride coating applied to improve wear performance (also giving the appealing gold colour). This is work from the MAPP-aligned Innovate UK FAST-STEP3 project, which aims to produce titanium alloy components at 20 percent of their current cost.



Artefacts and their manufacture runner up image by Dr Oliver Levano Blanch / Dr Daniel Suárez Fernández. This diagram is constructed with the information contained in the forces recorded with a dynamometer during a face turning operation. The machined sample has six different titanium alloys joined by the FAST technology. The alloys are distributed in the shape of the Sheffield Titanuim Alloy Research (STAR) group logo.

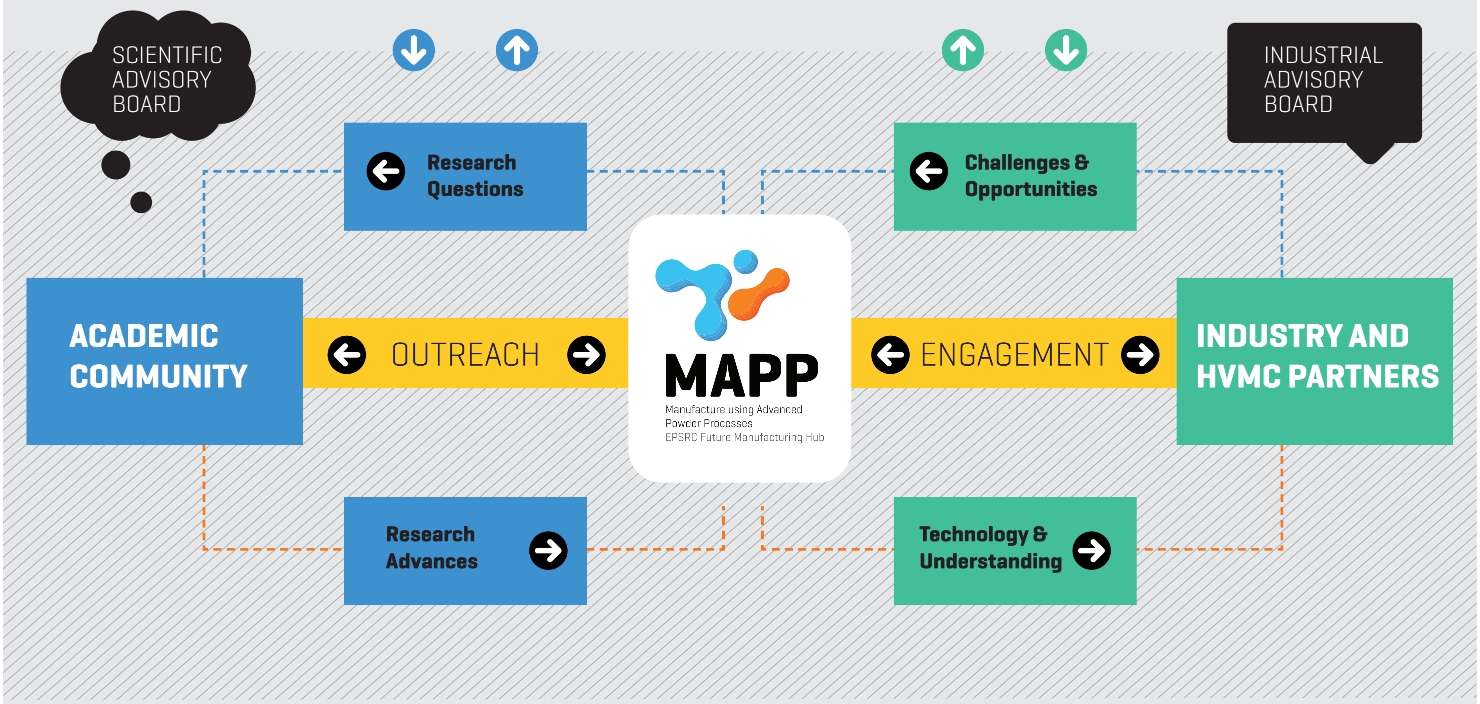
PATHWAYS
TO IMPACT

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

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

ACTIVITIES

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



SPOTLIGHT ON

THE UNIVERSITY OF CAMBRIDGE

The University of Cambridge has joined us as a new partner in order to further work that began as a MAPP feasibility study.

By Dr Phillip Stanley-Marbell

Manufacturing systems today use metrology-data-processing subsystems that are carryovers from the world of general-purpose computers.

There is a unique untapped opportunity to use the statistical information obtained during *in-situ* metrology as well as knowledge of constraints on data values (and their distributions) imposed by physics, to enable a new class of special-purpose *in-situ* computational hardware for manufacturing systems.

A previous MAPP feasibility study investigated a miniature self-contained bespoke computing platform that enabled *in-situ* analysis of in powder properties.

This project will build on the methods [9] developed in that work which use information on physics of processes to enable more efficient data dimensionality reduction.

In-situ metrology is essential for manufacturing systems to adapt to phenomena such as changes in material properties or variability in processes.

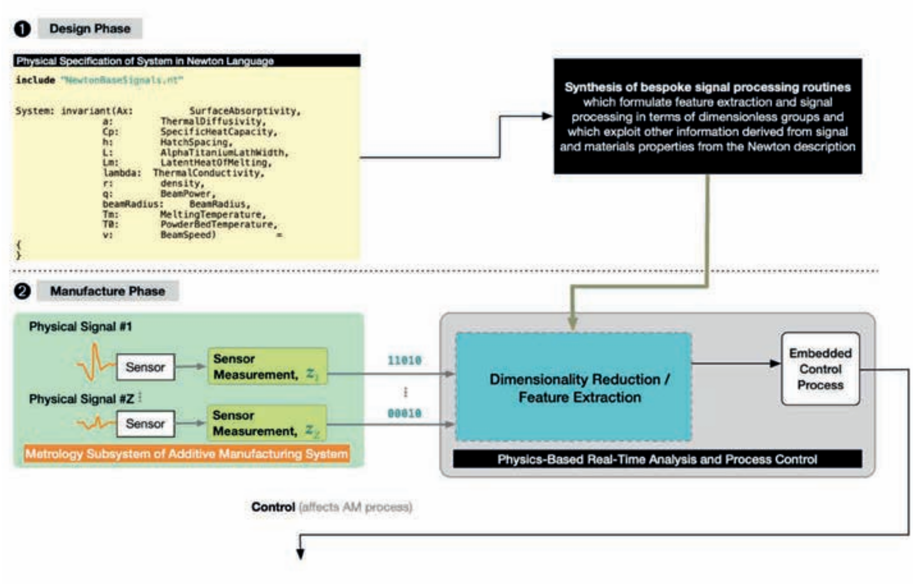
There are many opportunities for *adaptive and responsive manufacturing systems* across the areas of manufacturing, from metal powder bed fusion in aerospace applications[1], to crystallisation processes in pharmaceuticals manufacture[2].

The uncertainty of *in-situ* metrology during manufacturing process control results in over-provisioning for worst-case operation, wasting resources and reducing commercial competitiveness.

Computational methods which can track the uncertainty of their input data also hold the prospect of enabling data analyses that provide low-latency estimates with associated error bounds to enable realtime control driven by process measurements.

Recent advances in quantifying measurement uncertainty of metrology in manufacturing systems in a laboratory setting[3,4,5] have laid excellent foundations for an adventurous next step: characterising noise, in realtime, inside the signal processing of manufacturing systems.

The challenge of performing *in-situ* measurement uncertainty quantification and using such uncertainty estimates during realtime process control on physical signals however remains beyond existing research and practise.



Schematic view of the planned investigation to combine information about physics of materials and manufacture processes to enable new metrology data processing methods where the underlying computational operations exploit knowledge of the physics governing the sources of data they operate on.

Tackling this challenge requires an ambitious combination of insights across the disciplines of applied mathematics (e.g., new uncertainty distribution representations), computer science (new computer architectures for uncertainty tracking), and physics (using results from dimensional analysis to determine how to sample sensors in a manufacturing system instrumented with multiple sensors).

The project will investigate fundamental research challenges to *in-situ* metrology and process control that tracks information on measurement uncertainties throughout the steps of computation. We will investigate these goals using a combination of pyrometers in metal PBF systems in collaboration with colleagues in MAPP.

Our insight is that we can build on our recent advances in **(1)** mathematical representations for real-world sensor measurement uncertainty; **(2)** new methods for tracking uncertainty in signal processing computations; **(3)** automating dimensional analyses (today performed by hand[6,7,8]) to enable physics-inspired metrology for manufacturing systems.

[1] Mani *et al.* "Measurement science needs for real-time control of additive manufacturing powder bed fusion processes", International Journal of Production Research, 2015.

[2] Agimelen *et al.*, "Multi-sensor inline measurements of crystal size and shape distributions during high shear wet milling of crystal slurries". *Advanced Powder Technology 2018.*

[3] Sims-Waterhouse *et al.* "Uncertainty model for a traceable stereo-photogrammetry system." Precision Engineering 63 2020.

[4] de Pastre *et al.* "Polymer powder bed fusion surface texture measurement." *Measurement Science and Technology*, 2020.

[5] Santos *et al.* "Design and characterisation of an additive manufacturing benchmarking artefact following a design-for-metrology approach." Additive Manufacturing, 2020.

[6] Al-Bermani *et al.* "The origin of microstructural diversity, texture, and mechanical properties in electron beam melted Ti-6Al-4V." *Metallurgical and materials transactions*, 2010.

[7] Mukherjee *et al.* "Dimensionless numbers in additive manufacturing." *Journal of Applied Physics*, 2017.

[8] Cardaropoli, *et al.* "Dimensional analysis for the definition of the influence of process parameters in selective laser melting of Ti–6Al–4V alloy." *Journal of Engineering Manufacture*, 2012.

[9] V. Tsoutsouras, S. Willis, P. Stanley-Marbell. "Deriving Equations from Sensor Data Using Dimensional Function Synthesis" Communications of the *ACM*, 2021.

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

AMRC Advanced Manufacturing Research Centre / The University Of Sheffield.

AFRC Advanced Forming Research Centre, University of Strathclyde

Catapult High Value Manufacturing

cpi

mtc Manufacturing Technology Centre

Nuclear AMRC

WMG Innovative Solutions

INDUSTRY PARTNERS

Atomising Systems Limited

Eastman

element six

Carpenter Additive

freeman technology

GKN Aerospace

Johnson Matthey – Inspiring science, enhancing life

Maher

Metalysis

Morgan Advanced Materials

Photocentric

PSI

Renishaw – apply innovation™

Rolls-Royce

Safran Messier-Bugatti-Dowty

Seco

Wayland Additive

Weir

Xaar

Zeiss

DIAMOND LIGHT SOURCE WORKS WITH UNIVERSITY COLLEGE LONDON AND THE EUROPEAN SPACE AGENCY TO ADDITIVELY MANUFACTURE MULTI-METAL PARTS

By MAPP-aligned postgraduate researcher Caterina Iantaffi

Pictured are Caterina and Prof. Lee at The Science Museum, London, close to a building block made from simulated moon rocks - on loan from the ESA and manufactured using a 3D printer.

Additive manufacturing (AM) or 3D printing, a layer-by-layer process, is considered one of the most disruptive and fast-growing emerging technologies.

AM, in principle, can manufacture items with almost infinite design freedom and adaptability.

For the space industry, which requires the production of low volume and customised parts of low weight and complex geometries, AM is ideal.

The autonomous production of AM multi-metal systems has been highlighted as one of the key technological gaps to be overcome to ensure the success of future space exploration missions.

The potential to develop a compositionally graded structure with locally tailored properties can deeply revolutionise the way space technologies are designed and delivered.

Despite some tentative efforts in the research community, most AM techniques are limited to a single metal.

I am working in a synergic collaboration between University College London (UCL) and the European Space Agency (ESA) to define and develop a layer-wise AM method for multi-materials and functionally graded parts.

"Additively manufactured hierarchical structures for space system applications" is quite a broad project title which highlights the infinite design freedom of AM processes, especially in the case of laser direct energy deposition (L-DED).

I have started laboratory experiments on processing Al-2024 powder to print on dissimilar metal substrates to understand the interfacial behaviour in terms of grading evolution and metallurgical compatibility.

In the last part of the project, the attention will move to the manufacturing of new metal matrix composite materials (MMCs). Benefiting from Finite Element Analysis simulations, topological optimization criteria for spatial distribution and composition will be adopted for tailoring the material properties towards withstanding common failure mechanisms.

Using the innovative facilities at the Diamond Light Source and the expertise of Professor Peter Lee's group, which is pioneering the field of *in-situ* observation of AM phenomena, the challenges of transitioning from one material to another or co-depositing multiple materials will be addressed.

Therefore, I am confident that unique analyses will be pursued and new and valuable insights on the phenomena under examination will fill the gaps in the recent literature.

I am grateful to collaborate with an organization such as the European Space Agency (ESA) that is looking to do the impossible here on Earth and beyond, including taking the design and manufacturing of space applications to the next level. The project is boosted by a continuous synergy, mutual exchange of knowledge, creative ideas as well as innovative facilities and expertise. All this is priceless and truly challenges me to do my best.

FOCUS ON PUBLIC ENGAGEMENT –
BEAT THE MACHINE [LEARNING]!

Dr Freeman with pupils at STEM for Girls discussing the game

The engaging MAPP game Beat The Machine [Learning]! provides a fun introduction to metal additive manufacturing (AM) and closed-loop control.

It demonstrates some of the challenges faced when trying to optimise a manufacturing process, and how researchers are addressing these challenges.

One difficulty with metal AM is the need to balance the laser power and travel speed to avoid defects which may cause the material to have reduced mechanical properties.

Current research is looking to fit instrumentation, for example, thermal cameras, around the component being built, to monitor the temperature and shape of the melt pool. The data is processed through an algorithm to identify if it is within a target range. If it is outside the range, or approaching the limits, then the algorithm will calculate adjusted values of the laser power and travel speed to correct the behaviour, a process called 'closed-loop control'.

The game is designed to simulate closed-loop control, allowing the user to control power and speed in a Selective Laser Melting (SLM) AM build.

The free-to-download game, developed and created by Dr Felicity Freeman, is discussed in the journal *Physics Education.*

The paper Beat The Machine (Learning!): metal additive manufacturing and closed loop control, provides a background to AM, its benefits and challenges, and explains the importance of closed-loop control and machine learning.

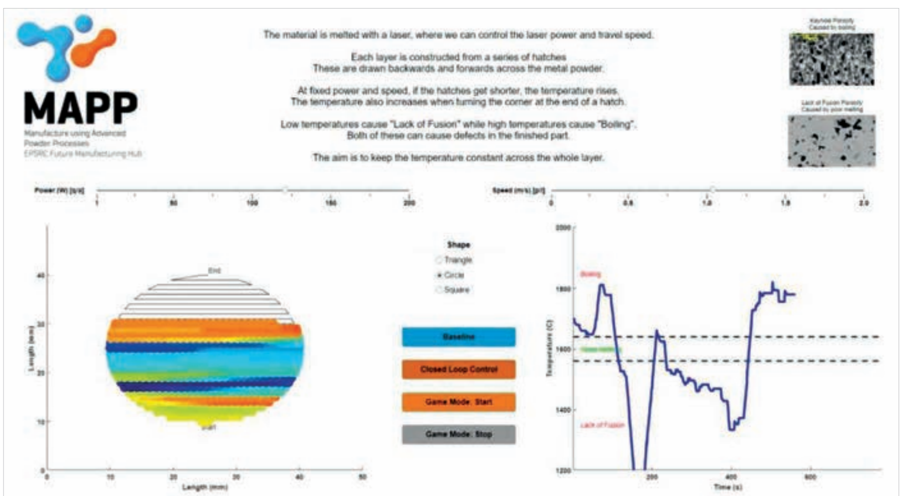
A pupil plays the game at STEM for Girls

Pupils getting a demonstration of Beat The Machine [Learning]!

It also discusses how the game has been successfully demonstrated at engagement events, including the STEM for Girls event at the University of Sheffield in March 2020.

At STEM for Girls, it was used by about 60 secondary school pupils, in Years 7-9. Groups of pupils were shown a desktop polymer 3D printer that was being monitored by a thermal camera during an ongoing build, and a range of components produced by polymer and metal AM. The pupils were then given an introduction to AM concepts and the game before trying the game themselves.

The game allowed pupils to control their own simulation of a metal AM build and see first-hand the need for control algorithms. The pupils feedback was positive.



A screenshot of the game in progress

FOCUS ON THE HENRY ROYCE INSTITUTE

AT THE UNIVERSITY OF SHEFFIELD

The new Royce Discovery Centre, based in the Harry Brearley Building at the University of Sheffield

The Henry Royce Institute at the University of Sheffield champions sustainable manufacturing through resource efficiency, providing an environment where academics and industry can collaborate to address materials processing challenges.

These collaborations create new engineering components for high performance industrial applications, generating new knowledge, translation into industry and impact.

Working closely with MAPP, the Henry Royce Institute at the University of Sheffield (Royce at the University of Sheffield) shares its vision to deliver on the promise of powder-based manufacturing to provide low energy, low cost and low waste high-value manufacturing routes and processes in order to secure and improve UK manufacturing's productivity and growth.

The new Royce Discovery Centre, based in the Harry Brearley Building at the University of Sheffield, will transform how we discover new materials for industry.

The facility benefits from the very latest in world-class equipment provided by the Henry Royce Institute for advanced materials.

Expected to be fully operational in 2021, the centre features state-of-the-art specialist laboratories and workshops, and houses the very latest technologies in 3D additive manufacturing, digital manufacturing and nanocharacterisation.

Professor Mark Rainforth, Principal Investigator at Royce at the University of Sheffield, said:
"Five years ago we were asked by the Government to create a world-leading Materials Science and Engineering Institute. We believe we have done just that. The Royce Discovery Centre will fulfil our vision of delivering world-class materials discovery and manufacturing and provide an international statement on developing future technologies."

The centre will work in tandem with the Royce Translational Centre, located at the University of Sheffield Innovation District, to take these new research discoveries and work with companies to help apply them to their manufacturing challenges.

Professor John Haycock, Head of the Department of Materials Science and Engineering at the University of Sheffield, added: "This state-of-the-art facility will integrate with applied research programmes at the Royce Translational Centre and create a platform for academic-industry partnerships across manufacturing, transport, energy and healthcare sectors through partnership of Royce at the University of Sheffield."

The workshop facility is a fantastic space to conduct important fundamental research into materials discovery. It is home to a broad range of cutting-edge equipment designed to facilitate the production of parts on a larger scale utilising highly efficient, flexible and cost-effective processes.

ROYCE AT THE UNIVERSITY OF SHEFFIELD – FEATURED EQUIPMENT

Spark plasma sintering – Model HP D 25 and Model HP D 250/C (FCT Systeme GmbH)

Spark Plasma Sintering (SPS), or Field Assisted Sintering Technology (FAST), is a rapid pressure and electrical current assisted sintering process. Ceramic, metal and mixed powders can be sintered in minutes, significantly faster than can be achieved with Hot Isostatic Pressing or furnace sintering.

The lab-scale HPD 25 machine can produce parts up to a maximum diameter of 80mm. It is used for developing fundamental understanding when sintering new powders. The HPD 250/C is a much larger machine capable of producing parts up to 250mm in diameter. As such, it is possible to conduct full-scale mechanical testing studies on single parts. Its separate air-locked secondary cooling chamber enables freshly sintered parts to cool while new powder is processing, allowing for incredibly flexible process runs.

Electron Beam Melting (EBM)

Arcam EBM machines build fully dense metal components using a high power electron beam. The process takes place in a vacuum at high temperature. The **Q20plus** is developed for easy powder handling and fast turnaround times. With a build volume of 350 x 380mm (Ø/H), it is ideal for larger parts such as aerospace components.

Directed Energy Deposition (DED)

DED uses focused thermal energy to fuse materials by melting them as they are deposited. The **BeAM Magic 800** specialises in blown powder additive manufacturing, which is commonly used by the aerospace sector to repair high-value components. The machine's capabilities include creating new alloys *in-situ* so the properties of the deposited material can be changed during the build process. The build volume is 1200 x 800 x 800 mm.

The Arcam Q20plus

Professor Iain Todd, Director – Royce Translational Centre and MAPP, said: "Our focus is on both developing new advanced material processes and technologies that have disruptive potential, whilst at the same time making existing processes more effective.

"The key driver for us is the goal of 'right first time' manufacture of materials, to reduce waste, make better use of resources and to create products with better in-service performance.

"Facilities such as those that we have at Sheffield are easy for industrial partners to access, enabling them to push the boundaries of their business further and faster than they've been able to do before."

To find out more about Royce at the University of Sheffield, visit www.sheffield.ac.uk/royce-institute.

FEASIBILITY FUNDING

MAPP's Feasibility Studies have led to four journal papers, a new MAPP partner in physical computation, and follow on funding.

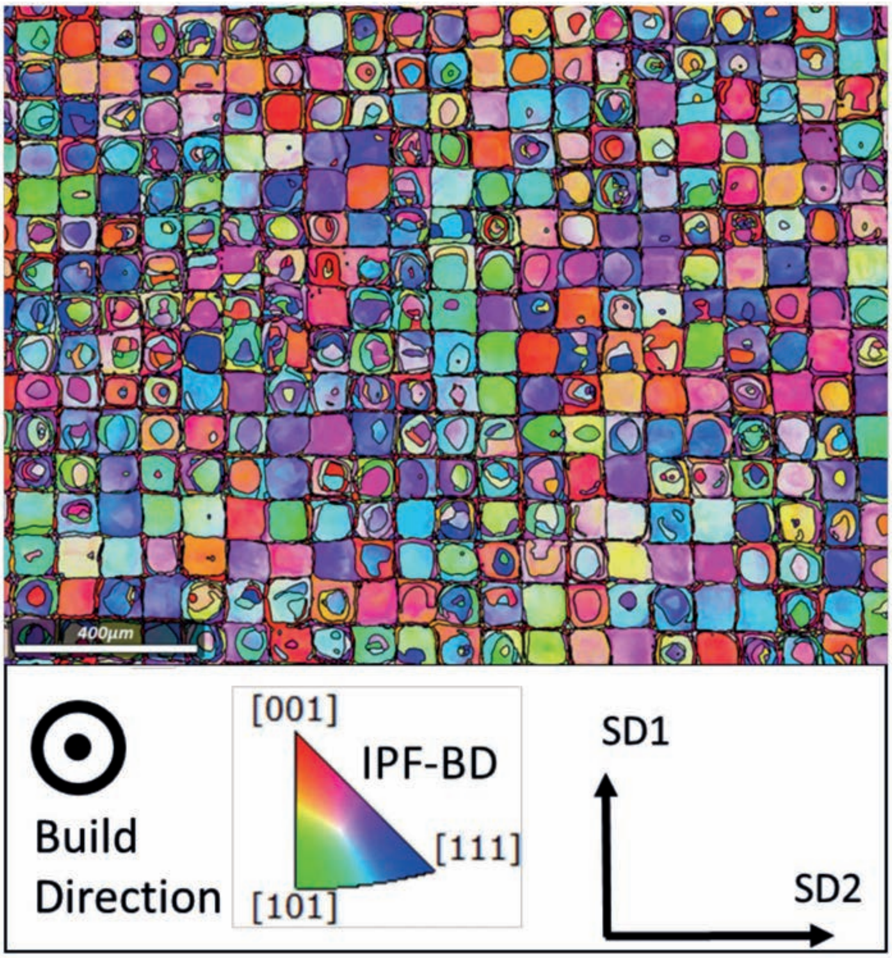
In 2018 MAPP opened its first round of feasibility funding in order to initiate collaborative projects that support the development of new research directions and draw in complementary expertise.

There was a large amount of interest in the call, which attracted a wide range of advanced powder and process development research.

MAPP's external Scientific Advisory Board formed part of the three-stage evaluation process.

The successful applications (alphabetically) and their outcomes were:

- Prof. Jawaad 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.
- Dr 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 (see p21 for more details).



'Assessing the printability of alloys for fusion-based additive manufacturing by coupling thermodynamics phase diagrams and machine learning.' Electron Backscattered Diffraction (EBSD) map of 3D printed alloy that exhibits very low susceptibility to solidification. Inverse pole figure orientation triangle is coloured along the Build Direction (BD). Scanning directions are marked as SD1 and SD2, indication a 90° rotation between layers. Image by Bogdan Dovgyy.

MAPP's second round of feasibility funding, which closed in November 2019, also attracted a range of applications from around the UK.

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.

Projects were awarded a maximum of £50,000 (80% FEC). All projects were funded for a duration of six months. The outcomes of the second round will be shared in the 2022 MAPP Annual Report, due to Covid-19 related delays.

EVENTS

IN 2020

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 the lectures moved online due to Covid-19 restrictions. They have continued to prove popular with each of the one-hour online lectures attracting more than 50 attendees from industry and academia. Each of the in-person MAPP Lectures attracted more than 30 attendees from industry and academia.

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

In November 2020 Dr Colin Hare's lecture, Measuring Powder Flow Under Low Stress Conditions, was the first to be held online. Dr Hare is a lecturer in Chemical Engineering at the University of Surrey.

Dr Catrin Mair Davies from Imperial College London joined MAPP online in February 2021 to give her lecture, Residual Stress Prediction, Mitigation and Model Validation in Laser Powder Bed Fusion of 316H Stainless Steel. Dr Davies is a Reader in Structural Integrity of Alloys at Imperial College London, and leads the EDF Energy High Temperature Centre there.

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

Prof. Lavery's lecture was the 12th in the MAPP Lecture Series.

MATERIALS RESEARCH EXCHANGE

MAPP Investigator Professor Philip Withers speaking at MRE

MAPP attended the Innovate UK/Knowledge Transfer Network Materials Research Exchange (MRE) 2020 exhibition and conference.

MRE, held in February 2020 in London, was a great opportunity to meet people from industry and academia, share ideas, showcase MAPP's research and investigate the possibilities for collaboration.

Members of MAPP spoke at MRE and the hub also had a well-attended exhibition stand at the event.

Although we have not been able to attend or host any in person events between March 2020 and the publication of this annual report, our researchers have been involved in many virtual events, as both delegates and presenters, as well as public engagement events on social media.

This has included:

Phantoms for Medical Research (December 2020)

MAPP Investigator Dr Candice Majewski spoke at the WEISS virtual mini-symposium on the use of 3D printing and phantoms in medicine.

Formnext Connect (November 2020)

Dr Candice Majewski sat on a panel as part of a virtual Happy Hour for Women in 3D Printing at Formnext Connect talking about careers in additive manufacturing and the role of education.

MAPP Virtual Poster Day (July 2020)

The MAPP researcher community organised and co-ordinated an exhibition of more than 30 posters, covering the majority of MAPP's cross cutting themes and platform research. MAPP's postgraduate students and researchers presented and discussed their work with wider members of the hub community at the event.

MAPP Hub Industry Briefing Event (held virtually in July 2020)

About 80 people attended the event held to share progress on MAPP's research, update on our new research programme, take feedback from partners and develop further collaborations.

Modelling of Casting, Welding and Advanced Solidification Processes 2020 virtual conference (June 2020)

Dr Yunhui Chen, MAPP PDRA, gave a presentation entitled *In-situ* and Operando X-ray Imaging of the Laser Blown Powder Directed Energy Deposition Process at the conference.

Social media and podcasts

In November 2020, Dr Jo Sharp, MAPP PDRA, shared insights into her work and life on Twitter and on an accompanying podcast by taking part in RealScientists Nano which provides a platform for materials and nanoscientists to communicate their research and engage with the public.

In September 2020, Dr Candice Majewski took part in the 3Degrees Discussions podcast discussing additive manufacturing.

PUBLICATIONS

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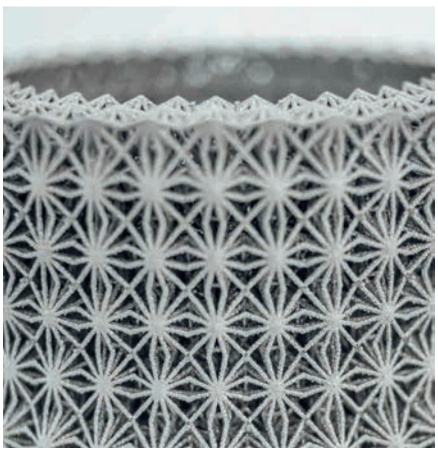

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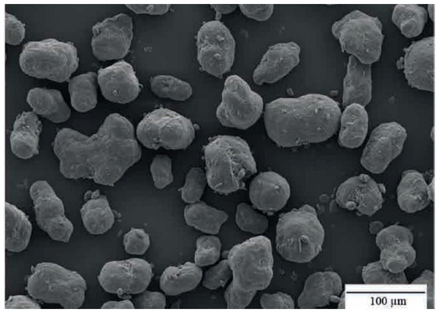

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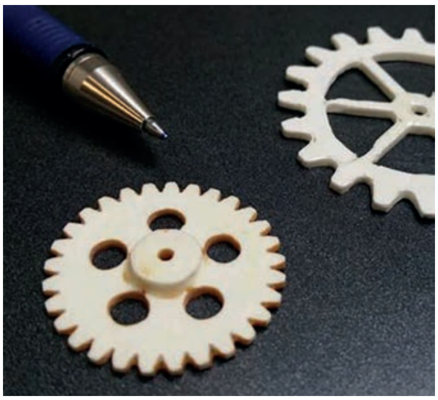

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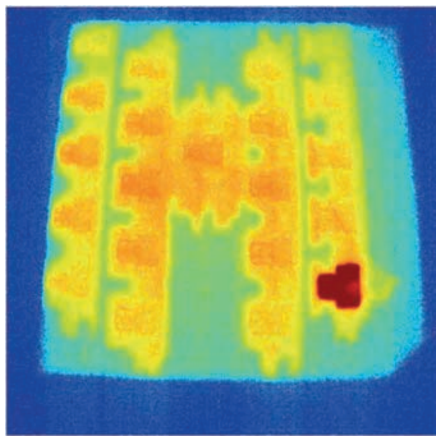

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Photograph of a selection of parts made from PA2200 (left) alongside the 1% B65003 composite material (right). Turner, R.D., *et. al.* (2019). Use of silver-based additives for the development of antibacterial functionality in Laser Sintered polyamide 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:
In-situ radiographic and *ex-situ* tomographic analysis of pore interactions during multilayer builds in laser powder bed fusion.

PUBLICATION:
Additive Manufacturing

AUTHORS:
Sinclair, L., Leung, C.L.A., Marussi, S., Clark, S.J., Chen, Y., Olbinado, M.P., Rack, A., Gardy, J., Baxter, G.J., Lee, P.D.

A laser powder bed fusion (LPBF) additive manufacturing (AM) machine (or metal 3D printer) was custom designed and built by the MAPP team to perform full AM builds on a synchrotron beamline, shedding new light on the process using ultra-fast X-ray imaging at ESRF – the European Synchrotron.

LPBF spreads layers of powder, which are melted by a focussed laser beam according to a computer-generated programme. The process repeats until a full 3D part is produced.

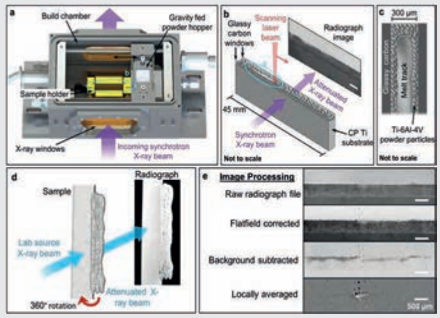
In the paper, the influence of processing parameters on Ti-6Al-4V additive manufactured thin-wall components are investigated for multilayer builds, using a custom-built process replicator and *in-situ* high-speed synchrotron X-ray imaging. The *In-Situ* and Operando powder bed Process Replicator (ISOPR) was developed to build multilayer tracks *in-situ* during LPBF.

More widespread use of LPBF is being hindered by a lack of understanding of the complex laser-matter interactions involved.

Most *in-situ* synchrotron studies of the melt pool and pore formation have involved the melting of a single layer of material but LPBF components are formed by many layers.

This paper aids the understanding of the multilayer process by characterising "multilayer builds *in-situ* using high-speed synchrotron X-ray radiography, capturing the rapid dynamics of laser remelting, layer cohesion (or lack thereof), and changes in pore formation."

Ex-situ examinations are also detailed in the paper.



"(a) Experimental build chamber with key components labelled. (b) Simplified schematic of the sample holder during *in-situ* melting. (c) Schematic of the substrate and powder particles and melt track. (d) Schematic of μCT sample scans. (e) Image processing methods." Reprinted from *Additive Manufacturing*, **36**, Sinclair, L., Leung, C.L.A., Marussi, S., Clark, S.J., Chen, Y., Olbinado, M.P., Rack, A., Gardy, J., Baxter, G.J., Lee, P.D., *In-situ* radiographic and *ex-situ* tomographic analysis of pore interactions during multilayer builds in laser powder bed fusion, 101512., Copyright (2020), with permission from Elsevier."

PAPER:
Conformable green bodies: Plastic forming of robocasted advanced ceramics.

PUBLICATION:
Journal of the European Ceramic Society

AUTHORS:
Elizarova, I., Vandeperre, L., Saiz, E.

MAPP members at the Centre for Advanced Structural Ceramics have developed a new phenolic resin-based paste for robocasting of ceramic powders that allows post-printing shaping.

Robocasting is an additive manufacturing technology based on the continuous extrusion of a ceramic paste. It has limited capabilities when printing complex unsupported structures such as overhangs.

The new type of paste addresses this limitation by allowing the shaping of the ceramic body, known as green bodies, before sintering (a heat treatment applied to impart strength and integrity).

The paste consists of a solution of phenolic resin in methyl ethyl ketone and ceramic powders.

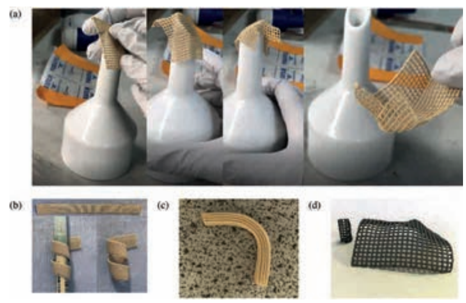
The phenolic resin in the paste acts as a binder and plasticizer and can be burned out during sintering, or, additionally, can be converted into carbon that can later act as a sintering aid.

After printing parts can be cut, bent, folded and draped over various objects. Once dry and fully solid, the parts become rigid and can be processed further by slow pyrolysis (slow heating in absence of oxygen) and sintering.

The shaping of the green bodies after printing does not affect the mechanical strength of the sintered parts. The paste was used to produce both alumina and silicon carbide parts, illustrating its flexibility.

The new paste also addresses the difficulty of processing ceramics into arbitrary shapes, allowing more applications to benefit from the advantages of ceramic materials including strength and hardness.

The Centre for Advanced Structural Ceramics is a world-leading centre for ceramics research and teaching at Imperial College London.



"Showcase of the conformability of the printed parts - Al_2O_3 nets moulded against sharp (a) and rounded (b) objects after 7 -h air-drying, Al_2O_3 bar bent after 18 -h air-drying (c), α-SiC/B_4C nets shaped after 10-minute air-drying (d)." Reprinted from *Journal of the European Ceramic Society*, **40**, (2), Elizarova, I., Vandeperre, L., Saiz, E., Conformable green bodies: Plastic forming of robocasted advanced ceramics, 552-557., Copyright (2020) with permission from Elsevier.

PAPER:

Understanding pore formation and the effect on mechanical properties of High Speed Sintered polyamide-12 parts: A focus on energy input.

PUBLICATION:
Materials & Design

AUTHORS:
Zhu, Z. and Majewski, C.

This paper provides 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).

Powder bed fusion (PBF) additive manufacturing techniques have demonstrated high potential for use in sectors as broad as aerospace, automotive, medical devices and consumer goods.

HSS is a novel advanced PBF polymer AM technique aimed at medium to high volume production. It uses a combination of an infrared lamp and a selectively-printed ink absorbing in the infrared region to provide intensive thermal energy to melt consecutive cross-sections of polymer powders.

Internal pores found in PBF parts are known to be detrimental to mechanical properties, but the majority of the research into the porosity of AM parts focuses on laser sintering (LS), selective laser melting (SLM) and electron beam melting (EBM). This study is the most detailed investigation to date relating energy input, pore formation, and the resultant effect on mechanical properties in HSS.

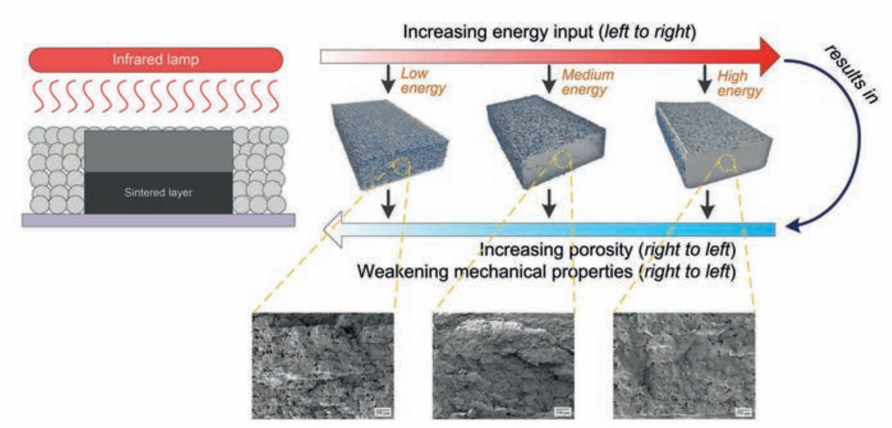
Test samples were produced at different lamp speeds which generated different amounts of energy input. The samples were scanned using X-ray Computed Tomography and then underwent tensile testing.

Pore morphology, volume, number density and spatial distribution were investigated.

The paper states there is: "a strong correlation between energy input, porosity and mechanical properties, whereby pore formation was caused by insufficient energy input.

"A greater amount of energy input resulted in a reduced porosity level, which in turn led to improved mechanical properties." (Zhu and Majewski, 2020).

In addition to this new understanding of the effects of porosity on mechanical properties, this work also identified significant differences between pore position and distribution. Pores in samples with high energy input (and therefore low porosity) tended to be located close to the top, bottom and side surfaces of the samples, whereas lower energy input led to pores being more evenly distributed throughout the part.



Graphical abstract, Zhu, Z., Majewski, C., (2020) Understanding pore formation and the effect on mechanical properties of High Speed Sintered polymide-12 parts: a focus on energy input. *Materials & Design*, **194**, 108937. Creative Commons Attribution 4.0 International (CC-BY 4.0) license. https://creativecommons.org/licenses/by/4.0/legalcode

PAPER:

A data-driven approach for predicting printability in metal additive manufacturing processes

PUBLICATION:
Journal of Intelligent Manufacturing

AUTHORS:
Mycroft, W., Katzman, M., Tammas-Williams, S., Hernandez-Nava, E., Panoutsos, G., Todd, I., Kadirkamanathan, V.

This paper details the first machine learning framework that explores the geometric limits of printability in additive manufacturing (AM) processes before manufacture.

Printability describes the ability of the AM process to produce a faithful realisation of the object.

AM allows for the use of geometries that would be difficult or impossible to produce with other methods.

This study focuses on electron beam melting (EBM) which is a form of metal powder bed fusion (PBF) that can build parts at a relatively high speed. Parts are checked for printability and fragility after they are built. Fragility describes its ability to withstand post-printing processing and normal usage.

EBM printability defects can be classified as large-scale deformations caused by stresses on the part during the build process and small-scale defects which describe when small regions are damaged, deformed or fail to print.

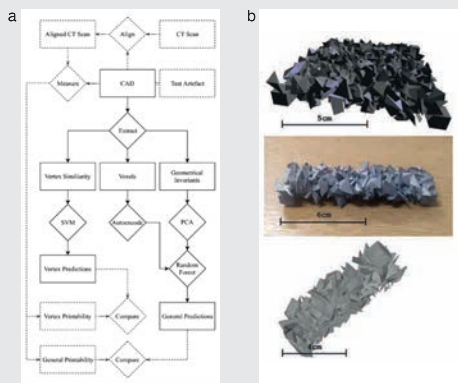
Large-scale defects can be predicted using physics based modelling. This paper focuses on small-scale defects.

The paper explains how manufacturers rely on "engineering know-how and ad-hoc rules" and often "err on the side of caution," to determine which geometric structures are additively manufacturable and the operation conditions required.

It goes on to detail a framework for predicting the printability of small-scale geometric features in AM.

The framework consists of:

- An algorithm for constructing informative test artefacts which can be used to evaluate the geometric limits of AM technologies,
- A method for measuring small-scale printability, even on strenuous components containing large-scale defects,
- Several descriptors of local geometry which correlate with printability and are suitable inputs for many machine learning algorithms,
- "Predictive models which significantly outperform naive benchmarks and approach an estimate of the maximum performance obtainable," (Mycroft *et. al.* 2020).



[a] Workflows for the algorithm for training (dotted and solid lines) and classification (solid lines). Rectangles denote variables and diamonds denote processing units.

[b] The CAD, slice of the build and CT scan of the test artefact. Mycroft, W., Katzman, M., Tammas-Williams, S. *et. al.* A data-driven approach for predicting printability in metal additive manufacturing processes. *J Intell Manuf* **31**, 1769–1781 (2020). Creative Commons Attribution 4.0 International (CC-BY 4.0) license. https://creativecommons.org/licenses/by/4.0/legalcode

MAPP

EXECUTIVE TEAM

Professor Iain Todd, MAPP Director

Iain holds a Royal Academy of Engineering GKN Aerospace Research Chair in Additive Manufacture and Advanced Structural Metallic Materials. His research is focused on both the development of new alloys and the development of new processes to enable engineering structures to be manufactured from them. Iain's manufacturing research is conducted on the near-industrial scale and actively supported by a number of industry partners including GKN, Rolls-Royce and Weir Group. Iain has led grants and research projects with a total value of £30M as PI. He is leading the activities to build powder manufacturing facilities within the Henry Royce Institute. He previously led the Mercury Centre at Sheffield, an ERDF supported activity which helped regional SMEs secure contracts worth >£7m and safeguarded/created 150 jobs. Iain is a Fellow of the Institute of Materials, Minerals and Mining. Iain leads the theme Metal Additive Manufacturing (P2.1).

Dr John Francis

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. In this role, John undertook contract research projects and consultancy work for both government and industrial clients. After seven years with CSIRO, John moved to the UK in 2005 to take up a post as a Research Fellow in the School of Materials at The University of Manchester. In 2009 he moved to The Open University to work as a Lecturer in Materials Engineering, before returning to The University of Manchester in 2011, where he is currently a Reader.

John's work has been closely aligned with the power generation sector over the past 15 years. His research interests focus on understanding how welding processes and procedures impact on 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.

Dr 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

Visakan is Director of Rolls-Royce University Technology Centre (UTC) in Control and Monitoring Systems Engineering. His primary area of research is in the field of signal and information processing, dynamic and spatio-temporal modelling, intelligent health monitoring and fault detection with applications in aerospace and biomedicine.

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 is focused 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. Visakan is Theme Co-Lead for X3 - Modelling, Optimisation and Control.

Professor Peter Lee

Peter is Professor of Materials Science at University College London and holds the Royal Academy of Engineering Chair in the Emerging Technology of Additive Manufacturing. He is an expert in characterising microstructural evolution during manufacturing using *in-situ* synchrotron imaging.

He uses these results to inform Integrated Computational Materials Engineering (ICME) models to predict processing-structure-property relationships, based on more than 30 years' experience at Alcan, Imperial, Harwell, and now University College London. He has published more than 300 journal papers and is a Fellow of the Royal Academy of Engineering, Institute of Materials, Minerals and Mining and the Institute of Cast Metals Engineers. Peter leads the X1 research theme in MAPP – '*In-situ* Process Monitoring'.

Dr Enzo Liotti

Enzo is a Departmental Lecturer in 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 particular interest in solidification of metal alloys. He obtained his BSc (2004) and MSc (2006) in Material Engineering from the Politecnico di Milano. He gained a PhD in Materials science from the University of Loughborough (2011), working on the characterisation of a nano-quasicrystalline containing Al alloy with high temperature mechanical properties. From 2011 to 2019 he was a PDRA at the department of Materials, University of Oxford, working on *in-situ* imaging of solidification within Prof. Patrick Grant's Processing of Advanced Materials Group.

Professor Eduardo Saiz

Eduardo directs the Centre for Advanced Structural Ceramics (CASC) at Imperial College London. His research interests include the development of new processing techniques for the fabrication of ceramic-based composites, in particular, hierarchical composites with bioinspired architectures. He has published more than 120 papers, including high impact journals such as Science and Nature Materials and holds several US patents. His work on the 3D printing of ceramics and graphene inks has been highlighted internationally from New York Times to Wired. Eduardo leads the theme P2.3c Ceramics.

INDUSTRIAL ADVISORY BOARD (IAB)

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,
Director of Technology,
Xaar 3D

Neil spent 20 years in academia conducting research in the field of additive manufacturing. His academic research has generated a strong Intellectual Property/Patent portfolio that has been licensed widely from small start-ups to global multinationals and is having a transformational impact on the additive manufacturing/industrial 3D printing industry.

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

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.

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.

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 an £80m turnover business.

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.

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. Ian has worked on the introduction of 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. Throughout these programs Ian has been responsible for coordinating high performing teams and delivering to incredibly demanding semiconductor fab environments, including customers such as IBM, Hitachi, SEAGATE, Hoya, KERI, NIST.

THE SCIENTIFIC ADVISORY BOARD (SAB)

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

Tresa graduated with a B.S. from Purdue University in 1984, and a PhD from MIT in 1989. She was employed at General Electric Aircraft Engines from 1989 to 1991, where she conducted research and development on high-temperature alloys for aircraft turbine engines. She was a professor in the Department of Materials Science and Engineering at Carnegie Mellon University from 1991 to 1999 and the University of Michigan from 2000 - 2010. Her current research focuses on the processing and properties of structural materials and coatings and on the use of ultrafast lasers for micro-fabrication and materials diagnostics. Prof. Pollock was elected to the U.S. National Academy of Engineering in 2005, the German Academy of Sciences Leopoldina in 2016, is a Fellow of TMS and ASM International, Editor in Chief of Metallurgical and Materials Transactions and was the 2005-2006 President of The Minerals, Metals and Materials Society.

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

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

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

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

Javier is the scientific director and founder of the IMDEA Materials Institute and head of the research group on Advanced Structural Materials and Nanomaterials at the Polytechnic University of Madrid. He has held visiting appointments at Brown University, Shanghai Jiao Tong University and Indian Institute of Science. Prof. Llorca, a Fulbright scholar, is Fellow of the European Mechanics Society and member of the Academia Europaea and has received the Research Award from the Spanish Royal Academy of Sciences. His research activities have been focused on the systematic application of computational tools and multiscale modelling strategies to establish the link between processing, microstructure and properties of structural materials. A key feature of his contributions is the use of novel experimental techniques to determine the properties of the phases and interfaces in the material at the nm and μm scale. So, simulations are fed with experimental values independently obtained and free of "adjusting" parameters. Some of these developments have become the foundation of the modern techniques of virtual testing of composites, which are starting to be used by the aerospace industry to minimise the number of costly mechanical tests to characterise and certify composite structures. His current research interests – supported by an Advanced Grant from the European Research Council – are focused in the development of multiscale modelling strategies to carry out virtual design, virtual processing and virtual testing of metallic materials, including the experimental validation at different length scales, so new alloys can be designed, tested and optimised in silico before they are actually manufactured in the laboratory.

Professor Jin Ooi,
University of Edinburgh

Jin received B.Eng.(Hons.) degree from The University of Auckland and a PhD degree from The University of Sydney. He is currently the Professor of Particulate Solid Mechanics and the Director of Civil and Environmental Engineering at Edinburgh and holds a Qiushi Chair Professor position at Zhejiang University China. His principal research interests lie in the mechanics of particulate solids, from soils and rocks to many industrial powders and solids. He has published extensively and is on the Editorial Board of the Canadian Geotechnical Journal and edited special issues in Powder Technology and Granular Matter. He co-founded DEM Solutions Ltd and Particle Analytics Ltd, bringing the impact of his research to many industrial and scientific problems. He collaborates actively with academic and industrial partners, providing leadership as Coordinator for the T-MAPPP European ITN Consortium on multiscale analysis of particulate processes, and the PARDEM ITN Project on DEM calibration and validation.

Professor Barbara Previtali,
Politecnico di Milano

Barbara is Full Professor in the Department of Mechanical Engineering of Politecnico di Milano, where she received her M.S. degree in 1997 and her PhD degree in 2002, both in Industrial Engineering. She is the director of SITEC—Laboratory for Laser Applications at Politecnico di Milano and leads PromozioneL@ser within AITeM association, which connects Italian laser users in industry and academia. Her research interests lie in the area of advanced manufacturing processes, specifically laser processes and additive manufacturing. Her current focus is on monitoring and close-loop control of laser cutting, development of innovative SLM solutions, such as multi-material and high-preheating chambers and robotic laser metal deposition of large components in aluminium and titanium alloys.

Professor Fabrice Rossignol,
Institute of Research for Ceramics [IRCER]

Fabrice received his PhD in 1995 at the University of Limoges in the field of Ceramic Processes and Surface Treatments. He was a post-doc fellow in the Agency of Industrial Science and Technology in Japan from 1996 to 1998. Then he joined industry as a technical manager for the Bosch Company from 1999 to 2001. In 2002 he returned to the academic field at the French National Research Council (CNRS) working in the Institute of Research for Ceramics (IRCER-200 members) in Limoges, France. From 2007 to 2017, he was the Team Leader of the Ceramic Processes Team at IRCER. He is now Deputy Director of IRCER. He conducts integrated research ranging from powder synthesis to the fabrication of prototype objects with improved or new properties using various shaping and consolidation techniques. He aims to control preparation steps to obtain micro(nano)structures and macroscopic architectures adapted to specific functionalities of technical ceramics. Prof. Rossignol's personal research interests are more in the shaping of nanostructured ceramics (top-down and bottom-up approaches) and in the development of additive manufacturing technologies (ink jet printing). One key application field of his research is energy, for example, supported catalysts for H2 production.

MAPP

INVESTIGATORS

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

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

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

Dr Kristian Groom, University of Sheffield. Kristian graduated with an MPhys (1999) and a PhD (2003) both from the Dept. of Physics at The University of Sheffield. His research focuses on semiconductor optoelectronic component design and manufacture, with an interest in photonic integration and in the application of near- and mid-IR semiconductor lasers, superluminescent diodes, amplifiers, detectors and passive optical elements for application in high value manufacturing methodologies.He is currently working on projects to develop capability for the heterogeneous integration of III-V semiconductor components and circuits upon a range of substrates to enable new sensor technologies, both through the collaborative EPSRC Heteroprint project and via the EPSRC Future Photonics Hub. At the same time, he is pursuing research into the application of laser diode arrays for efficient high-speed additive manufacturing of both metallic and polymer parts.

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

Dr Chu Lun Alex Leung, University College London. The lecturer in Imaging of Advanced Materials and Manufacturing in the Department of Mechanical Engineering, obtained his PhD in Material Science (University of Manchester, 2018) and MEng in Aerospace Materials (Imperial College London, 2010). He specialises in the application of synchrotron and laboratory X-ray imaging techniques to study additive manufacturing (AM) processes. His research focuses on the development of intelligent advanced manufacturing using cutting-edge sensing technologies. His role in the MAPP team is to (1) develop and apply multi-modal imaging (e.g. optical, thermal and X-ray) and diffraction techniques for studying rapid solidification phenomena during AM and (2) provide key insights into the fundamentals of AM and generate 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 the MAPP hub and its members.

Dr Candice Majewski, University of Sheffield. P2.3b Future Manufacturing Platforms – High Speed Sintering & Polymer AM Theme Lead. Candice is a senior lecturer with almost 20 years' experience in the field of additive manufacturing (AM). During her career to date, she has built up a large network of academic and industrial collaborators, focusing much of her research towards improving powdered polymer AM materials and processes in order to increase their potential for widespread industrial usage. As part of these activities, she manages the University's Advanced Polymer Sintering Laboratory. In 2011 she was awarded the International Outstanding Young Researcher in Freeform and Additive Manufacturing Award for her contributions in this field. She is also a keen advocate for Equality, Diversity, Inclusion and Accessibility, leading the MAPP EDI committee, and acting as deputy head of her Departmental Well-being and EDI committee. Externally she is a member of TIGERS (The Inclusion Group for Equity in Research in STEMM), a group working towards equality, diversity, inclusion and accessibility in STEMM, with a particular focus on the UK research funding landscape.

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

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

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

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

Professor Mark Rainforth, University of Sheffield. His research interests are the high resolution characterisation of microstructures, in particular interfaces and surfaces. His research programmes are broadly based, covering metals, ceramics and coatings. He is leading the development of the Sheffield wing of the Henry Royce Institute and is the principal investigator on the EPSRC DARE project (Designing Alloys for Resource Efficiency – a Manufacturing Approach).He is a winner of the IOM3 Rosenhain Medal and is a Fellow of the Royal Academy of Engineering. Mark has published more than 300 papers and is involved in >£40m of current grants. He co-directed the Mercury Centre with Prof. Iain Todd.

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

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

Professor Philip Withers, University of Manchester, 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. He is the Theme Lead for X2 Advanced Characterisation.

MAPP PDRAs:

Dr Daliya Aflyatunova
Dr Yunhui Chen
Dr Wen Cui
Dr Yun Deng
Dr Iuliia Elizarova
Dr Oliver Hatt
Dr Yi He
Dr Samy Hocine
Dr Yuze Huang
Dr Ashfaq Khan
Dr Samuel McDonald
Dr Scott Notley
Dr Jo Sharp
Dr Rob Snell
Dr Ben Thomas
Dr Rahul Unnikrishnan
Dr Rhys Williams
Dr Xun Zhang

MAPP-aligned PDRAs

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

MAPP-aligned PhDs

Hussam Abunar
Abdullah Alharbi
Mohammed Alsaddah
Alisha Bhatt
Nick Boone
Matthew Boreham
Ryan Brown
Florian Buschek
Louise Chan
Lev Chechik
Max Chester Jude Emmanuel
Imogen Cowley
Ben Evans
Xianqiang Fan
Lucy Farquhar
Kubra Genc
Anna Getley
Adam Gothorp
Simon Graham
Abdul Haque
Caterina Iantaffi
Addhithya Ashok Kumar
Dr Oliver Levano Blanch
Elaine Livera
Alistair Lyle
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Ollie Osborn
Sourabh Paul
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David Rees
Tom Robb
Elena Ruckh
Beatriz Fernandez Silva
Leigh Stanger
Emmanouil Stavrouakis
Pawel Stuglik
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Kylee Yingwei Wu
Jiaqi Xu
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MAPP PhDs

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Cameron Favell Gallifant
Alex Goodall
Guy Harding
Oliver Leete
Mozhdeh Mehrabi
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MAPP Operations Team:

Jess Bamonte
Project Administrator

Clare Faulkner
Project Administrator

Dr Richard France
Senior Business Development Manager

Danielle Harvey
Marketing and Communications Officer

Karen Wood
Project Manager

INDUSTRY AND ACADEMIA

COLLABORATE

PROVIDING ENGINEERING STUDENTS WITH REAL-LIFE LEARNING

MAPP's industry partners are helping to train the engineers of the future. Taking part in the University of Sheffield's Industry Training Programme (ITP) is one of the many ways industry partners are supporting MAPP.

The ITP, run by the Department of Automatic Control and Systems Engineering, allows industry to support real-life learning.

The module aims to prepare students for professional practice, via an industry-led group project in advanced manufacturing systems.

Working in groups of four to six, students undertake computational and theoretical work and experience real industrial practice and processes through interactions with industry.

Over 12 weeks they develop a project plan, working on technical challenges designed to be representative of real industrial research and development projects.

As part of the ITP MAPP's industrial partners - the Manufacturing Technology Centre (MTC), Wayland Additive and GKN Aerospace - provided direct technical support and expert process knowledge to a recent cohort.

The 74 students used digital learning and virtual meetings to overcome the challenges created by Covid-19.

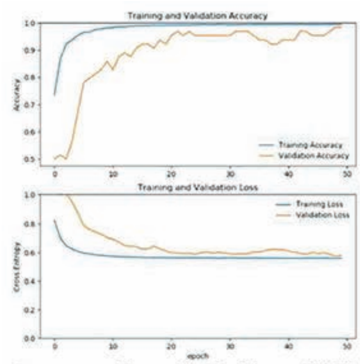
This included a virtual poster workshop for industry and academics that allowed students to showcase their work in May 2020.

The posters summarised each group's technical approach as well as main findings and recommendations.

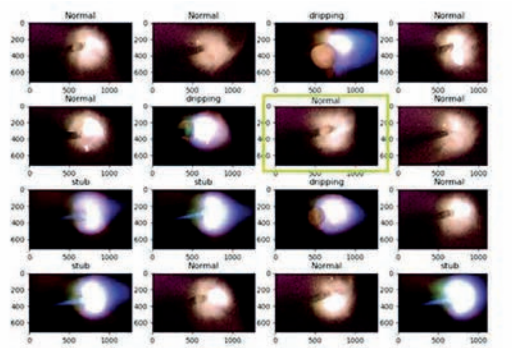
The poster above is one example answering the GKN Aerospace industry challenge, how to autonomously predict and classify defects in wire Laser Metal Deposition.

The student's results showed more than 90 percent accuracy on predicting and classifying unseen data by a Convolutional Neural Network modelling framework.

The 2019/20 module was led by MAPP's joint X3 Theme Lead Professor George Panoutsos, Faculty Director of Research and Innovation - Faculty of Engineering.



Accuracy and Loss of the Training and Validation set



Predicted Labels of 16 Samples on Test set

Prof. Panoutsos said: "The ITP's activities, tasks and assessments are designed to give students the realistic experience of an industrial challenge, via working directly with industry as part of this module.

"The 12-week module concludes with a poster presentation and this year the students overcame the challenge of Covid-19 restrictions by embracing digital learning and providing fantastic online poster presentations.

"This year all projects and industry partners were MAPP-affiliated, demonstrating how MAPP is supporting taught programmes."

The project's themes were:

- **Active feedback control in Laser-Powder Bed Fusion.**
- **Process optimisation in Additive Manufacturing using Machine Learning.**
- **Electron Beam Melting process monitoring using Machine Learning.**
- **Using deep learning to classify defects in Laser Metal Deposition - wire.**
- **Process monitoring in Laser Metal Deposition - powder.**

A spokesperson for GKN Aerospace said: "Your students have done really wonderful work."

Students were positive about the module with one commenting in the ACS6402 ITP in Avionics student feedback questionnaire 2019/2020: "I'm very glad I chose this as my optional module."

The ITP relates to three ACSE MSc degrees; MSc Advanced Control and Systems Engineering, MSc Autonomous and Intelligent Systems and MSc Robotics.

MAPP's X3 Theme: Modelling, Optimisation and Control's aim is to turn the data and information from advanced processing and monitoring technologies into process understanding and control, via computational intelligence modelling and machine learning.

MAPP and INTEGRADDE (Intelligent data-driven pipeline for the manufacturing of certified metal parts through Direct Energy Deposition) Post-Doctoral Research Associate (PDRA) Scott Notley and VULCAN PDRA Bo Luo supported the 2019/20 ITP.

SPOTLIGHT ON ALIGNED PROJECT

JEWELPRINT

DIODE AREA MELTING FOR EFFICIENT, MULTI-LASER PROCESSING OF PRECIOUS AND REFLECTIVE METALS

The JewelPrint project focuses on processing precious and highly challenging reflective metals using the multi-laser additive manufacturing process Diode Area Melting (DAM).

The DAM process has been developed within MAPP's Future Manufacturing Technologies theme and uses an architectural array of low power, fibre coupled diode lasers to process pre-deposited powder (Figure 1).

Efficiently packed fibre arrays are integrated into a custom laser head designed to traverse across the powder bed. Each laser diode is individually controllable, enabling selective laser processing of powder bed cross-sections and layered fabrication of 3D net-shape components (Figure 2).

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

The Jewelprint Project, supported by Innovate UK and Diamond Centre Wales, has focused on tuning laser wavelengths to the optimum absorption profiles of precious, reflective and engineering grade alloys e.g platinum, gold, copper and titanium alloys (Figure 3).

Operating at shorter wavelengths (450-808nm) compared to traditional selective laser melting systems (1064nm), the powdered material's ability to absorb laser energy increases, processing becomes more efficient and less laser energy is subsequently required to melt the material.

Highly reflective metals such as platinum, gold and copper were processed using individual laser powers of only 3.5W at 808nm, with further increased melt pool temperatures observed using shorter wavelength blue lasers (450nm).

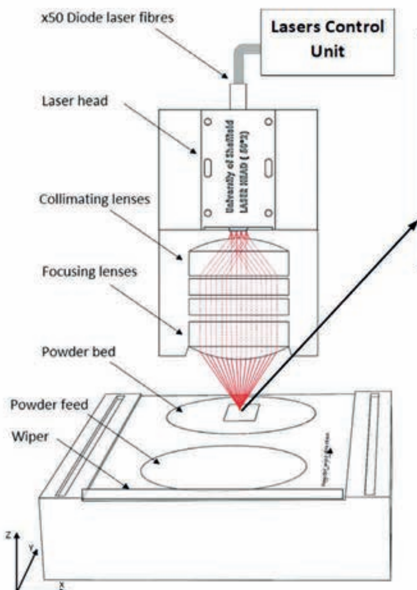


Figure 1 – Diode area melting

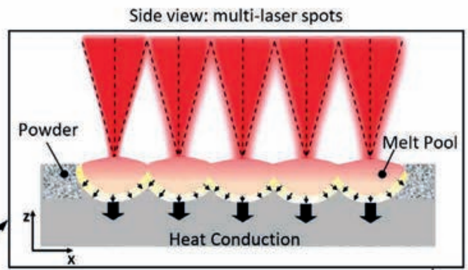


Figure 2 – Individual laser spots and melt pools created on powder bed

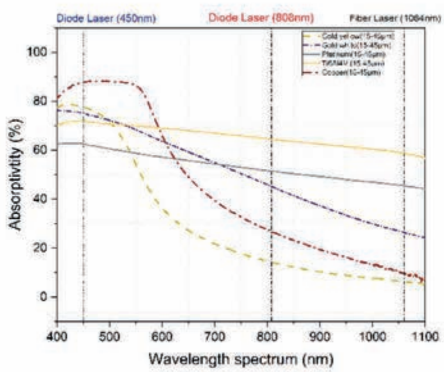


Figure 3 – Increase in absorption at different laser wavelengths

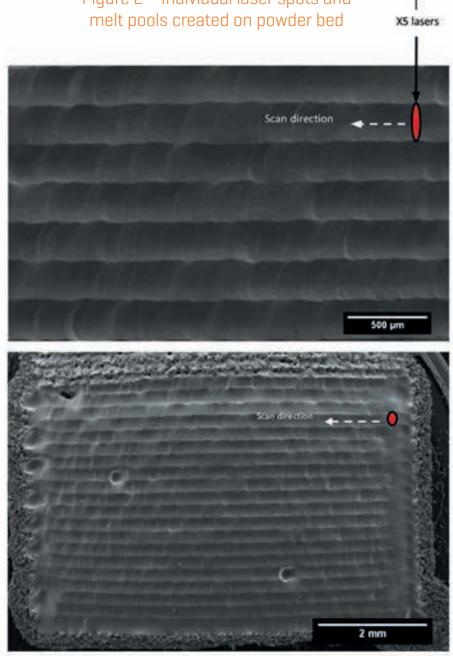


Figure 4 – Top view of laser processed Ti64 using x5 808nm lasers in linear array (3.5W each) simultaneously processing during parallel scans

Figure 4 shows the top surface profile of multiple parallel scans using x5 lasers, simultaneously scanning across a titanium alloy powder bed, creating broad melt pool tracks (250um), with components approaching 99 per cent density.

This project has shown the potential use of low power, low cost, short wavelength laser sources.

Using a highly scalable methodology for the production of components from even the most reflective metals with efficient matching of absorption profiles with laser wavelength.

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

Spotlight on AIRLIFT and DAM

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

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

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

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

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

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

DAM (Developing Design for Additive Manufacturing) is a £14m programme aimed at developing the next generation of design tools and methods for additive manufacturing using a data driven, material centric approach. The funding period is December 2018 - November 2021.

AIRLIFT (Additive Industrialisation for Future Technology) is a £19M technology industrialisation programme that uses Industry 4.0 and simulation competencies to enhance both laser metal deposition with wire (LMD-w) and powder bed AM technologies. The funding period is December 2018 - November 2022.

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

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

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

GKN AEROSPACE

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

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

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

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

ALIGNED PROJECTS

AMITIE (Additive Manufacturing Initiative for Transnational Innovation in Europe)

Funder: European Commission - Horizon 2020

Value of award to the consortium: £774,147

Funding period: March 2017 - 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.

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.

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.

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

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.

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

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

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

Funding period: April 2019 - March 2029

Organisations: University College London

VULCAN

Funder: Innovate UK

Funded value: £267,650

Funding period: January 2020 - December 2021

Organisations: The University of Sheffield, Wayland Additive

ALIGNED PROJECTS

COMPLETED PROJECTS

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

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

Project costs: EUR 3 439 420

Funded value: EUR 3 439 420

Funding period:
January 2015-December 2017

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

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

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

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

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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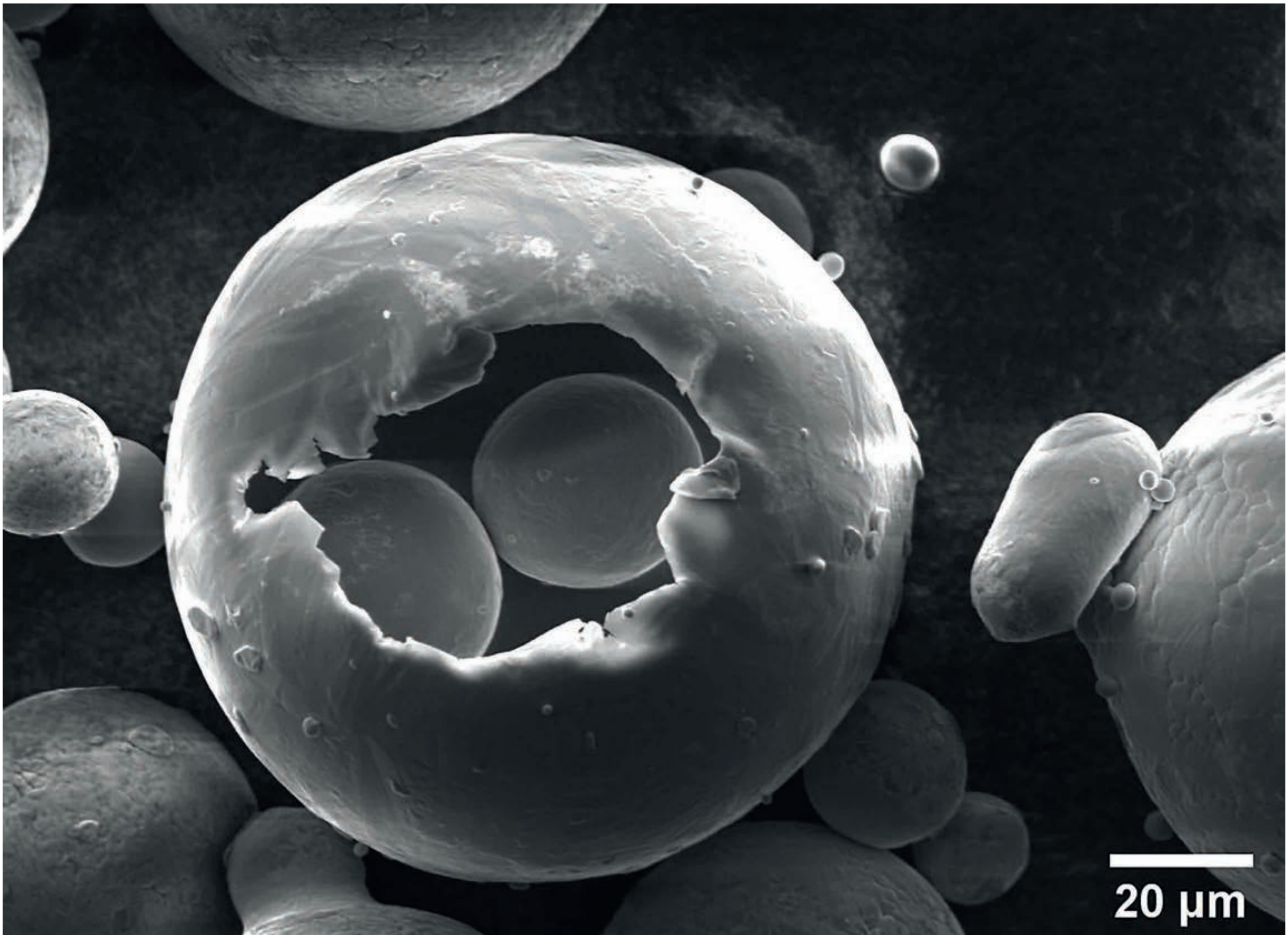

Image above: Scanning electron microscope image of a Ti-6Al-2Sn-4Zr-2Mo gas atomised powder particle by Lorna Sinclair. Although usually solid, this particle is hollow, and a fractured surface reveals two smaller powder particles hidden inside, likely trapped during atomisation. This image was one of the runners up in the MAPP Image Competition, see p18-19 for more information.

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