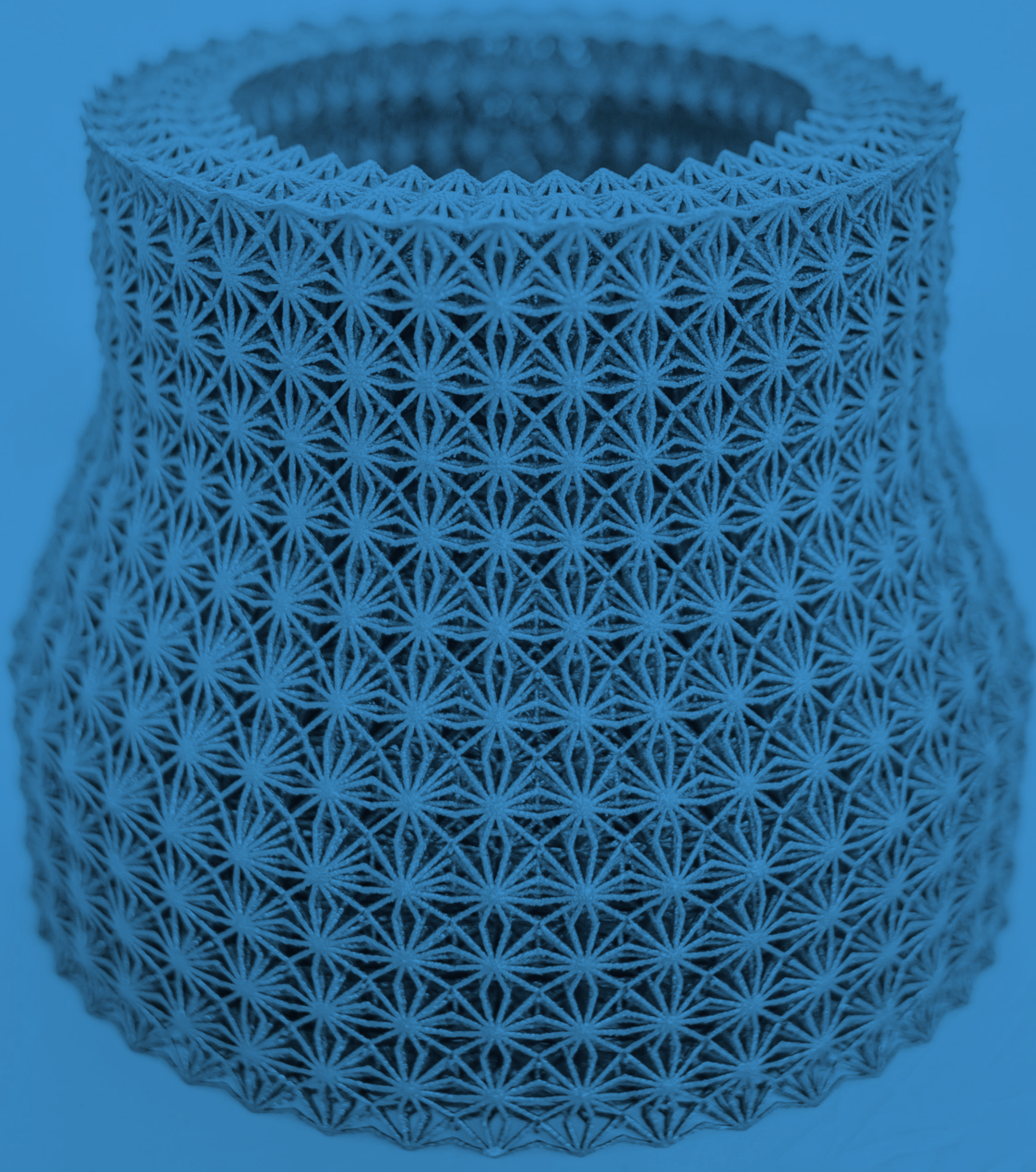
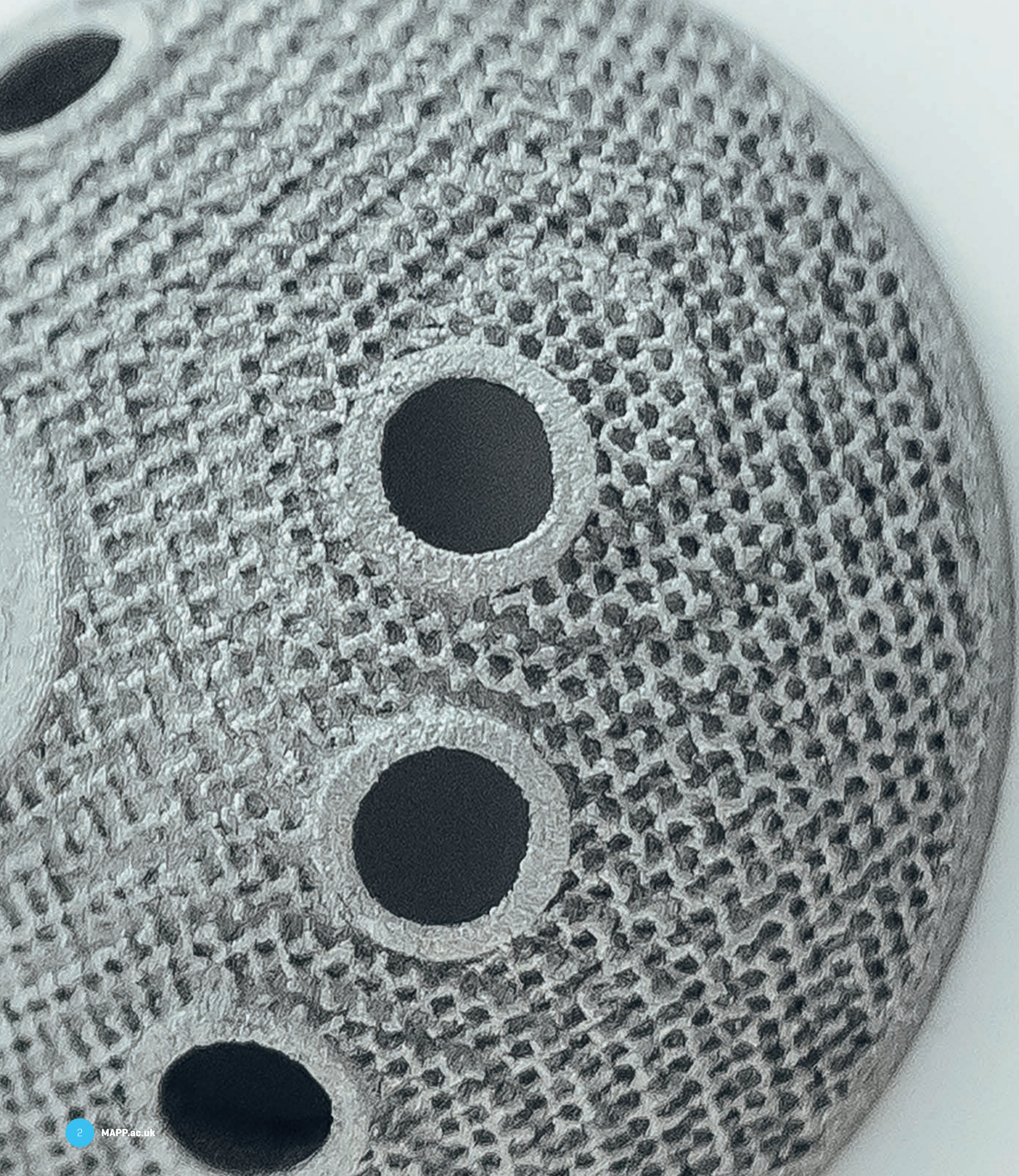
MAPP

Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

Annual Report 2018



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



Acetabular Cup, used in hip surgery. Manufactured using Electron Beam Melting. The surface structure has been designed and manufactured to encourage bone growth into the surface of the implant and better bonding of the implant to the patient's hip.

CONTENTS

WELCOME

After a busy and truly successful first year MAPP EPSRC Future Manufacturing Hub is now moving on to even greater things and focusing on delivering its vision for the future.

Professor Iain Todd
MAPP Director

MAPP's vision is to deliver on the promise of powder-based manufacturing to provide low energy, low cost and low waste high value manufacturing routes and products to secure UK manufacturing productivity and growth. As an open Hub our goal is to continue to work with a wide range of representatives from industry and academia to help us achieve this.

Our formal launch in January 2017 was attended by 150 delegates from across industry, universities and the UK's High Value Manufacturing Catapult (HVMC) centres.

Since the Hub funding was awarded we've been working hard - establishing an interdisciplinary team of researchers across the university partner sites and developing a core research programme which brings together and integrates research activities across the partner sites.

Early research highlights - many of which are expanded upon in this report - include work on *in-situ* process monitoring at the Diamond Light Source, which is uncovering new understanding about the fundamental physics of additive manufacturing (AM) and work on Diode Area Melting, a new approach to AM with higher process speed. There have been successes too in the rapidly developing Field Assisted Sintering Technology (FAST) technology and in the processing of ceramics from powder starting materials. Exciting times indeed.

We brought our industry and HVMC partners together in the summer of 2017 for a workshop to identify and develop new research collaboration opportunities, and we have been busy establishing a portfolio of aligned projects with commercial and HVMC partners to develop processes to higher Technology Readiness Levels, funded by industry, Innovate UK and the Aerospace Technologies Institute.

The interdisciplinary nature of our work within MAPP was reflected in the breadth of the work showcased at our First International Conference in January 2018, which was a resounding success attracting 180 delegates with representatives from over 35 companies and 20 universities. The invited contributions from our International Scientific Advisory Board, the talks selected from the large number of abstracts we received and the poster sessions stimulated interesting conversations and led to new collaborations. It was wonderful to be able to welcome everyone and to see our community working together.

HEADLINE SUCCESSES

Headline successes in our first year include the publication of 10 research papers (see p26), with others in preparation.

In addition to our core industry and HVMC (High Value Manufacturing Catapult) partners, we have established a number of new collaborations with commercial partners, including several aligned projects (supported by Innovate UK and ATI funding) and sponsorship.

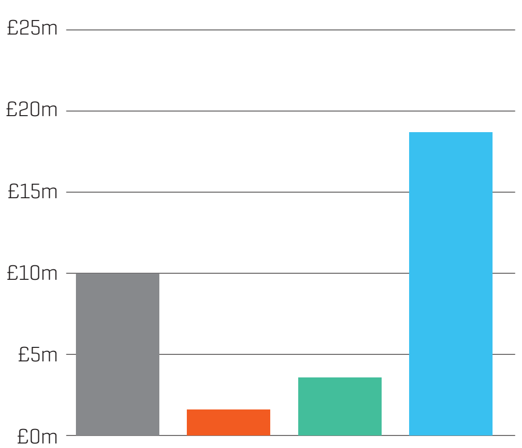
MAPP is a £20m Hub with £10m of EPSRC (Engineering and Physical Sciences Research Council) funding matched by £10m of support committed from our industry, HVMC and university partners. To date, we have secured >£3.2m further funding for 10 aligned projects (total value >£20m) and >£1.2m of funding from our industry partners.

Our world-leading researchers have been engaging in activities around the globe, such as invited keynotes, with over 50 activities at national and international events including conferences in UK, France, South Korea and the USA.

INDUSTRIAL AND HVMC PARTNERS

- MAPP Industry Partners (17)
- MAPP HVMC Partners (7)
- Additional companies on aligned projects (16)
- Conference sponsorship (10)

FINANCIAL IMPACT TO DATE



- Initial EPSRC Funding
- Industry Partner Funding
- Funding secured for aligned projects
- Total Value Aligned Projects

MAPP Director Professor Iain Todd said:

"We've pulled together a complementary and interdisciplinary team of leading UK researchers to solve some of the fundamental challenges limiting the uptake of a vital class of new and emerging technologies, and train the scientists and engineers to implement them."

MAPP RESEARCH PROGRAMME OVERVIEW

CORE RESEARCH PROGRAMME

Our platform research themes focus on two key scientific and technological areas which are essential to delivering our vision – 'Powders by Design' and 'Process by Design'.

Together with our cross-cutting research themes, they provide the enablers to our two Grand Challenges – 'Right First Time Manufacturing' and 'Future Manufacturing Technologies'.

PLATFORM RESEARCH

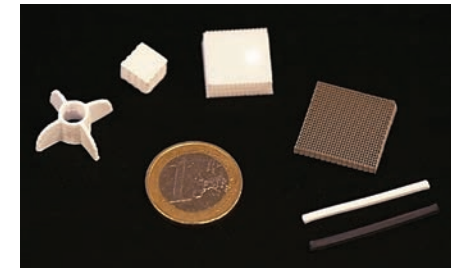
POWDERS BY DESIGN (P1 THEME)

Powders are currently not well enough understood to easily enable consistent manufacture via powder processing routes. Granular media are complex non-equilibrium systems; their collective behaviours and interactions with external forces and stimuli are highly non-linear. The traditional descriptors for powders - morphology, surface area, particle size distribution, compressibility and flowability – all fail to adequately describe their overall complexity as a system. To fulfill MAPP's vision we need to begin with our material input and develop a systems level approach to describing powder behaviour.

P1.1 Powder Descriptors

Powder characteristics have a significant impact on particle based manufacturing processes, affecting production rate, process reliability and product quality. In this project we are developing an understanding of the link between fundamental powder properties and the behaviour of powders in process. In particular the link between particle scale properties, the distribution of these properties, and their fundamental flow and compaction behaviours. We want to be able to identify the minimum and critical set of powder descriptors for a given material and process combination which will enable the prediction of performance in process and subsequent control of output.

Discrete Element Modelling (DEM) techniques will be used to investigate the behaviour at the particle level and develop the link to bulk behaviour and the full-scale process performance. Advanced experimental set-ups, coupled with advanced and *in-situ* characterisation (X1 and X2 themes) will be used to explore these links experimentally by investigating the particle behaviour in geometries chosen to replicate process behaviour.

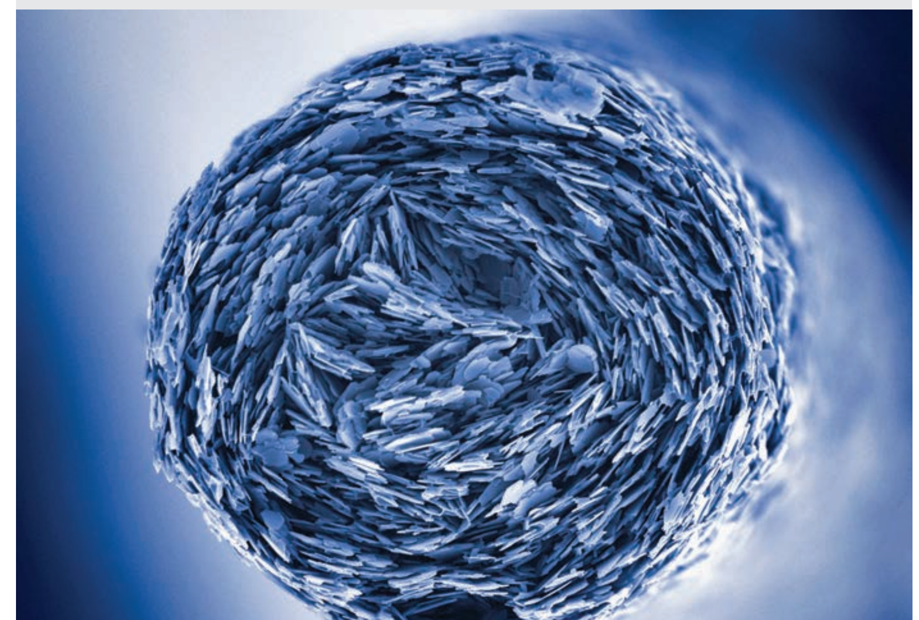


Macro photo showing sintered SiC and Al2O3 scaffolds, parts and test bars printed using the hydrogel inks. (Feilden et al, J. Eur. Ceram. Soc. 2016, 36, 2525)

P1.2 Two Phase Powder Flow

Powder processes, such as 3D printing by continuous extrusion or freeze casting, offer a route to materials with new structural and functional capabilities (e.g. new composites, novel thermal / electrical properties). Achieving these new capabilities requires the ability to design and control the production of engineered microstructures that are heterogeneous and/or anisotropic.

We are looking to understand and control the rheology of particle loaded flows for applications in printing, and understand fibre and platelet orientation mechanisms in extruded and freeze cast parts. The project will involve the development of experimental rigs for *in-situ* observation of processing and the development of models of particle flow and alignment.



Aligned platelets via 3D printing / robocasting (Feilden et al, Mat. Today 2016, 19, 544)

P1.3 Heterogeneous Powders

Fine control of powder shape, size and size distribution is important for many processes, such as additive manufacturing, which requires good powder flow. The production of different particle structures and non-spherical particle shapes (e.g. hollow, needles) opens up new application areas (e.g. anisotropic magnetic materials, impact absorption).

The most commonly used method for metal powder production – gas atomisation – yields powders with a wide size distribution. In this project we will be developing gas atomisation process, using high speed video analysis and CFD modelling to refine nozzle design and process conditions, to yield greater control over powder size and distribution. We will also be exploring the production of heterogeneous powders – e.g. non spherical or hollow – via the gas atomisation process.

Arcast Atomiser, Henry Royce Institute, University of Sheffield.

PROCESS BY DESIGN (P2 THEME)

Powder processes are currently considered a black box and suffer from low manufacturing throughput. A lack of clear process control also results in a high incidence of component rejection due to manufacturing defects.
This theme is initially focused on additive manufacturing (AM) and Field Assisted Sintering (FAST) as they will generate the greatest impact for our industrial partners, whilst allowing the innovative processing, control and modelling approaches (from cross-cutting themes X1-3) to be rapidly developed and applied.

P2.1 Process Definition and Control in Powder Bed Fusion

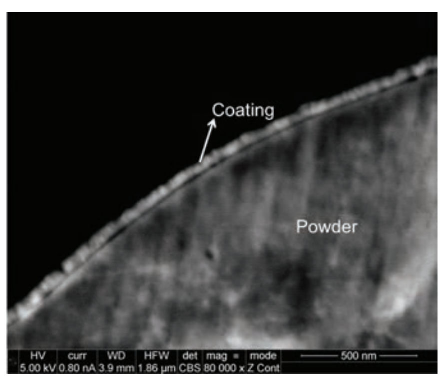
We are developing strategies for defect detection, correction and avoidance in powder bed fusion (PBF) of metals. Our initial focus is identifying the critical parameters in PBF, which provide isotropic properties in components, defect free components and will ultimately allow for real time process control.

In-situ and *ex-situ* characterisation techniques are being developed in our cross-cutting (X1 & X2) themes and applied to PBF. A wide range of process parameters and materials responses are being captured and analysed, e.g. melt pool temperature and dynamics and the relationship between thermal history and component microstructure. The process modelling and control approach developed within the cross-cutting (X3) theme is being used to create control systems which yield consistent and desired properties.

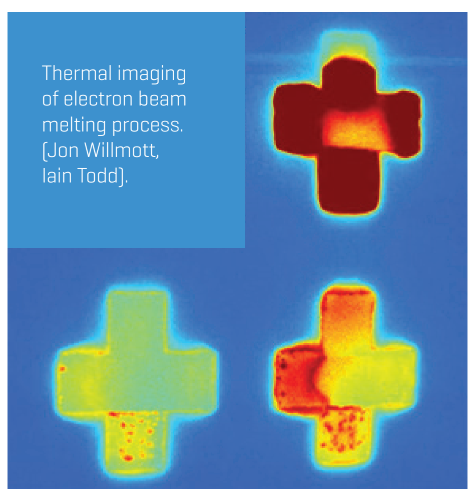
P1.4 Functionalisation of Powders

One of the challenges in metallic powder based manufacturing is the pick-up of oxygen on powder surfaces leading to oxide inclusions and poor mechanical properties in components. We need design coatings which can protect the metal powders prior to processing and/or become active during the processing step.

The proposed research project explores possibilities of protecting powders and therefore enabling the easier and more cost effective application of non-stainless steel powders. The driver for using such powders is the application of Hot Isostatic Pressing (HIP) to form functionally graded components. Applications include the production of transition components to replace the welding of dissimilar materials in the nuclear industry.



Cross-section of 316L powder highlighting chromium coating applied using Magnetron sputtering technique (Sandeep Irukuvarghula & Michael Preuss)

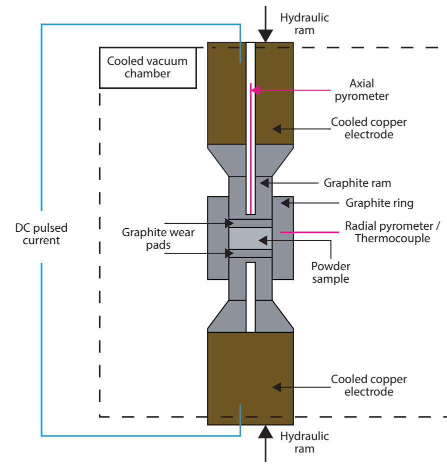


Thermal imaging of electron beam melting process. (Jon Willmott, Iain Todd).

P2.2 Process Definition and Control in Field Assisted Sintering / Spark Plasma Sintering

In this project we are developing a better understanding of FAST / SPS consolidation process, in order to improve the control of the process and the resultant component properties. We are developing novel sintering equipment with improved monitoring technologies – including thermal metrology and imaging – to allow us to probe the consolidation process directly.

We are characterising the effect of critical sintering parameters on the densification of a wide range of industrially relevant powder materials. Our experimental approaches will be coupled with modelling to allow us to determine optimum process conditions, powder morphologies and chemistries.



FAST Schematic

FAST powder to forging

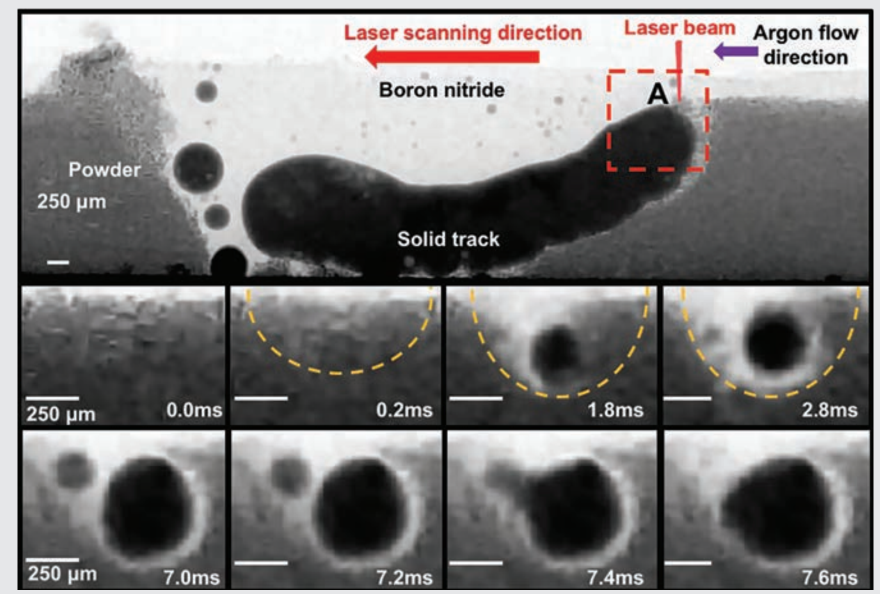
CROSS-CUTTING (X) THEMES

The success of the Platform Research is underpinned by three cross-cutting themes that connect and enable the research programme and underpin MAPP's knowledge-base. The X themes focus on developing novel *in-situ* observation, characterisation, modelling and control, to gain deeper understanding of the interaction of the complex processes and materials under consideration. Elements of the X1, X2 and X3 themes are integrated into all of the P1 and P2 activities.

X1. *In-Situ* Process and Performance Characterisation

In this theme, the team are designing and commissioning novel *in-situ* experimental cells for in-process measurements, allowing time-resolved synchrotron (Diamond Light Source) and neutron (ISIS Neutron Source) observation of structure, chemistry and phase evolution across the length scales from nano to mm during powder-based manufacturing. This will enable a new understanding of how powder compositions and processing routes first affect the phases formed in the powder, and then how these can be tailored to optimise their processing, informing our process modelling and control theme, and validating their outputs via well-controlled experiments. The approaches developed at Harwell are being combined with optical and infrared imaging, to develop in-process production monitoring and metrology techniques to provide real-time feedback.

Using I12 and the LAMPR (a novel LAM process replicator) the complete process of track formation during 3D printing is revealed. A first complete track and details on the laser/gas flow are shown at the top. The first stages of the formation of this track are shown below for the first few milliseconds of track formation. (Leung ACL et al. (2018). *In-situ* X-ray imaging of defect and molten pool dynamics in laser additive manufacturing, Nature Communications, 9, 1355).

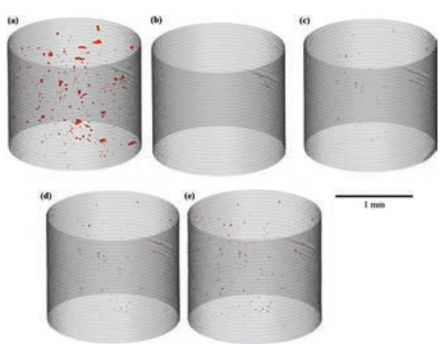


RESEARCH PROGRAMME

X2. Advanced Characterisation

A full understanding of the nature of our starting materials, the changes they experience at critical stages in processing, and the final component properties, is key to developing a full understanding of the underpinning material-process interaction phenomena.

We are developing innovative characterisation technologies and techniques to examine process-related material change at higher resolutions than currently possible using *in-situ* methods. These range from automated high-resolution optical microscopy and analysis, high-resolution transmission and scanning through to tomography of powders and resultant products. We are developing an improved understanding of powder materials and their behaviours via determination of inter-particle interactions and elasticity using techniques such as AFM and nano-indentation, measurements of roughness, density, flowability, hardness, toughness, size and shape, microstructure, behaviours of particles when in suspension (viscosity, rheological testing, calorimetry, zeta potential), optical spectroscopy and particle flow analysis. We are looking to develop a depth of understanding which will enable us to identify and define the critical minimum set of descriptors for a powder to ensure its performance within subsequent processing operations.



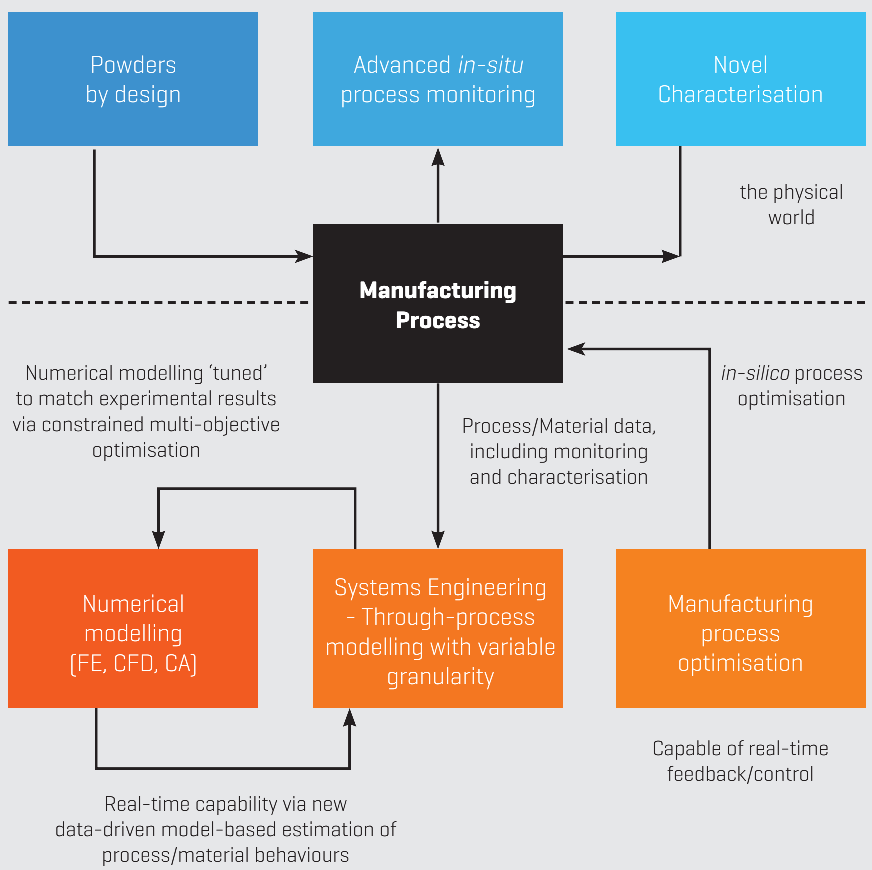
3D visualisation of the porosity (red) imaged by CT scans of the same cylindrical sample (build direction vertical) (a) as-built; (b) following HIPing; (c) 10 min at 1035 °C; (d) 10 h at 1035 °C; and (e) 10 min at 1200 °C. (S. Tammas Williams et al. [2016] Porosity regrowth during heat treatment of hot isostatically pressed additively manufactured titanium components. Scripta Materialia. 122, 72)

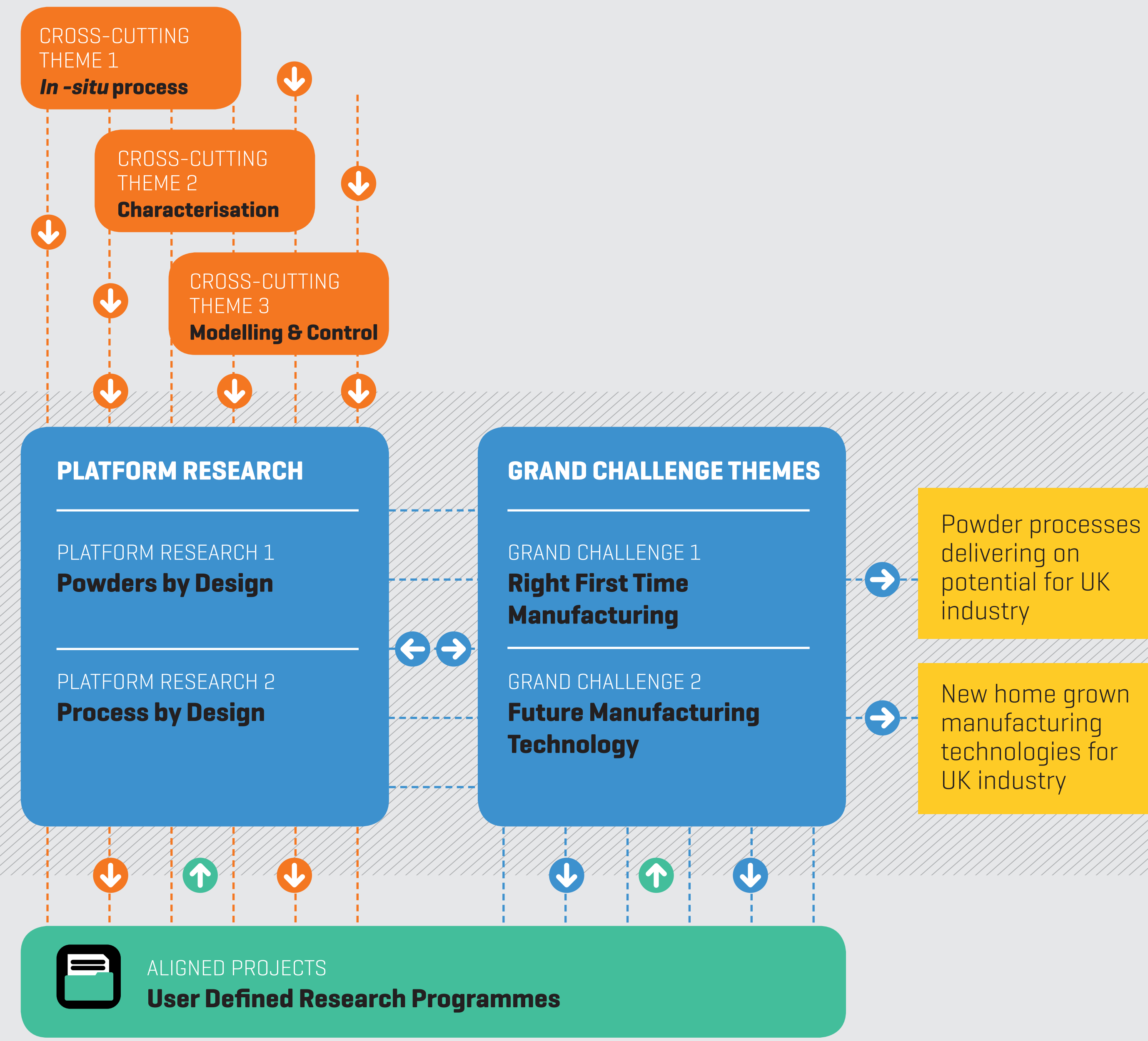
X3. Modelling, Optimisation and Control

Under X3 we are looking to turn the information and data from advanced processing and monitoring technologies into process understanding and control. The fast track development of emerging powder-based process technologies will be enabled through merging knowledge capture from intelligent experimental design and the novel approaches developed in X1 and X2 with computational intelligence (CI) modelling / machine learning (ML).

By employing CI/ML methodology we will directly address the inevitable uncertainties that exist with these processing technologies which are relatively immature. The abundance of process data that can be captured from our processes via real-time process monitoring, historical data, or *in-situ* monitoring provides enormous systems based modelling opportunities. We envisage real-time usage of a few well-defined key performance indicators to 'guide' in real-time process optimisation routines. The proposed framework will also form a platform for real-time condition monitoring tasks, such as monitoring and controlling the fluctuations in process performance and its link to final part quality.

Hybrid modelling approach used within MAPP.





MAPP PROJECT PARTNERS

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

HIGH VALUE MANUFACTURING CATAPULT CENTRES

- The University Of Sheffield Advanced Manufacturing Research Centre Boeing
- AFRC Advanced Forming Research Centre University of Strathclyde
- Catapult High Value Manufacturing
- cpi
- mtc Manufacturing Technology Centre
- Nuclear AMRC
- WMG Innovative Solutions

INDUSTRY PARTNERS

- Eastman
- element six
- freemantechnology
- GKN Aerospace
- Johnson Matthey Inspiring science, enhancing life
- LPW
- Maher
- Metalysis
- Morgan Advanced Materials
- PSI
- Renishaw apply innovation™
- Rolls-Royce
- Safran Messier-Bugatti-Dowty
- Seco
- Weir
- Xaar
- Zeiss

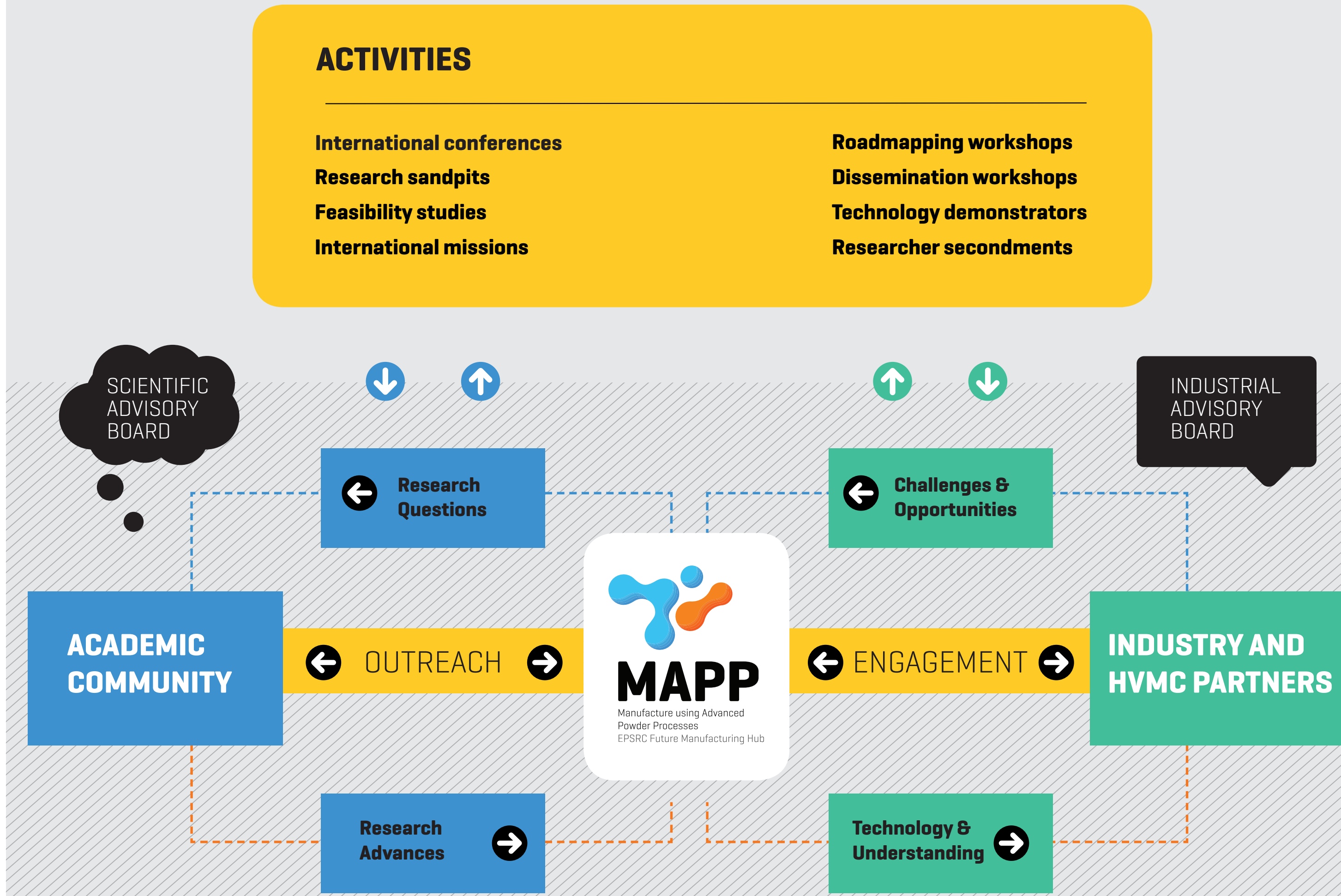
UNIVERSITY PARTNERS

- The University Of Sheffield
- Imperial College London
- University of Leeds
- Manchester 1824 The University of Manchester
- University of Oxford

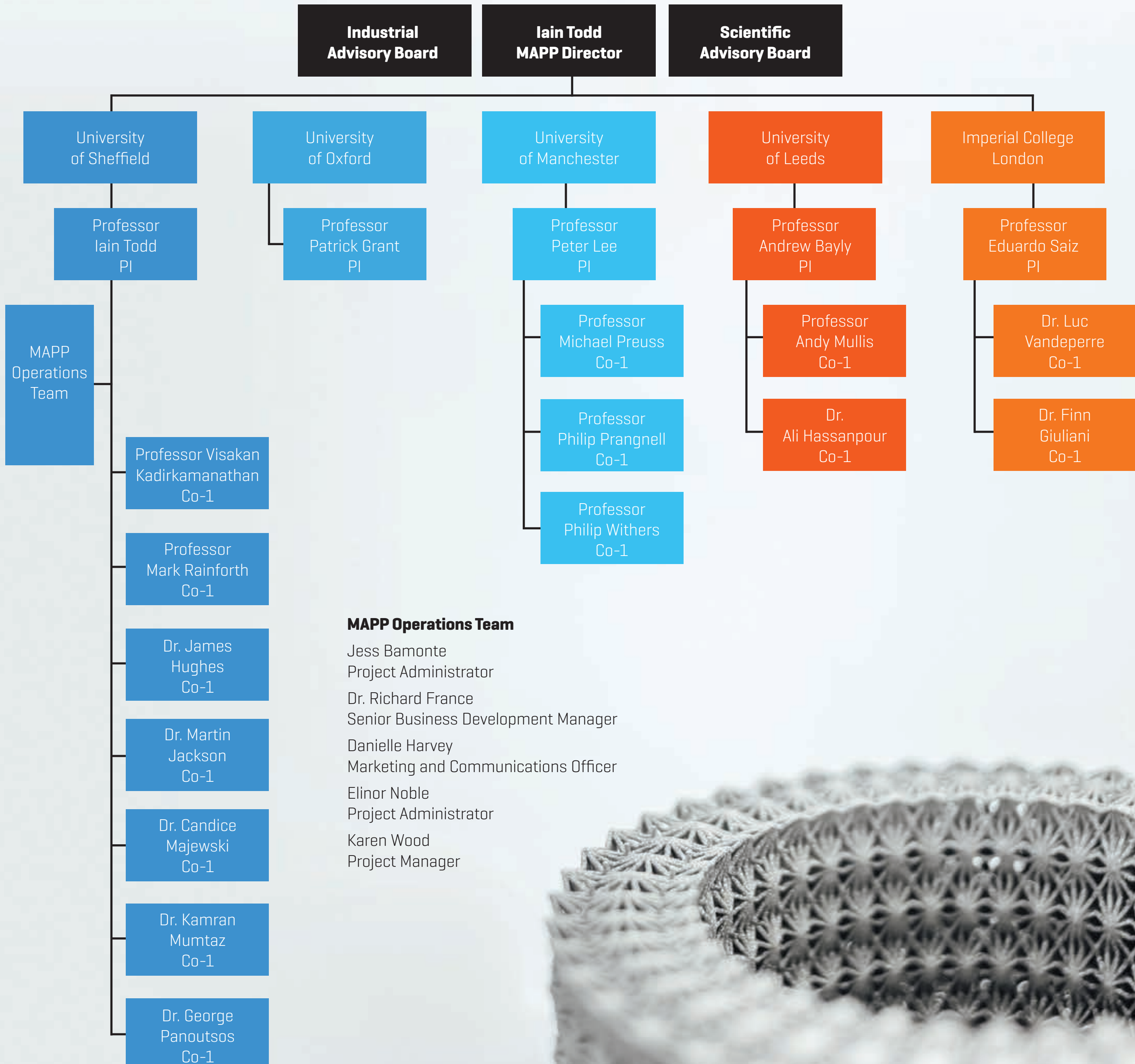
PATHWAYS TO IMPACT

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

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



MAPP ORGANISATION CHART



MAPP Operations Team

Jess Bamonte
Project Administrator

Dr. Richard France
Senior Business Development Manager

Danielle Harvey
Marketing and Communications Officer

Elinor Noble
Project Administrator

Karen Wood
Project Manager

WORKING TOGETHER

SHEFFIELD

- Advanced powder processes
- *Ex-situ* characterisation
- Systems based modelling, control and optimisation

LEEDS

- Advanced powder manufacture
- *In-situ* characterisation
- Modelling - powder formation & granular materials

MAPP
Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub

OXFORD

- Advanced powder processes
- Materials for energy generation and storage

IMPERIAL

- Ceramic processing
- *Ex-situ* characterisation
- Manufacture of complex ceramic forms

MANCHESTER

- Advanced *ex-situ* characterisation
- Materials modelling
- *In-situ, in-operando* synchrotron 4D structure analysis

CASE STUDY

3D PRINTING OF CRITICAL AIRCRAFT STRUCTURES

Rolls-Royce have used additive layer manufacturing (ALM) to construct a titanium front bearing housing (FBH) which is held inside a Rolls-Royce Trent XWB-97 engine.

ALM, also known as 3D printing, is a process by which a component is built up in discrete layers using a high energy source to melt or fuse metal powders.

The construction of the bearing marks the first time ALM has been used to produce such a significant load bearing component, rather than the conventional processes of casting or forging.

MAPP researchers worked with Rolls-Royce and the Manufacturing Technology Centre to develop its ALM techniques through a programme of testing, research and quality assurance, building on Rolls-Royce's experience of innovation in high value manufacturing, the academics' excellent research base in additive manufacturing and Catapult Centre expertise with process scale up.

MAPP Director, professor Iain Todd said:

"This is a great example of how academics can work with industrial partners like Rolls-Royce and the HVM Catapult Centres to translate our ground-breaking early stage research to industrial practice.

"The fundamental research work we conduct gives a strong underpinning to development activities that are closer to application providing insights into the process that increase confidence in its capabilities. That the activity we initiated here has facilitated this huge step forward in additive manufacture is a wonderful thing to see."

Trent XWB-97 flying test bed engine front bearing housing. Showing 3D printed core inlet vane assembly. Courtesy of Rolls-Royce.

VIEW FROM A MAPP PhD STUDENT

FIRST INTERNATIONAL CONFERENCE

By James Wingham

Professor Tresa Pollock

Professor Carolin Körner

First place Poster Presentation Luke Fox, University of Sheffield.

The MAPP First International Conference provided a great opportunity to gain a wider knowledge of what is happening in the general field of additive manufacturing (AM).

As a new University of Sheffield PhD student, who had never been to a conference before, I was keen to attend and potentially get inspiration for things to implement in my own research.

My research is in Laser Sintering (polymers), so MAPP is directly related to my work.

The highlight for me was the way the speakers used amazing pictures and videos of the printing processes as they were happening. I hadn't come across most of the methods used to do this, so the results looked spectacular. A video showing the melt pool spatter blocking up a gas pocket and being spat back out again was particularly impressive.

Another highlight was seeing a polymers poster - from our very own Luke Fox - win first prize (see photo above).

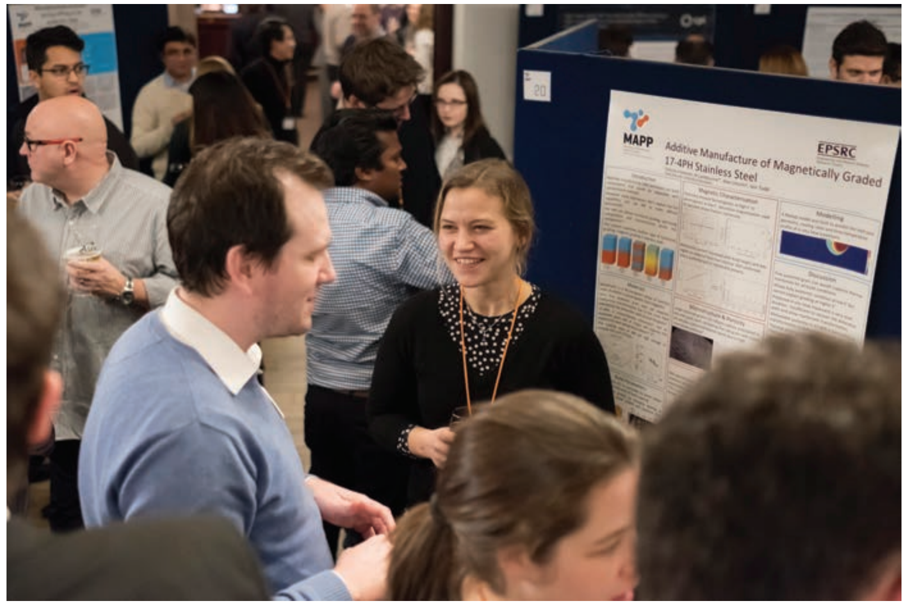
It was great to hear about the variety and ingenuity of different methods of collecting data *in-situ*, for example in Prof. Carolin Kőrner's keynote. As well as from the finished parts, both below the surface, as discussed in Prof. Tresa Pollock's keynote, and just from the surface as discussed during a presentation from the University of Nottingham. The sheer amount of research into this opens up a whole host of exciting possibilities for the future.

The thing that I took away from the conference, was just how much data we collect but do not use. The potential for increasing the capabilities of *in-situ* measurements to design smarter machines is huge. The possible benefits of combining these different approaches would completely change the AM industry and could change the way we use these parts. This, in a nutshell, is what MAPP is all about. Combining the research from all over the world to deepen our understanding of what is happening during the manufacturing process, and using that wealth of knowledge to design new, smarter systems, the like of which have never been seen before.

MAPP FIRST INTERNATIONAL CONFERENCE

THERE'S A MAPP FOR THAT!

By Rachel Park, RP Editorial Services



Manufacturing using Advanced Powder Processes is increasing in both quantity and quality, and these are indeed the fundamental drivers for the foundation of the EPSRC Future Manufacturing Hub: MAPP.

Launched in January of 2017, one year on, MAPP hosted its First International Conference over two days in Sheffield.

As Professor Iain Todd, an additive manufacturing (AM) industry veteran and project leader at MAPP, pointed out in his welcome address: "Sheffield is one of the homes of the first Industrial Revolution, so it is really interesting that around the city we are witnessing a renaissance with the AMRC and advanced manufacturing park."

Moreover, he also highlighted how the university and the city are contributing to the Fourth Industrial Revolution / Industry 4.0. "Our future manufacturing hub is part of that – and this conference is one of the activities in this regard."

MAPP's central premise is to deliver on the promise of powder-based manufacturing to provide low-energy, low-cost and low-waste high value manufacturing routes and products to secure UK manufacturing productivity and growth. Relatively speaking, it is actually a narrow and specific remit, but one that is absolutely fundamental to progress with a broad reach into a number of connected industries.

The goal of the first MAPP conference was to draw together scientists, researchers and commercial powder manufacturers from around the world and at every career stage to disseminate the work — and progress — that is being made in this area.

CONFERENCE PROGRAMME

A carefully curated mix of in-depth keynote presentations (based on research) together with some faster paced talks and followed by round table Q&As were blended well to provide delegates with an engaging format.

There was also a session dedicated to some "flash presentations" as well as a poster competition detailing the many areas of research being conducted (29 in total) — in a bid to provide insight into the comprehensive scope of the MAPP initiative. The interactive poster session invited delegates to vote for their top three posters during the course of the event.

Indeed, networking opportunities were abundant and formally recognised as a key motivating factor for conference attendance. It was also heartening to witness the real diversity across the programme.

CONTENT

The key powder material themes driving MAPP research were consistently in view, focused as they are on novel *in-situ* observation, characterisation and modelling and control, to gain a deeper understanding of the interaction between complex processes and materials.

The first in-depth session focused on "*In-situ* process and performance characterisation" and was keynoted by Professor Tresa Pollock from the University of California. It was hard not to make a mental note that starting with a strong female presenter was a nice touch, however, if it was unintentional — even better. Prof. Pollock's presentation considered the 3D analysis of structure and defects at the scale of the melt pool, and provided considerable insight into her team's research using Femtosecond Lasers and Tomography to achieve workable systems for 3D data set collection and analysis during AM builds. As she noted: "In-process monitoring is essential." In this way, challenges can be identified and overcome, including how "we have to think harder about designing alloys for AM – to minimise residual stresses," and "develop more amenable alloys, nano functionalisation of high strength alloy powders and design of solidification paths." This requires large 3D and 4D datasets, but Professor Pollock was optimistic that Femtosecond laser tomography is a promising new approach.

Professor Pollock's keynote was followed by a second keynote presentation delivered by Professor Barbara Previtali from the Politecnico di Milano. Another strong female scientist (and role model) working on temporal beam shaping in Selective Laser Melting (SLM) and molten pool sensing during continuous and pulsed wave laser processing. Describing the research approach and the experimental set up (due to commercial SLM platform set up not allowing tests), which includes machine and materials (AISI); pulse temporal profiles; and high speed imaging (camera synchronised with illumination) for process diagnosis; Professor Previtali was able to show videos of melt pool monitoring in SLM at different build speeds, which were fascinating. The team's subsequent image analysis identified molten pool attributes and provided a comparison of pulsed wave (PW) and continuous wave (CW) laser processing using differing modes and geometry and concluding that a mixed strategy produces improved results, which in turn will be the focus of future development for higher quality and productivity results with SLM.

These very specific, highly detailed presentations were followed by three short, fast-paced presentations and a Q&A session. The highlight of the morning (probably the whole event), from my point of view, was the presentation given by Prof. Adam Clare from the University of Nottingham, which considered the issue of 'finding and fixing defects in metal powder bed processes.' Apart from the fact that the title of the presentation didn't require a definition search, and that the science was no more or less impressive than any of the other fields of research, Professor Clare's insight and delivery was wholly accessible to a layman like me. Plus, he has a wicked sense of humour — that always helps.

Describing the current situation of defect identification in AM as a "minefield" he went on to evoke the "dream," namely "put the metal powder into a machine - press go – get a high integrity part out!" I think every AM user has probably daydreamed about that scenario at one time or another. However, we're not there yet and Professor Clare is one of many people figuring out how to get closer to that. After highlighting many of the challenges (powder variation, energy sources, design choices, parameter choices, inspection limitations etc) he went on to outline a "hierarcy of needs for analysis."

And while Adam identified some commercial analysis tools that are starting to emerge from vendors, he delved into the research he is conducting at Nottingham, which takes a different approach – spatially resolved acoustic spectroscopy — the goal of which is to develop an "information rich production machine" supported by in-process monitoring (online), which requires a specific instrument in the machine. There are many logistical challenges here, including the optical measurement of rough surfaces; fitting the tool inside the build chamber and the necessity to miniaturise the optical train and use of galvanometer; as well as the impact on build time. Moreover, beyond monitoring the research is considering how to produce real time feedback and correction / action by developing algorithms for controlling microstructure repair.

This information was delivered so well, it actually lifted the room, the potential excited people — even more so considering what it enables: the ability to effect rework in-process, which will drastically enhance the economics of AM.

In a similar vein, Prof. Andrew Moore of Heriot-Watt University and Prof. Peter Lee of the University of Manchester also provided research insights into the "High speed imaging of the powder bed and shield gas during metal PBF additive manufacture" and "Shining new light on the mechanisms controlling laser additive manufacturing using synchrotron imaging" respectively.

Again, there were some fascinating videos, courtesy of high speed imaging (8000 frames per second) and Schlieren imaging techniques that provided real time footage from within the chamber showing laser meltpool spatter etc, at different angles and speeds. It was incredible imagery that offers real learning material. Some of the videos are available online.

Other presentations across the event drilled down into projects funded through MAPP. Notable among these the work being undertaken at the Harwell campus and research complex (home of the Diamond Light Source) to develop and build new equipment using synchrotron hard X-rays to see inside the build – not just the surface of it, to track what happens layer by layer and then build up a valuable dataset including a process map and a mechanistic map. Beyond the process, however, and in line with the MAPP remit, the research here also investigates powder quality and new material development including comparing virgin powder against oxidised powder to understand how much oxidisation can be tolerated without impacting quality. It was interesting to learn that "powder flows better when slightly oxidised" but the team is looking to discover how AM can be used with a laser to directly process ceramics and correlate results with other methods (Optical and IR / X-ray etc) as well as develop machine learning algorithms based on what is happening in the meltpool.

Another key theme of MAPP research with a dedicated session at the conference is that of Advanced Characterisation. This is a fascinating area of research, and at this conference, it was all about the what, why, where, who and how material characterisation was progressing for AM. Essentially, though, these details are not pre-requisite for the vast majority of the AM industry, but I know that the results are, and they will have a massive impact on future industrial capabilities of the technology in the real world. That's a key take-away here. Indeed the MAPP conference provided repeated examples of why such conduits between academic research and industry are vital.

As you might expect, the characterisation of material powders is a complex and multi-disciplined field that involves understanding — and utilising — their physical structure and chemical composition to understand and measure their properties, including but not limited to stiffness, strength, ductility, hardness, electrical/thermal conductivity etc, in relation to how they can be processed, react in-process and ultimately, finished part quality and integrity.

Professor Jin Ooi from the University of Edinburgh looked at this from a top down view with his presentation: Computational modelling of powder processes from model conceptualisation to industrial application; while Dr. Hongtao Zhang from Loughborough University got more specific with the "Microstructural characterisation of oxide dispersion strengthened ferritic steels fabricated by spark plasma sintering for nuclear applications."

The two days were concluded with a final session comprising an expert panel talking about getting "from research to results: Is powder research responding to industry needs?" and chaired, expertly by Sophie Jones, General Manager of Added Scientific.

ROUNDING UP

I think my biggest take-away that I can share is that this event provided an opportunity to better understand the advanced techniques that are taking place deep inside the PBF additive manufacturing platforms. Powders demand a different approach to other material states and this is the remit of MAPP — to find the best ways to make powders work for industrial applications.

A FEW OTHER INSIGHTS

The conference, as often is the case, included an evening dinner reception — these things serve multiple purposes. The obvious one of necessary refuelling after brain overload is superseded by the opportunity to network with other attendees. On this occasion, my dinner companions for the evening were most lovely – Iain Todd (MAPP Director), Hugh Hamilton (Johnson Matthey), Kelly Moran (AMRC / Rolls-Royce) Dan Johns (Oerlikon), and Javier Llorca (IMDEA Madrid).

Conversations were free flowing and varied and often reverted back to families and commonality — a vital under-pinning of human interaction. Of course, there was a great deal of chatting about the MAPP commonality (the reason we were all sat at the same table) its intent, where it fits in the UK AM community/global ecosystem, academic community and more. The breadth of experience, global locations and motivations and how we interacted were a perfect analogy for the current status of AM, I mused.

To sum up, it was a really interesting and useful event to attend — not too big, lots of extremely intelligent people, with passion in abundance soaking up the science behind some fundamental AM developments — disseminating, reporting, sharing and learning. How it should be.

EXPERT PANEL REVIEW

One of the highlights of the conference was an expert panel, chaired by Sophie Jones, General Manager, Added Scientific, posing the question **'From Research to Results: Is powder research responding to industry's needs?'**

The panel featured Dr. Kate Black, University of Liverpool, MAPP Investigator Dr. Candice Majewski, University of Sheffield, Dr. Hoda Amel, Manufacturing Technology Centre and Dr. Nicola Jones, LPW Technology.

Delegates took advantage of the opportunity to ask the experts for their opinion on current challenges.

The discussion was wide-ranging and included the importance of sharing information about what didn't work as well as information about successes, the importance of training and the relationship between industry and academia.

Karen Wood, MAPP Project Manager, said:

"The MAPP Conference aimed to bring together leading experts across the whole of its portfolio, this panel was yet another example of the calibre of advanced powder processes engineers that are engaging with MAPP."

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PARTNER WORKSHOP

As an open and collaborative research hub, relationships are at the heart of our work. That's why our partner workshops and quarterly meetings are so important to us.

Over 50 people, including MAPP's academic investigators and senior representatives from MAPP's industry and High Value Manufacturing Catapult partners, attended our partner workshop in June 2017.

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

The event was run by the Centre for Facilitation and featured a number of different small group activities and discussions, ensuring partners had the opportunity to network and learn more about the different interests involved across the consortium.

At our quarterly meetings our researchers and investigators get the chance to forge new links between our projects, learn more about each other's work and attend training sessions.

Senior Business Development Manager Dr. Richard France said:

"Both our partner workshop and quarterly meetings have been a tremendous success with fantastic input and energy from all attendees."

MAPP LECTURE SERIES

The MAPP Lecture Series launched in 2017 and features experts in the field of AM.

Speakers have included Richard Leach, Professor of Metrology at the University of Nottingham, Dr. Hector Basoalto, University of Birmingham, and Dr. Kate Black, University of Liverpool.

Prof. Leach's research is dominated by what he calls "information-rich metrology (IRM)": the enhancement of manufacturing metrology through the use of a priori information, often utilising concepts from artificial intelligence.

Examples of IRM in action in additive manufacturing were presented in his lecture, including the measurement of form and texture, external and internal features, and post- and in-process metrology.

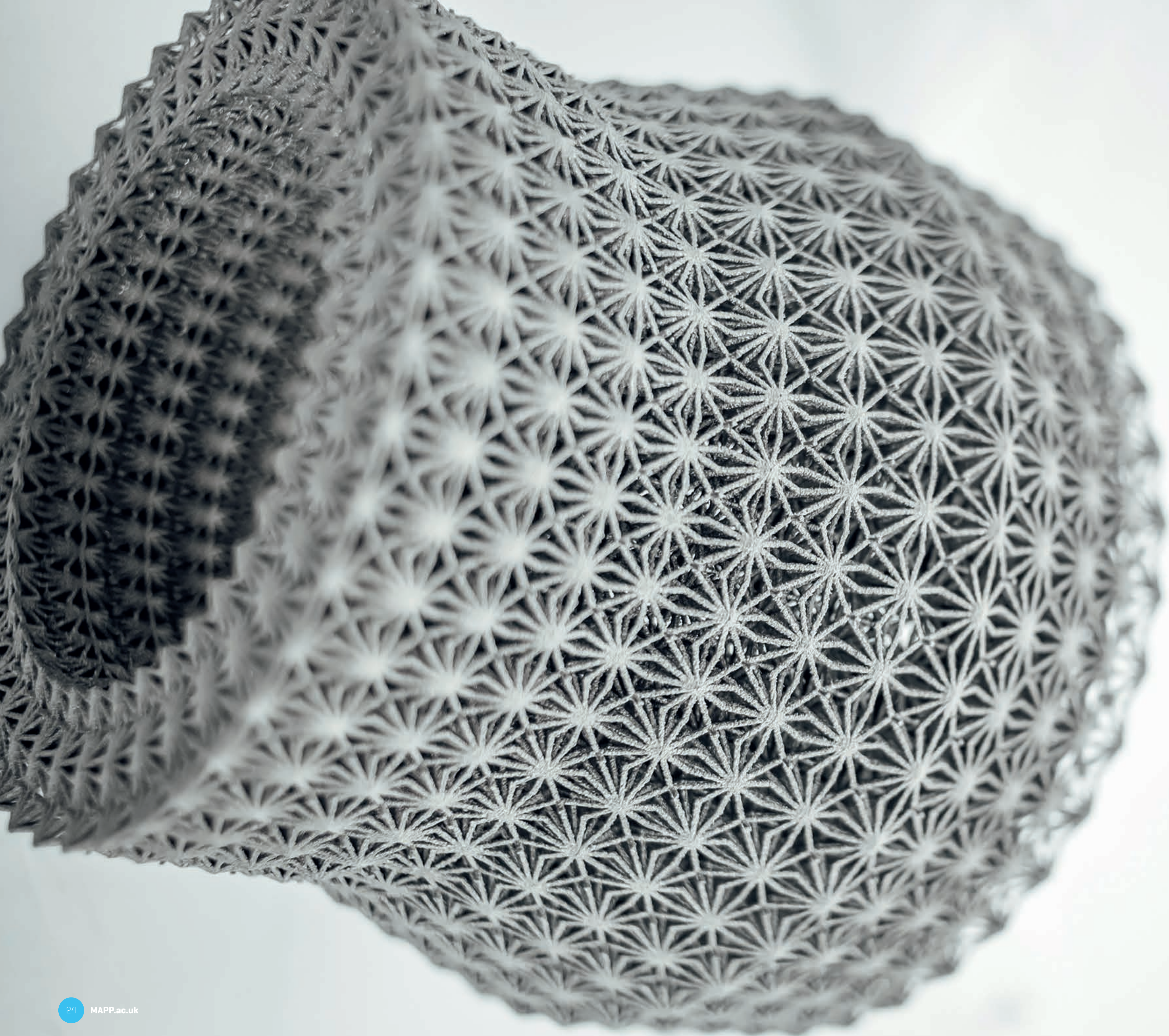
Dr. Hector Basoalto's research explores the causal relationships between microstructure, manufacturing process routes and mechanical properties of engineering alloys.

His lecture was titled Multiscale Materials Modelling of Microstructure Variations and Property Scatter in Additive Manufacturing.

Dr. Kate Black's research interests are primarily focused on the development of novel functional materials, using inkjet printing, for the manufacture of electronic and optoelectronic devices. Her main area of expertise is in the development of novel Reactive Organo-Metallic inks (ROM) which are particle-free and can be exploited to produce a wide variety of functional materials, such as conductors, insulators and semiconductors. Her lecture explored the use of ROM precursors to produce materials spanning metals, oxides and nitrides, which can be processed to print novel functional 2D and 3D materials.

Project Manager Karen Wood said:

"The MAPP Lecture Series is about high-quality speakers giving their insight into advanced powder processes and related subjects."



Lattice structure. These are attractive for a number of applications, such as reducing weight in automotive and aerospace components. Additive manufacturing offers unprecedented control in their design and manufacture.

PUBLICATIONS

Journal Paper: Zavala-Arredondo, M., Ali, H., Groom, K.M., Mumtaz, K. (2018). Investigating the melt pool properties and thermal effects of multi-laser diode area melting. The International Journal of Advanced Manufacturing Technology. 1-14.

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

Journal Paper: Hong Z., Morrison A., Zhang H., Roberts S., Grant P. (2017). Development of a Novel Melt Spinning-Based Processing Route for Oxide Dispersion-Strengthened Steels. Metallurgical and Materials Transactions A. 49A, 604-612.

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

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

Journal Paper: Zavala-Arredondo, M., Groom, K.M., Mumtaz, K. (2018). Diode area melting single-layer parametric analysis of 316L stainless steel powder. The International Journal of Advanced Manufacturing Technology. 94, 2563-2576.

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

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

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

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

Comment: Todd I., (2018). Metallurgy: Printing steels. Nature. 17, 13-14.

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

PAPER:

3D Printing Bioinspired Ceramic Composites

PUBLICATION:
Scientific Reports 7.1 (2017)

AUTHORS:
Ezra Feilden; Claudio Ferraro, Qinghua Zhang, Esther García-Tuñón, Eleonora D'Elia, Finn Giuliani, Luc Vandeperre, Eduardo Saiz

The complex internal structures of natural materials such as bone, wood and mother-of-pearl give them resistance to cracks and fracture.

Replicating these structures with traditional manufacturing methods is impossible, but this research demonstrated that robocasting can be used to produce bio-inspired structures in a reasonable timeframe.

Robocasting, in which a paste is extruded through a computer-controlled nozzle, building up objects layer by layer, can be used to 'print' with a wide range of materials, including graphene, bioactive materials, ferroelectric materials, and ceramics.

Sub-micron additive manufacturing offers a high level of control but is a slow process that is impractical for manufacturing larger objects. A technique is needed which combines sub-micron scale structural control with macroscopic printing speeds. Robocasting is a strong candidate to achieve this goal.

It can be used to build ceramic-based composite parts with a range of geometries, possessing microstructures unattainable by other production technologies.

To demonstrate the versatility of the approach the researchers fabricated highly mineralized composites with microscopic Bouligand structures that deflect crack propagation in three dimensions - retaining strength while enhancing toughness by using strategies taken from crustacean shells.

A key feature of these experiments was the high percentage of ceramic material in the printed objects, achieved using alumina platelets. The researchers controlled both the composition of the ceramic paste and the shear forces in the nozzle and used X-ray tomography on the I13-2 beamline, at Diamond Light Source, to quantify platelet alignment in the nozzle.

Robocasting was used to build ceramic scaffolds with complex shapes - in practical times and sizes. Their architecture can be used to direct crack propagation with a degree of control not currently possible using other approaches.

This paper shows new possibilities in the control of fracture, enhancing toughness and defect tolerance while maintaining a high specific strength, of interest to a wide range of industries from aerospace to automotive.

Further work will focus on exploring other material combinations, further toughening strategies and decreasing the characteristic microstructural dimensions.

PAPER:

Diode area melting single-layer parametric analysis of 316L stainless steel powder

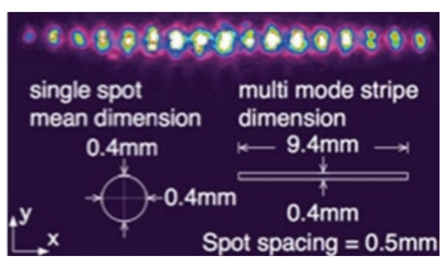
PUBLICATION:
The International Journal of Advanced Manufacturing Technology (2018).

AUTHORS:
Miguel Zavala-Arredondo, Kristian M.Groom & Kamran Mumtaz

The development of a new additive manufacturing (AM) process - Diode Area Melting (DAM) - a highly scalable approach using energy efficient diode lasers, has opened the door to faster, smaller and cheaper technologies. This is important as one of the challenges to the adoption of AM in high volume sectors such as automotive is overcoming the slow speed of the process.

The paper looks at further understanding the process in regards to the laser energy density required to build parts as quickly as possible. DAM uses a shorter laser wavelength than typical SLM systems allowing for better energy absorption within the powder materials.

The paper presents a parametric analysis of the DAM process and identifies the effect of laser beam profile, laser power, powder characteristics and scan speed on the melt pool, and the conditions needed to produce fully dense metallic components.



Beam profile. [Zavala-Arredondo, M., Groom, K.M. & Mumtaz, K. Int J Adv Manuf Technol (2018) 94: 2563.]

PAPER:

In-situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing.

PUBLICATION:
Nature Communications, 9, 1355 (2018)

AUTHORS:
Chu Lun Alex Leung, Sebastian Marussi, Robert C. Atwood, Michael Towrie, Philip J. Withers, Peter D. Lee

Laser additive manufacturing (LAM) uses a laser to fuse together metallic, ceramic or other powders into complex 3D shapes, layer by layer. The cooling rates are extremely rapid, and since they are unlike conventional processes we don't know the optimal conditions to obtain the best properties, delaying the uptake of LAM in the production of safety-critical engineering structures, such as turbine blades, energy storage and biomedical devices.

We need a method to see inside the process of LAM to better understand and optimise the laser-matter interaction and powder consolidation mechanisms.

For this research, the team created a novel LAM process replicator, the LAMPR, which allows them to image and quantify the formation of the melt track as the layers are printed during AM.

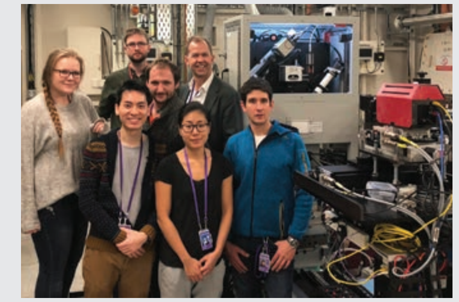
The LAMPR was designed to fit on the beamline, at Diamond Light Source, the UK's national synchrotron, and mimics a commercial LAM system, with windows that are transparent to X-rays, allowing scientists to see right into the heart of the LAM process as it takes place.

They used X-ray radiography with high temporal and spatial resolution to uncover key mechanisms of laser-matter interaction and powder consolidation during LAM, including the formation and evolution of melt tracks, spatter patterns, the denuded zone (a powder-free zone) and porosity in the deposited layers. The time-resolved quantification of the pore and spatter movements gave crucial information of their flow velocities and direction, which are not possible to acquire using other techniques.

The results of these experiments clarify aspects of the physics underlying LAM, which are crucial for its development. The previous hypothesis was that the formation of surface porosity on finished objects was due to incomplete melting or insufficient liquid feeding. However, this research shows that it is formed via a pore-bursting mechanism. Pores near the surface escape into the atmosphere, leaving behind a surface depression.

Further, the team's results reveal that the continuous track of melted material often occurs via pre-melting ahead of the main track, driven by surface tension (Marangoni flow), before merging into the main track. Metal vapour and heating of inert gas is a potential source of defects, forming a plume which ejects powder and molten droplets away from the main track.

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



The Additive Manufacturing Team from the Research Complex at Harwell on the Joint Engineering Environment Processing (JEEP, I12) beamline. The Laser Additive Manufacturing Process Replicator (or LAMPR) on the right is used to reveal the underlying physical phenomena during LAM.

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

PAPER:

The Influence of Porosity on Fatigue Crack Initiation in Additively Manufactured (AM) Titanium Components

PUBLICATION:
Scientific Reports, 7, 7308 (2017)

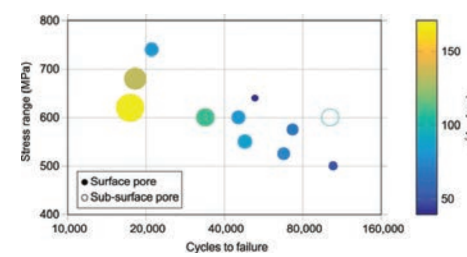
AUTHORS:
Sam Tammas-Williams, Philip Withers, Iain Todd and Philip Prangnell.

Fatigue life relates to how long components will last before failing due to weakening caused by repeated loading. There are a number of different factors that can influence fatigue life including the type of material, its microstructure, its shape, loading conditions and temperature. Understanding and improving the fatigue performance of components made by new manufacturing methods is essential for safety critical components used in aerospace. This paper sheds new light on the fatigue properties of materials manufactured using electron beam melting (EBM) and possible strategies for improving fatigue performance.

The paper demonstrates the use of a new time-lapse x-ray computed tomography (CT) method to improve the understanding of the effect of pores on the fatigue life of components made using EBM by tracking fatigue crack initiation and growth in 3D.

It confirms that the fatigue lives of samples manufactured by EBM are strongly influenced by the presence of retained porosity, with fatigue life proportional to pore size.

A ranking technique is developed to predict which pores are the most detrimental to fatigue life. The analysis shows fatigue life improvement may be achieved by minor adjustment to the manufacturing process to avoid defects appearing in critical locations.



Effect of pore size on fatigue life – S-N curve showing only those samples that failed from porosity for samples tested in the z-direction. The size and colour of the markers indicate the size of the pore (A_n) measured from SEM images of the fracture surface [Tammas-Williams, S., Withers, P.J., Todd, I., Prangnell, P.B., (2017). The Influence of Porosity on Fatigue Crack Initiation in Additively Manufactured Titanium Components.Scientific Reports, 7, 7308.]

Part of the super lightweight, aerodynamic stem and handlebars manufactured using Electron Beam Melting for Sir Bradley Wiggins.

MAPP
EXECUTIVE TEAM

Professor Iain Todd

MAPP Director Professor Iain Todd holds a Royal Academy of Engineering GKN Aerospace Research Chair in Additive Manufacture and Advanced Structural Metallic Materials. His research is focused on both the development of new alloys and the development of new processes to enable engineering structures to be manufactured from them. Iain's manufacturing research is conducted on the near-industrial scale and actively supported by a number of industry partners including GKN, Rolls-Royce and Weir Group. He 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 more than £7m and safeguarded / created 150 jobs. Iain is a Fellow of the Institute of Materials, Minerals and Mining. Iain leads the theme Process by Design [P2.1].

Professor Andrew Bayly

Professor Andrew Bayly is a chemical engineer with more than 20 years' experience in the development of particulate products and processes. He had significant experience in industry before moving to academia in 2013, including the position of Principal Scientist at Proctor and Gamble. His research focuses on the link between process, particle structure and process/product performance and application to optimisation and scale-up. His research is supported by ATI, AMSCI, EPSRC, EU and industry. Andrew leads the theme Powders by Design [P1.1].

Professor Patrick Grant

Professor Patrick Grant is the Vesuvius Professor and Head of Materials at Oxford University. Patrick's 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 8 patents. Patrick is a co-investigator on LiME, the EPSRC Future Manufacturing Hub in Liquid Metal Engineering. Patrick is a Fellow of the Royal Academy of Engineering.
Patrick leads the Grand Challenge theme GC2 in MAPP – 'Future Manufacturing Technologies'.

Professor Peter Lee

Professor Peter Lee is Assistant Director, Physical Sciences, of the Research Complex at Harwell (RCaH). He is an expert in characterising microstructural evolution during manufacturing, and predicting processing-structure-property relationships using Integrated Computational Materials Engineering (ICME), with over 30 years' experience at Alcan, Imperial, Manchester and now University College London. He has published over 250 journal papers and is a Fellow of the Institute of Materials, Minerals and Mining and the Institute of Cast Metals Engineers.
Peter leads the X1 research theme in MAPP – '*In-situ* Process and Performance Characterisation'.

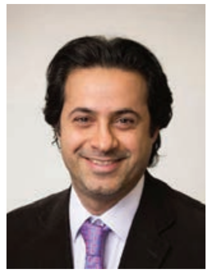
Professor Eduardo Saiz

Professor Eduardo Saiz directs the Centre for Advanced Structural Ceramics (CASC) at Imperial College London. His research interests include the development of new processing techniques for the fabrication of ceramic-based composites, in particular hierarchical composites with bioinspired architectures. He has published more than 120 papers, including high impact journals such as Science and Nature Materials and holds several US patents. His recent work on the 3D printing of ceramics and graphene inks has been highlighted internationally from New York Times to Wired. Eduardo leads the theme Powders by Design [P1.2].

MAPP

INVESTIGATORS

Dr. Finn Giuliani, Imperial College London. His research interests are in ceramic materials, particularly powder manipulation, characterisation and small scale testing, particularly of interfaces. He has published over 50 papers and holds over £1M in active grants. He has collaborated with companies including SECO Tools and Element 6.



Dr. Ali Hassanpour, University of Leeds, leads the Complex Systems and Processes research group at Leeds. His research is focused on the link between single particle properties and their collective properties and behaviours, especially multi-scale modelling approaches such as Discrete Element Modelling (DEM). He has more than 100 publications and his research is supported by Innovate UK, EU, EPSRC and industry.

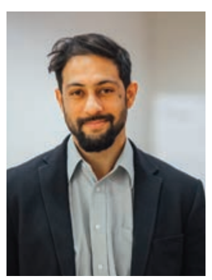
Dr. James Hughes, University of Sheffield, Director of the National Metals Technology Centre (NAMTEC), part of the Advanced Manufacturing Research Centre (AMRC) at the University of Sheffield. He is working closely with Prof. Iain Todd on the development of the powder manufacturing and translational facilities within the Henry Royce Institute.

Dr. Martin Jackson, University of Sheffield, P2 Theme Lead. His research centres on the effect of solid state processes from upstream extraction technologies through to downstream finishing processes on microstructural evolution and mechanical properties in light alloys, in particular titanium alloys. A major research interest is to provide a step change in the economics of titanium based alloys through the development of non-melt consolidation routes such as the FFC Process, FAST-Forge and continuous rotary extrusion. Martin was awarded a RAEng/EPSRC Fellowship in 2005 and the IOM3 Ti Prize in 2003,

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

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

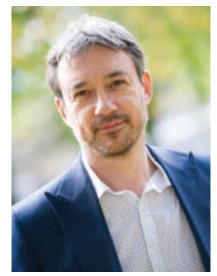
Professor Andrew Mullis, University of Leeds, P1 Theme Lead. His research focuses on advanced materials, particularly with regards to the solidification processing of metals far from equilibrium (rapid solidification). He is a co-investigator on LiME, the EPSRC Future Manufacturing Hub in Liquid Metal Engineering. He is a Fellow of the Institute of Materials, Minerals and Mining.



Dr. Kamran Mumtaz, University of Sheffield. His 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.

Dr. George Panoutsos, University of Sheffield, GC1 Theme Lead. His research is focused on the optimisation of manufacturing processes, systems design using computational intelligence and machine learning, as well as autonomous systems for manufacturing. A particular interest is metals design and processing with applications focusing on 'through-process modelling and optimisation' as well as 'prediction of mechanical properties' and 'real-time process monitoring' using data-driven methodologies.

Professor Philip Prangnell, University of Manchester. 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. Phil 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 Michael Preuss, University of Manchester. His research focuses on microstructure, mechanical properties and residual stresses in high temperature materials - zirconium alloys, titanium alloys and nickel-base superalloys - for application in aerospace, oil and gas and nuclear sectors. Michael is Champion of the Materials for Demanding Environment Theme within The Royce Institute and deputy director of the Nuclear Rolls-Royce University Technology Centre (UTC) at Manchester. He is a Fellow of the Institute of Materials, Minerals and Mining.

Professor Mark Rainforth, University of Sheffield, X2 Theme Lead. His research interests are the high resolution characterisation of microstructures, in particular interfaces and surfaces. His research programmes are broadly based, covering metals, ceramics and coatings. He is leading the development of the Sheffield wing of the Henry Royce Institute and is 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.

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

Professor Philip Withers, University of Manchester, is the Regius Professor of Materials at Manchester and a major international figure in advanced characterisation. He is Chief Scientist at the Henry Royce Institute, Director of the BP International Centre for Advanced Materials (ICAM) and co-directs the Manchester X-ray Imaging Facility (MXIF). Philip is a Fellow of the Royal Society and a Fellow of the Royal Academy of Engineering, he has over 500 publications in the field.

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

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

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

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

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

Professor Javier Llorca,
University of Madrid

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

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

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

Professor Jin Ooi,
University of Edinburgh

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

Professor Barbara Previtali,
Politecnico di Milano, Italy

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

Professor Fabrice Rossignol,
Institute of Research for Ceramics (IRCER), France

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

INDUSTRIAL ADVISORY BOARD (IAB)

Dr. Phil Carroll,
Chair IAB, Chief Executive Officer, LPW Technology

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

Passionate about metal powders and their central importance throughout the AM process, Phil is an advocate of focusing on AM applications from the perspective of the powder. He has overseen the development of LPW's highly-respected applications and R&D team, creating AM metal powder hardware and software systems to control risk in critical manufacturing processes.

Phil has demonstrated what an enterprising individual can accomplish in business, achieving significant sustainable growth and financial performance through a culture of quality, innovation and operational efficiency. His vision and ambition have led LPW to establish a global presence and win numerous awards, including the Queen's Award for Export 2016 and the European Business Awards Ruban d'Honneur for Import/Export 2017.

Dr. Hugh Hamilton,
Johnson Matthey, Scientific Consultant

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

Professor Neil Hopkinson,
Director of 3D Printing, Xaar

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

In 2016 Neil left academia and became Director of 3D Printing at Cambridge based inkjet printhead manufacturer Xaar where he is building a 3D Printing business utilising Xaar's world leading piezo-electric inkjet printing technology across a range of 3D Printing technologies including one of his own inventions, High Speed Sintering.

Marc Saunders,
Director - Global Solutions Centres, Renishaw

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

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

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

The board appraise and advise on the research programme to ensure the link to industry's longer-term challenges and advise on and help support the development and growth of MAPP, including its leadership role within the national research and innovation landscape.

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

Dr. Rob Sharman,
Global Head of Additive Manufacturing, GKN Aerospace

Dr. Sharman is responsible for GKN Aerospace's global research and development, future strategy and direction for additive manufacturing (AM) technologies across airframe and aeroengines, including co-leading GKN's AM cross divisional R&D activities. Rob has worked in the aerospace industry for more than 15 years and is a materials scientist and engineer by training and did a P.h.D. in additive manufacturing of titanium with Rolls-Royce plc. He started his career working as a forensic engineer on air accident investigations and then moved into central UK government (DTI, later BIS) working as an aerospace and defence industry market analyst; responsible for market forecasting for UK government aerospace launch investment projects, including the Airbus A350XWB and Bombardier C-Series. Later he moved into industrial policy writing for UK aerospace, space, and defence sectors. During this time, he was responsible for setting up the UK Composites and Space National industrial strategies and was responsible for EADS, Finmeccania and Thales groups' links and relationships into UK government. He moved to GKN Aerospace as Global Head of Metallics Technology in 2011 and became Global Head of Additive Manufacturing in 2014.

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

Dr. Tsopanos' specialities are Rapid Prototyping & Manufacturing, Selective Laser Melting, Laser Welding, Additive Manufacturing and STL file manipulation.

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

Professor Ken Young,
Chief Technology Officer, Manufacturing Technology Centre

Professor Young did both his BSc in Mechanical Engineering and his PhD in the Mechanical Engineering Department at the University of Nottingham, before spending six years in industry writing CAD based programming systems for industrial systems including robots, machine tools and CMMs. He then spent 20 years at Warwick Manufacturing Group during which time he led their IMRC and the Manufacturing Technologies research group.

In his current role as Technology Director for the Manufacturing Technology Centre, he oversees research in fields as diverse as additive manufacturing, electronics, informatics, simulation, friction welding, advanced fixturing and intelligent automation. The MTC specialises in maturing manufacturing processes from laboratory proof of concept through to being proven at low volume. Since he joined the MTC in 2011 it has grown from two people to more than 500 and has become a £40m turnover business. It has already delivered complete world-leading production facilities into UK factories.

EDUCATION
AND ENGINEERING

Higher Education's role in addressing the additive manufacturing skills gap.

By Dr. Candice Majewski

With all the talk about how additive manufacturing (AM) is going to change the world, it is becoming increasingly important for us all to do our bit to help it reach its full potential.

We are clearly moving in the right direction in terms of research and development, with increasing levels of funding into improving the technical aspects of AM—for example, properties, repeatability and automation—and we are starting to see a lot more evidence of the importance of AM at a strategic/policy level.

Having said that, one area we still need to catch up on is in making sure our workforce has the relevant skills and training. This is clearly an issue that cannot be addressed by a single individual, group or sector; we all have a part to play in making sure the workforce is equipped with relevant and up to date skills.

So, what can Universities do? As AM researchers and educators, how can we use our experience and expertise to support the needs of industry?

We are all aware of the hype and that there are inaccuracies and in some cases, outright untruths, about AM in the public domain. While we cannot fix everything that is wrong on the internet, we do need to do more to tip the balance in favour of facts and substance.

Currently, most people are playing 'catch-up' with AM, and it is crucial that they can easily find accurate and useful information among a mountain of information.

Universities come with an expectation of independence and lack of bias, which also gives us a responsibility to help get the truth out there. We shouldn't be afraid to correct things, whether by responding to articles, writing to editors or simply saying 'yes' more often when asked to comment.

At degree level, it is essential to keep reinforcing the need to be critical when reading about AM. That might be recognizing that a technical-sounding article is actually a cleverly-worded sales pitch, wondering why certain data has not been presented or simply seeking out more information to back-up or disprove what students are reading.

As part of an exercise I run with my undergraduate and masters students, I ask them to discuss a selection of (in my opinion) badly written AM-related articles. I admit it can be fun seeing their irritation levels rise as they discuss the number of errors, misleading comments and lack of any form of factual detail, but it also fulfils a crucial purpose. As a student, it is easy to feel that external people (the 'experts') know more than you, but going through this process reminds them that they really do know more than they realize. Providing a safe space to discuss, debate and form opinions should help give our future graduates the confidence to question what they see when they get out into industry.

The need for an honest and straightforward approach applies just as much to our dissemination activities; as researchers, we are pretty good at presenting the 'best' results of our work, but we tend to forget the things we tried that didn't go so well. Every time a build fails, we learn something. So why are we not sharing these things too and stopping others from making the same mistakes? Equally, a large amount of information is 'common knowledge' if you've been involved in AM for years, but where do you go to find that information if you're just starting out in the industry? Much of this information exists throughout industry, but institutions often find it difficult to share information that might help their competition get ahead.

As University researchers, much of our work is publicly-funded and we are required to disseminate the results. We need to stop giving the impression that everything we try works perfectly first time and start getting really useful extra information out there.

TELLING THE WHOLE STORY

We also need to talk more about the wider context of AM, rather than just the most interesting bits. We are all used to seeing some fancy in-process video or shiny images of the final product, but what our students need to understand are all the stages that led to the end result. It is highly possible that some of my current undergraduate and master's students will be in a position to decide whether and how to use AM in their future company, which means my job is to provide them with the tools to make that decision.

Processes and systems change so rapidly that there is only limited use in covering more than the general process categories and their relative capabilities. Add to that the large number of 'hands-on' courses available through original equipment manufacturers (OEMs) and other organisations, and it quickly becomes clear that we need to be complementing rather than duplicating these activities.

By all means we should be introducing our students to actual AM processes, otherwise it can all be a bit too abstract. All of our engineering undergraduates, at the University of Sheffield, have access to 3D printers in the Diamond, our multidisciplinary engineering building, and 3D printing vending machines have started to pop up in various universities including Virginia Tech and the University of Texas, Austin. Where we can really add value though, is in teaching the principles that underpin AM, rather than focusing too much on specifics.

If we help our students to understand the generic process chain, how it might affect their choices and the other implications of AM, they should be able to adapt to the ever-changing landscape. They need to understand that nesting and orientation of parts will affect both build time and mechanical properties, that supports take time and resources to remove and that this process can lead to a poor surface finish. The point is not to be able to quote numbers and values—anyone can look those up—but to be aware of these issues in the first place.

We need our graduates to look at a mechanical property value and immediately think 'what orientation was that built in?', or when quoted a cost per part to question whether that includes pre- and post-processing. By embedding that sense of inquiry, we end up in a situation whereby it doesn't matter which process or system we are considering, our graduates know what questions to ask in order to reach an appropriate conclusion.

We also need to be sending out people who can clearly articulate the intricacies of AM and how it fits within the overall supply chain. In other words, we want graduates who can explain that there is no single answer to the question 'how long would it take to manufacture that part if I wanted to switch to AM?'. Rather, we need people who can explain to a finance person that yes, the part itself may cost more to produce but that its other benefits—light-weighting, added value through personalisation or a host of other potential considerations— make it the most appropriate and cost-effective method in the long run.

We must also be careful to teach them that AM does not exist in its own little bubble; it is essential that we teach them about traditional manufacturing techniques. How can I understand the benefits and limitations of AM if I don't understand the benefits and limitations of the other processes at my disposal? What we certainly don't want is a generation of graduates who think everything should be produced using AM. By showing how and where AM fits into the broader manufacturing context, we can do much more for its success in the longer-term than if we teach it in isolation.

BROADENING OUR HORIZONS

One other thing to keep in mind is that the first step towards sending out good graduates is to attract good students into relevant disciplines in the first place. While there are a large number of Science, Technology Engineering and Maths (STEM)-specific events across the country, one major thing we are lacking at the moment is follow-up. How do we capitalise on the excitement generated in a single event and maintain that enthusiasm all the way through to degree choices and beyond?

This is where we need to remember the key role of both teachers and parents in influencing the choices of the children in their care. If they don't understand the subject, it can be difficult to engage in conversations about it, and we risk losing the momentum we've started to build up. But if we take the time to inform, enthuse and educate the adults too, they can play a vital role in maintaining that interest.

This should not be all that hard to achieve. All that's really needed is for us to provide the relevant level of accurate information in an easy-to-use format. At its most basic, this might be simple fact sheets including basic information about AM and signposting to other sources of information.

We can take that further, in the form of online activities, games or apps to encourage parents and children to learn together or through lesson plans and case studies to make it easier for teachers to include in the classroom. Involving our degree-level students in these activities can provide an enhanced learning experience, whilst simultaneously helping to attract future cohorts.

Of course, outreach doesn't stop there. In general, we could do much better at getting our work out to a broader audience. There is a danger of becoming so focused on our next big journal publication or conference presentation that we forget the potential impact of a well-placed article in a relevant magazine or adept use of social media. Often this falls way outside of our comfort zone. Working out how to explain something to a non-expert in a way that doesn't make their eyes glaze over can be much more difficult than writing a technical paper, but it is also something we have to do if we are to reach the broader community.

The other researchers working directly in our field are likely to see our publications and presentations anyway, but what about the people in other sectors or disciplines who might also

benefit from AM? Getting our work out there to the wider world should not only increase their understanding of AM but benefit all of us by bringing in an increasingly diverse range of expertise into the community.

MOVING FORWARD

I am happy to say we are already picking up momentum. Increasing numbers of universities are beginning to engage with AM, and we are starting to see more modules and courses in this area. UK National Strategy for Additive Manufacturing/3D printing has a specific working group focused around skills and is currently in the process of mapping current activities against industry needs. The next step will be to 'plug the gaps', which will mean all of us—universities, schools, industry, media and anyone else we can bring in—working together to make it happen. The good news is that the vast majority of us who work in AM research do so because we're passionate and excited about it, and we love it in spite of any of its current flaws. So, while the journey is in many ways just beginning, it should be a fun ride.

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ALIGNED PROJECTS

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

LIVE PROJECTS

MIAMI (Improving the productivity of industrial additive manufacturing)

Funder: University of Sheffield (EPSRC Impact Acceleration Account)

Project costs: £552,732

Funded Value: £200,000

Funding period: July 2017 – March 2020

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

The MIAMI project is focused on improving the productivity of additive manufacturing (AM) via improved monitoring and control to achieve 'right first time' manufacturing and novel approaches to improving the speed of AM.

MIAMI brings in new academic investigators at Sheffield to the MAPP Hub and builds links with new commercial and academic partners including the Future Metrology Hub at Huddersfield.

MIAMI will accelerate the development and translation of new technologies including thermal metrology systems being developed by Dr. Jon Willmott, an EPSRC Manufacturing Fellow in the Department of Electronic and Electrical Engineering, University of Sheffield (UoS) and the Diode Area Melting (DAM) system being developed by Dr. Kamran Mumtaz in the Department of Mechanical Engineering, UoS, and Dr. Kristian Groom from Department of Electronic and Electrical Engineering, UoS

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

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

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

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

COMPLETED PROJECTS

TiPOW (Titanium Powder for Net-shape Component Manufacture)

Funder: Aerospace Technology Institute and Innovate UK

Project costs: £3,129,835

Funded value: £1,555,610

Funding period: March 2015 – February 2018

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

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)

FACTUM

Funder: Innovate UK

Project costs: £1,427,215

Funded value: £725,001

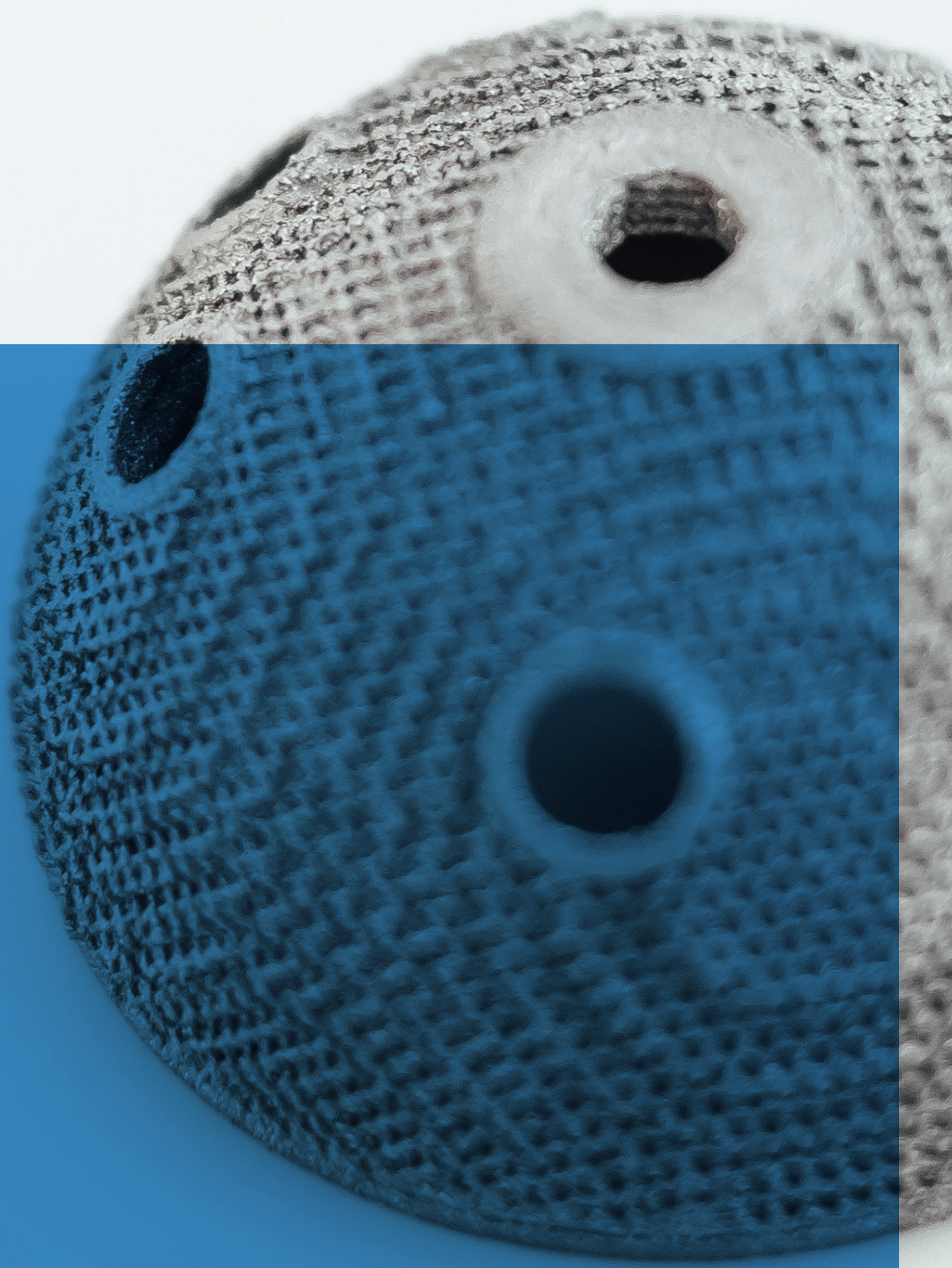
Funding period: November 2013 - October 2016

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

MAPP

Manufacture using Advanced Powder Processes

EPSRC Future Manufacturing Hub



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The University Of Sheffield.

Imperial College London

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