Centre for Additive Manufacturing (CfAM)

Biennial Report

May 2021 – April 2023

SCAN ME

Contents

PhD Student Diego Della Crociata at work in the CfAM lab.

Progress at the Centre for Additive Manufacturing

With the winding down of the coronavirus pandemic, many actors in industry and public life expected a period of recovery, stability and, above all, predictability. In the introduction to our last Biennial Report in 2021, we anticipated that this period of relative calm would be used to decisively address the looming environmental crisis, the effects of which are inching ever closer to everyday life in the United Kingdom. This is reflected in the priorities of our funders at UKRI and EPSRC who have formulated research agendas targeting net zero carbon emissions and more circular ways of organising industrial processes.

With the return of large-scale military conflict to eastern Europe, however, the world has been shaken again in early 2022. These most unwelcome events continue to impact global markets and supply chains and reach into everyday life in the UK. In the manufacturing domain, they have re-emphasised the need for resilient supply chains and adaptable manufacturing systems. In some ways, the war in Ukraine has added momentum to developments already in motion in manufacturing, such as the “reshoring” of manufacturing activities and the adoption of information technology to increase the capability and adaptability of manufacturing processes.

As prominent members of the international Additive Manufacturing (AM) community, we are keenly aware that AM technology will have a pivotal role to play in meeting these challenges. Our track record underlines that CfAM has traditionally placed an emphasis on interlinking complementary strands of research, such as the formulation and selection of highly novel materials, new approaches to material deposition, and digitally enabled design techniques. Given the current global challenges we think that our approach is timelier than ever.

Those who have followed us in the past will recognise our continuing efforts to knit together different aspects of processes, materials, and applications to create radically new research. This is most clearly reflected in CfAM’s long-standing commitment to multimaterial systems that are capable of depositing dissimilar materials in unison.

To bring our research agenda to fruition, we benefit from the continuing support of a thriving global research community. This community features high-calibre industrial and academic collaborators, including AstraZeneca, AWE, BAE systems, GSK, PPG, Texas Instruments, Lawrence Livermore National Laboratory, Karlsruhe Institute of Technology, and our esteemed research partners at the Universities of Birmingham, Oxford, Stanford, and Warwick. Their support has helped us further our research track record and build a reputation of research excellence. It has also allowed us to create additional impact through our dedicated contract research business, Added Scientific Ltd.

In this report we proudly present the latest activities at CfAM in the period May 2021 – April 2023. This includes summaries of our projects, which provide an outlook on our complementary and interacting fields of research. To more fully present our activities we have adopted a format with many scannable and clickable QR codes. We invite readers to use this report to navigate to additional information.

Of course, none of our efforts would be possible without the dedication of the academics, researchers and supporting staff at CfAM. We thank all of them. We also thank our doctoral researchers, who propel the research activities at CfAM forward through their valued and innovative work. We would also like to thank the students on our AM MSc course who will serve as ambassadors of both AM technology and of CfAM once they have graduated. We express our deep gratitude to our funders, particularly EPSRC, and the members of our advisory boards. Without their commitment and support, CfAM would not be the place it is today.

Professor Richard Hague,
Director of CfAM

Additive manufacturing
in a changing world

316L/CuSn10 test specimen created using the Aerosint dual material recoater.

Manufacturing finds itself at a crossroads. Having emerged from the global coronavirus pandemic, the war in Eastern Europe has plunged industry into new political and economic disruption. In this section, we briefly summarize our view on the current situation and the likely impacts on research into AM technology in general and on the activities of CfAM in particular.

A decades-long era of global stability appears to be ending. This order promoted, among other things, the formation of global supply chains, the mass movement of ideas and knowledge, and a general feeling that international cooperation would ensure a reliable, rules-based order of things. As the coronavirus pandemic and the subsequent invasion of Ukraine have shown, this should not be taken for granted. In their search for an adequate response, decisionmakers and politicians in Western countries now appear to pivot towards de-risking, and perhaps also decoupling, longstanding international linkages. It is hard to imagine a sector more affected by these developments than manufacturing.

Apart from these recent global events, it is important to realise that the manufacturing sector is experiencing an underlying long-term transformation towards the use of digital technologies. As many observers have noted, manufacturing has responded more slowly to new digital technologies than other parts of the economy, such as the service sector. The slow rate of adoption of digital technologies is particularly concerning given the considerable investment horizons in manufacturing.

As researchers in this field, we think that sooner, rather than later, there will be increased pressure to develop coherent and general digitalisation strategies, most likely involving novel digital approaches such as artificial intelligence and quantum computing. This will support manufacturing's transition towards more sustainable and adaptable processes.

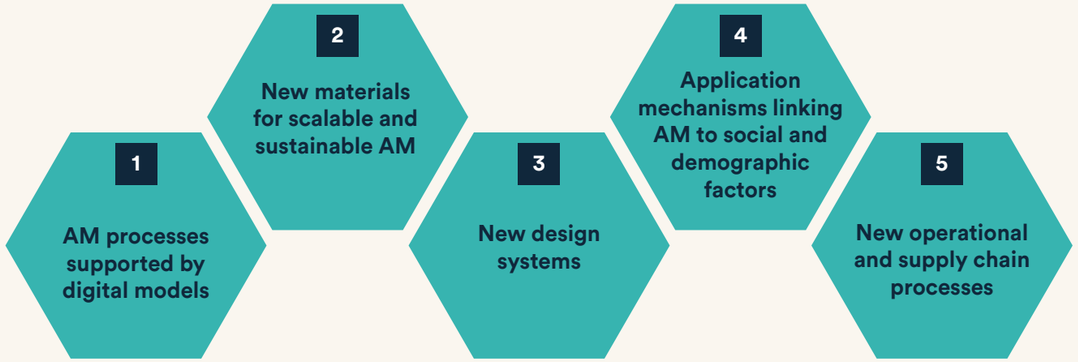
As active members of the global AM research community, we see a pivotal role for AM in producing such change, in turn supporting manufacturing's transition towards more sustainable and adaptable processes.

Specifically, we think that AM has the potential to decarbonise supply chains through the digitalisation of many processes, to enable the introduction of circular lifecycle patterns for many products through its inherent flexibility and openness, and to realise novel and more environmentally benign products through advances in materials and design methods. Moreover, AM's toolless nature means that it is, in principle, a technology ideally suited to more distributed, local manufacturing operations.

As technology observers, we are aware, however, that significant technological obstacles need to be overcome, including robust characterisation of products and materials, standardisation, process stability, data collection and interchangeability, and the availability of supporting operational processes. In combination, these problems point to a need for the AM community to formulate its own digitalisation strategy.

To meet this challenge, local and regional manufacturing businesses, universities, and research and technology organizations (RTOs) must collaborate more closely than ever before. As a leading academic AM research group, we have a special responsibility and must be measured against the impact we have in our own sector. The figure below summarises how the research activities at CfAM relate to significant macroenvironmental factors and shows how our activities propel AM towards creating next generation products with unprecedented levels of functionality and environmental performance.

1. Development of new processes, with an emphasis on multimaterial systems that allow the deposition of multifunctional structures, supported by robust digital models. This will unlock unprecedented degrees of functionality and product efficiency. See, for example, our work towards reactive fusion (p.16).
2. Creating a palette of novel materials suitable for scalable and environmentally benign AM, including the discovery of new organic materials, raw materials for the in-situ creation of high-performance polymers, new metallic alloys for structural and functional use, low-dimensional functional materials for advanced electronics, and innovative glass materials. See, for example, our work towards dialling up materials formulations (p.13).
3. Researching new design systems enabling future adopters to tap into the full potential offered by AM processes. We see a special role for artificial intelligence, for example for the design of customised, next generation lattice structures. See, for example, our work towards adopting AI for the design of novel lattice structures (p.17).
4. Developing new applications for AM to address critical challenges and to respond to social and demographic factors, including an increased focus on regenerative medicine and innovative clinical practice, and the cost-effective provision of complex, personalised medication. See, for example, our work towards next generation rehabilitation technologies (p.14).
5. Establishing new operational and supply chain processes to enable resilient, transparent, and agile AM operations. This includes raw material handling and diversification, inventory strategies, and quality control methods. See, for example, our work towards establishing Overall Equipment Effectiveness (OEE) metrics for AM (p.27).

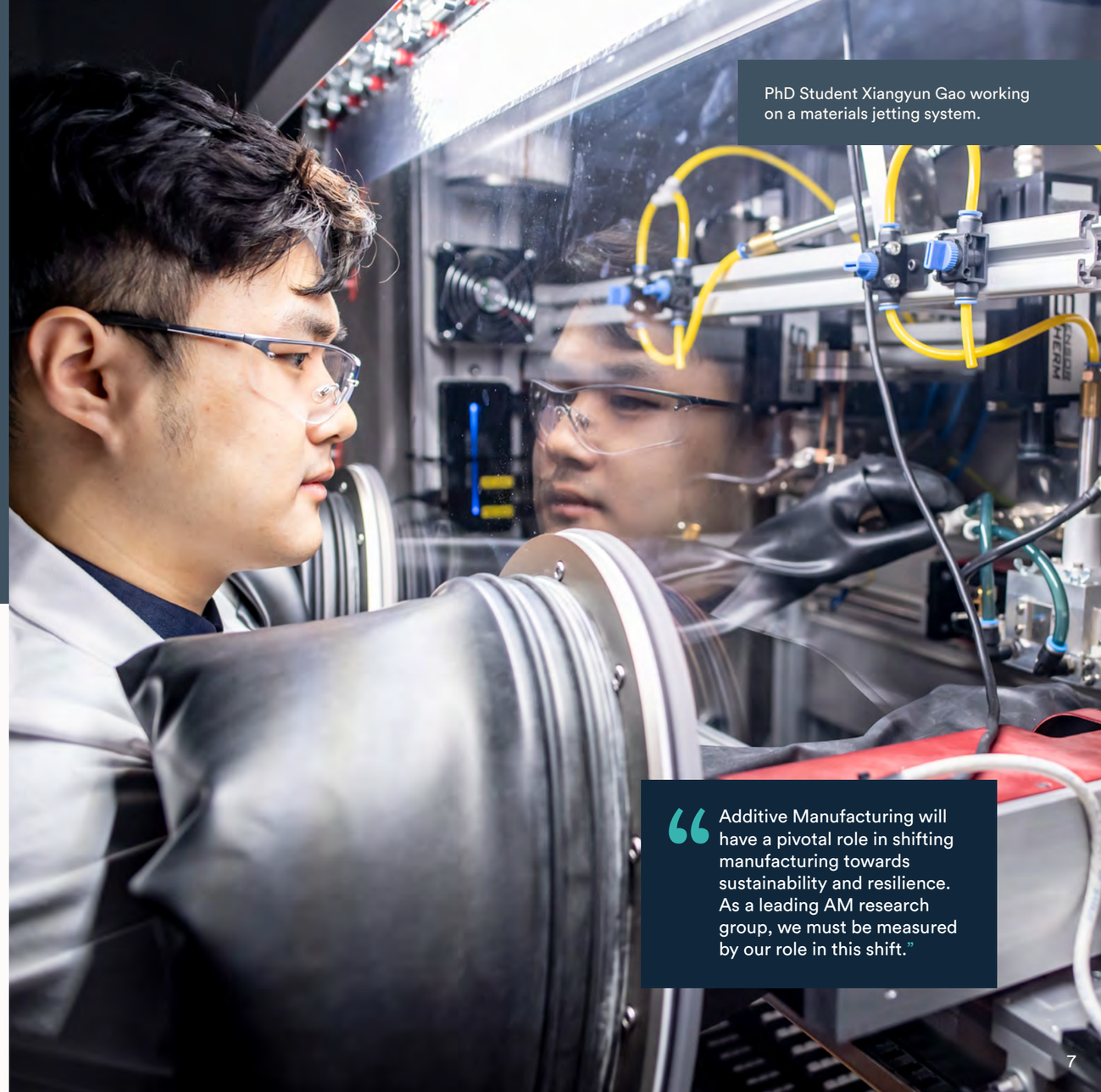


Key research areas at CfAM:

- Development of design systems and software tools for both single material and multifunctional AM
- Generating robust digital models of AM
- Discovering organic materials for scalable processes
- Development of new metallic alloys for structural and functional use
- Reactive jetting of high-performance polymers
- Multimaterial jetting of functionalised nano-particulate inks and dielectric materials
- Drop-on-demand jetting of high-temperature metals
- Micro- and nano-scale multimaterial AM and supporting analysis methods
- Next generation biomaterials
- AM of innovative solid dosage forms for pharmaceutical applications
- AM of low-dimensional functional materials for advanced electronics
- New operations management techniques for AM implementation
- Translating AM innovation into effective clinical solutions
- Production of complex glass structures via AM
- Development of polymer nanocomposites for powder bed fusion technologies

Centre highlights

- Funding success in multiple large grants, including the EPSRC Programme Grant “Dialling up Performance for on Demand Manufacturing” and The EPSRC Network “Next Generation Rehabilitation Technologies”.
- Opened the Additive Biofabrication Laboratory within the Biodiscovery Institute at the University of Nottingham.
- Established an AM laboratory in Clinical Engineering at Queen’s Medical Centre (QMC), in a joint venture with Nottingham University Hospitals NHS Trust.
- Major reconfiguration of our main laboratory in the Advanced Manufacturing Building.
- Successfully resumed the Additive International conference in 2022 in Nottingham with a line-up of world-renowned experts from across industry and academia.
- Welcomed new staff, including Ginny Birney, Dr Negar Gilani, Dr Helena Henke, Keyvan Jodeiri, Dr Sathish Pandiyan, Dr Luke Parry, Flavia Villarroel, Dr Simeng Wang, Dr Leijian Yu, and Dr Atabak Ghanzi Zadeh.
- Contributions to the Royal Society Summer Science Exhibitions in 2021 and 2023, providing an outlook on highly novel applications of AM.



PhD Student Xiangyun Gao working on a materials jetting system.

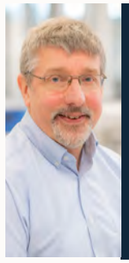
> “Additive Manufacturing will have a pivotal role in shifting manufacturing towards sustainability and resilience. As a leading AM research group, we must be measured by our role in this shift.”

Key individuals **Academics**

Professor Ian Ashcroft
Professor of Mechanics of Solids, Faculty of Engineering, University of Nottingham

Professor Ruth Goodridge
Professor of Additive Manufacturing, Faculty of Engineering, University of Nottingham and Biomedical Engineer, Nottingham University Hospitals NHS Trust

Professor Richard Hague
Professor of Additive Manufacturing, Director of the Centre for Additive Manufacturing, Faculty of Engineering, University of Nottingham



Professor Derek Irvine
Professor of Materials Chemistry, Faculty of Engineering, University of Nottingham

Professor Chris Tuck
Professor of Materials Engineering, Director of the EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing, Faculty of Engineering, University of Nottingham

Professor Ricky Wildman
Professor of Multiphase Flow and Mechanics, Faculty of Engineering, University of Nottingham

Dr Martin Baumers
Associate Professor, Faculty of Engineering, University of Nottingham

Dr Lyudmila Turyanska
Associate Professor, Faculty of Engineering, University of Nottingham

Dr Yinfeng He
Assistant Professor, Seconded to the University of Nottingham in Ningbo, China Professor, Faculty of Engineering, University of Nottingham

Dr Ian Maskery
Assistant Professor, Faculty of Engineering, University of Nottingham

Dr Luke Parry
Assistant Professor, Faculty of Engineering, University of Nottingham

Dr Marco Simonelli
Assistant Professor, Faculty of Engineering, University of Nottingham

Key individuals **Research fellows**

Dr Simon Attwood
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Anil Bastola
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Valentina Cuzzucoli Crucitti
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Aleksandra Foerster
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Negar Gilani
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Helena Henke
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Jisun Im
Research Fellow, Faculty of Engineering, University of Nottingham

Keyvan Jodeiri
Research Associate, Faculty of Engineering, University of Nottingham

Dr Damien Leech
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Anna Lion
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Sathish Pandiyan
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Geoffrey Rivers
Research Fellow, Faculty of Engineering, University of Nottingham

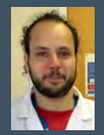
Dr Adja Touré
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Feiran Wang
Research Fellow, Faculty of Engineering and School of Physics and Astronomy, University of Nottingham

Dr Simeng Wang
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Robyn Worsley
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Leijian Yu
Research Fellow, Faculty of Engineering, University of Nottingham



Dr Atabak Ghanzi Zadeh
Research Fellow, School of Life Sciences, University of Nottingham

Dr Peng Zhao
Research Fellow, Faculty of Engineering, University of Nottingham

Key individuals **Support staff**

Mirela Axinte
Centre Manager, EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing, Faculty of Engineering, University of Nottingham

Ginny Birney
Research Network Manager, EPSRC Network in Rehabilitation Technologies, Faculty of Engineering, University of Nottingham

Mark East
Senior Technical Specialist – Additive Manufacturing Research, University of Nottingham

Mark Hardy
Senior Research Technician, Faculty of Engineering, University of Nottingham

Yuan Liu
Centre Administrator, Faculty of Engineering, University of Nottingham

Flavia Villarroel
Programme Manager, EPSRC Programme Grant, Enabling Next Generation Additive Manufacturing, Faculty of Engineering, University of Nottingham

Adam Whitbread
Trainee Technician, Faculty of Engineering, University of Nottingham

Sn honeycomb test specimen created on a Cu substrate using the MetalJet process.

Staff updates since April 2021

We are welcoming the following new members of staff who have joined CfAM:

- Dr Helena Henke, Dr Anna Lion, Dr Simeng Wang and Dr Leijian Yu, who have joined CfAM as Research Fellows
- Ginny Birney, who has joined us as Research Network Manager for the EPSRC Network in Rehabilitation Technologies
- Flavia Villarroel, who has joined us as Research Manager for the Enabling Next Generation Additive Manufacturing Programme Grant

We congratulate the following members of staff who have been successful with a promotion or commenced a permanent academic position:

- Dr Lyudmila Turyanska and Dr Martin Baumers, who have been promoted to Associate Professor
- Dr Ian Maskery and Dr Marco Simonelli, who have commenced their permanent academic positions as Assistant Professors after completing their Nottingham Research Fellowships
- Dr Luke Parry, who has been promoted to Assistant Professor
- Dr Negar Gilani for securing a position as Research Fellow
- Keyvan Jodeiri for securing a position as Research Associate

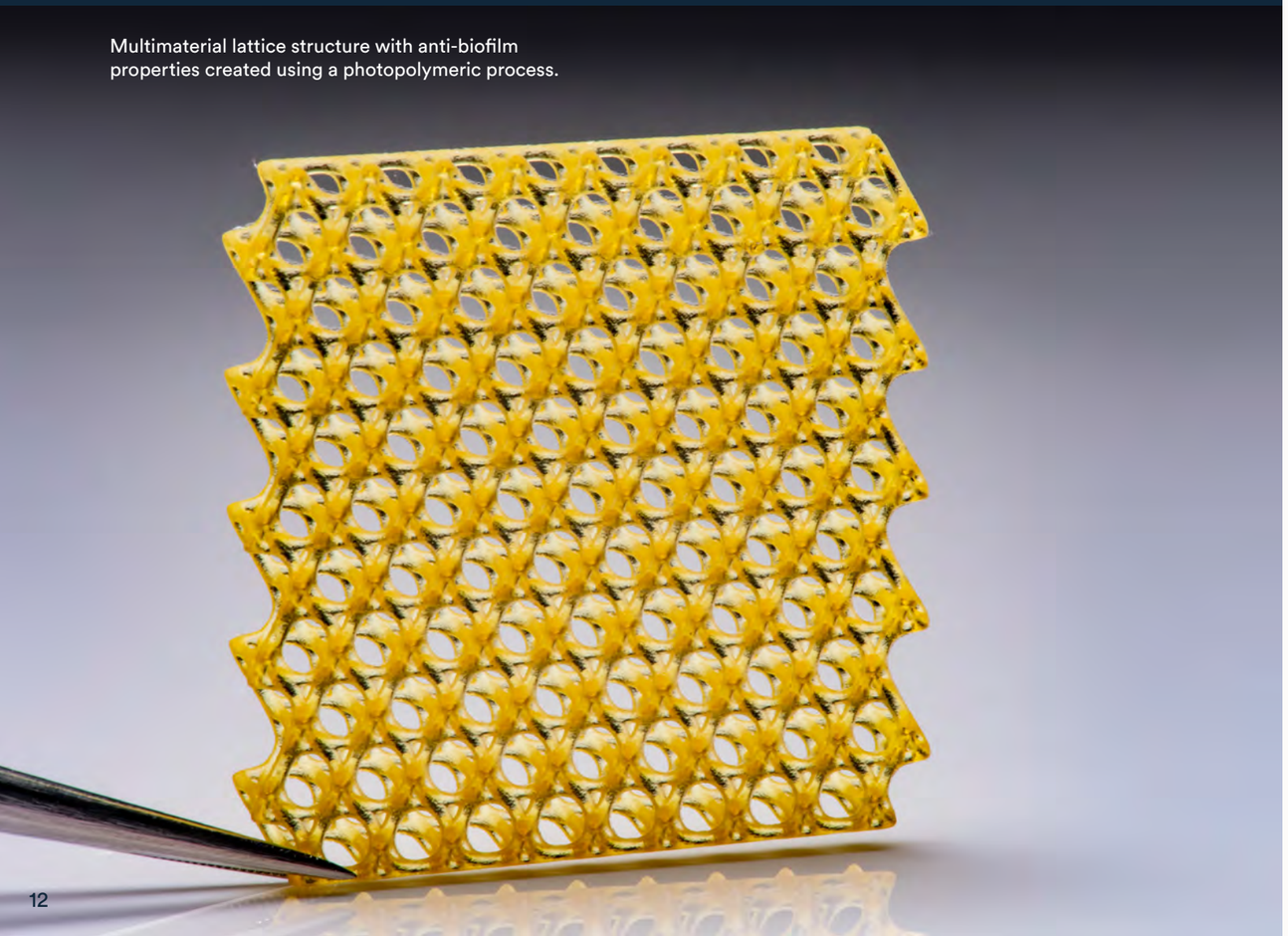
The following members of staff have left CfAM. We thank them for their hard work and wish them all the best for their new positions:

- Dr Laura Ruiz-Cantu, Dr Harinee Selvadurai, Dr Cordula Hege, and Dr Gustavo Ferraz Trindade

Additionally, Dr Yinfeng He has been seconded to the University of Nottingham in Ningbo, China, where he is investigating innovations for AM materials and equipment (funded by the China Beacon Institute).

Ag nano ink structure deposited on a kapton substrate using material jetting.

Research at CfAM



Multimaterial lattice structure with anti-biofilm properties created using a photopolymeric process.

Major grant successes

Dialling up performance for on demand manufacturing – programme grant

Principal investigator: Prof Ricky Wildman

Co-investigators: Prof Felicity Rose (Nottingham), Prof George Malliaras (Cambridge), Prof Clive Roberts (Nottingham), Prof Richard Hague (Nottingham), Dr Anca Pordea (Nottingham), Prof Blair Johnston (Strathclyde), Prof Wayne Hayes (Reading), Prof Róisín M. Owens (Cambridge), Prof Anna Croft (Nottingham), Dr Yinfeng He (Nottingham/Ningbo), Prof Morgan Alexander (Nottingham), Prof Cameron Alexander (Nottingham), Prof Derek Irvine (Nottingham), Prof Alastair Florence (Strathclyde), Prof Ian Ashcroft (Nottingham), Prof Chris Tuck (Nottingham), Dr Lyudmila Turyanska (Nottingham).

This EPSRC-funded programme (EP/W017032/1, started October 2022) has the ambitious goal of realising highly functional, smart products with the potential to transform key UK industries, including (bio)pharma, cell therapy, regenerative medicine, and (bio)catalysis.

Its guiding vision is to create a deployable toolkit and workflow for the rapid formulation of 3D printable materials with automated selection and dial up of bespoke properties. Industry across multiple sectors has identified that whilst it needs personalised/tailored devices, the required materials are not available. Moreover, product development forms an arduous process and the route to market is long. This project will address this challenge by creating a toolkit platform by which industry can deliver, on demand, the materials, and processes necessary for functional products.

Ines Evangelista Barreiros using a pharmaceutical AM system.

The programme grant is executed through four interlinked research challenges (RCs):

- **RC1:** Smart product creation
- **RC2:** Materials development
- **RC3:** Design systems development
- **RC4:** Process integration

For more information, and for a full list of academic and industrial partners, please visit the programme website:

Major grant successes

Next generation rehabilitation technologies – network grant

Principal investigator: Prof Ruth Goodridge

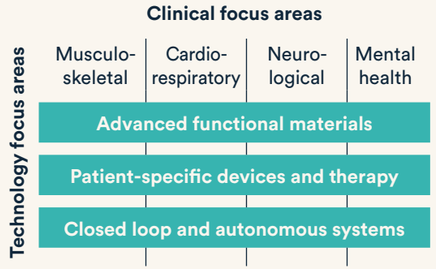
Co-investigators: Prof Mark Lewis (Loughborough), Prof Pip Logan (Nottingham), Dr Ayse Kucukyilmaz (Nottingham).

This EPSRC-funded network (EP/W000679/1, started January 2022) focuses on developing the next generation of advanced technologies for rehabilitation, targeting musculoskeletal, cardiorespiratory, neurological, and mental health conditions. It is connected to the new £70m National Rehabilitation Centre (NRC), a major national investment in patient care, innovation and technology, due to open to patients in 2024.

This multidisciplinary network brings together a range of stakeholders, including academic researchers, technicians, healthcare practitioners, patient representatives, and industry. It consists of a core membership of clinical and technical experts from the rehabilitation field, alongside patient representatives sharing their lived experience of conditions and rehabilitation. The network introduces researchers who are not typically involved in rehabilitation research, but who have potentially transformative technologies and materials, into the rehabilitation technology community.

Following a series of “Grand Challenge Workshops”, the network will fund feasibility research in support of new interdisciplinary collaborations to the value of £400,000.

The following matrix summarises the clinical and technological focus areas of the network:



For more information, and for a full list of academic and industrial partners, please visit the programme website:

Large active research grants

Enabling next generation Additive Manufacturing – programme grant

Principal investigator: Prof Richard Hague

Co-investigators: Dr Lyudmila Turyanska (Nottingham), Prof Derek Irvine (Nottingham), Prof Mark Fromhold (Nottingham), Prof Yulii Shikhmurzaev (Birmingham), Prof Ricky Wildman (Nottingham), Prof James Sprittles (Warwick), Prof Chris Tuck (Nottingham), Prof Clive Roberts (Nottingham), Prof Ian Ashcroft (Nottingham).

In collaboration with the universities of Warwick and Birmingham, as well as with the School of Pharmacy and Physics at Nottingham, CfAM is continuing a deeper exploration in the area of multifunctional AM through this EPSRC-funded Programme Grant (EP/P031684/1).

The programme vision is to establish controlled next generation multifunctional AM and translate this to industry and researchers. Initially focussing on novel electronic and pharmaceutical/healthcare applications, this research has moved beyond single material AM by exploiting the potential to deposit multiple materials contemporaneously for the delivery of spatially resolved function and structure in three dimensions. Owing to potentially radical differences in physical state, chemistry and compatibility, the primary challenge addressed lies at the interface of the deposited materials.

After a highly successful mid-term review, this programme grant is due to end in April 2024.

Ana Gonzalez Abrego using the BMF nanoArch system.

For more information, and for a full list of academic and industrial partners, please visit the programme website:

Project highlights

A biopesticidal lease of life for crop protection: Additive Manufacturing for tailored timing of biopesticide release by natural triggers

Principal investigator: Prof Ricky Wildman

Co-investigators: Prof Cameron Alexander, Prof Simon Avery, Dr Almudena Ortiz-Urquiza, Prof Felicity Rose

The need to meet the increasing demand for food while growing crops more sustainably is a major global challenge. For more sustainable crop production, there is an urgent need to reduce reliance on synthetic chemical pesticides on farms. This project (funded by BBSRC, BB/X005399/1) introduces AM capability to engineer the encapsulation and delivery of biopesticidal fungal spores via concepts similar to those used for 3D printed ‘polypills’ in biomedicine.

Reactive fusion – revolutionary technology for 3D printed polyurethane products

Project team: Dr Ian Halliday, Prof Chris Tuck, Prof Richard Hague, Prof Ricky Wildman, Dr Yinfeng He, Dr Le Ma

This InnovateUK (ICURe) funded project aims to transform polymer AM by using chemistry rather than heat or ultra-violet light to convert powdered and liquid materials into engineering grade polyurethane and polyurea components. These high-performance materials are available all with the design freedoms that AM allows.

AI Synthesis of Structures for AM (ASSAM)

Principal investigator: Dr Ian Maskery

Co-investigators: Dr Luke Parry and Prof Ender Ozcan

This project launches a new field of research combining digital manufacturing and cutting-edge artificial intelligence (AI). It creates an AI design assistant capable of generating 3D manufacturable structures that go beyond current design practices. This is grounded on suitable learning techniques based on deep neural networks, sources of training data, and the manufacturability of AI designs for a range of AM processes. This project seeks to address the question: what can AI learn from nature and apply directly to engineering problems?

316L/CuSn10 test specimen created using the Aerosint dual material recoater.

Doctoral research

CfAM has an extensive portfolio of doctoral research projects, spanning mechanical engineering and materials research to biochemistry and pharmaceutical investigations. Overall, CfAM is currently hosting more than 40 doctorate students.

Over the recent years, the EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing has played a particularly important role in the doctoral research taking place at CfAM. Led by the University of Nottingham in collaboration with the universities of Liverpool, Loughborough, and Newcastle, the CDT recruited its final cohort of students in 2019. The students in this cohort are now finalising their doctoral projects.

Additionally, CfAM has intensified its collaboration with other schools and faculties at The University of Nottingham, (including Pharmacy, Chemistry and Physics) and with industrial partners (including GSK, AstraZeneca, Quotient Sciences, MTC, Siemens, and many others).

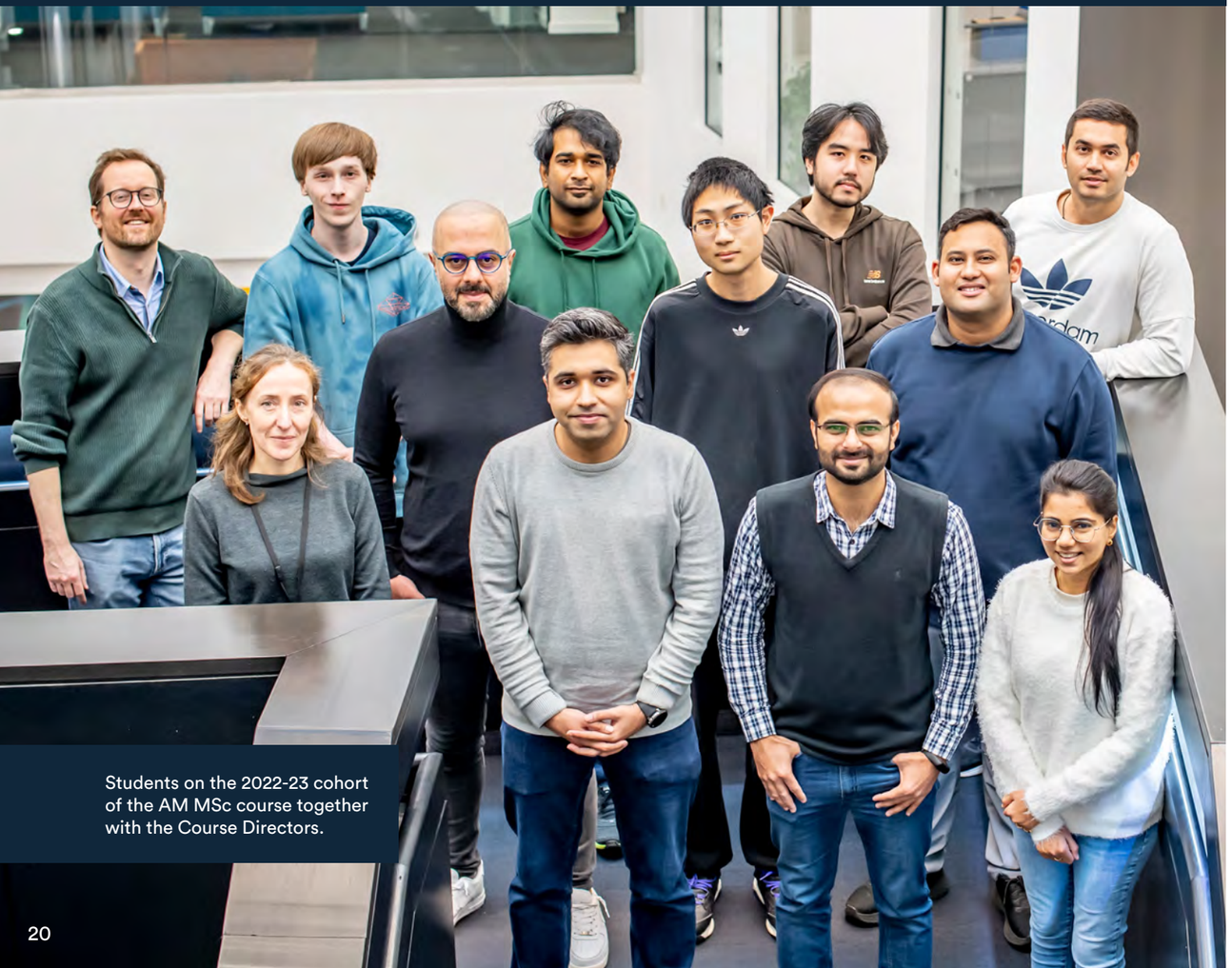
All doctoral students at CfAM benefit from their participation in a comprehensive programme of support activities. These include regular team building events, training sessions, academic seminars, guest lectures and presentations by visiting thought leaders, and sessions with industry specialists, such as recruiters. In a number of cases, CfAM was able to send doctorate students on bespoke additional training programmes in specialist subjects, such as Prince2 project management, and academic writing trainings.

The academics at CfAM are keenly aware that the doctorate students we are training now and have trained in the past are not only essential for our current research activities but will also act as multipliers for our future initiatives. Irrespective of whether they will pursue a career in academia or industry, in the UK or elsewhere, they will be strong and lasting ambassadors of CfAM. We would like to use this opportunity express how much we value them and their contributions.

CfAM students and staff at the June 2022 away day.

PhD Student name	Topic of doctoral project
Ben Sutcliffe	Development of a holographic 3D printing system to produce sustainable cultured meat
Cristina Ferro Barbosa	Design, modelling and biofabrication of osteochondral scaffolds
Jonathan Austin	Additive Manufacturing of 0D/2D heterostructure for optoelectronic devices
Robert Plant	Using stereolithography to construct complex geometries onto non-standard substrates for the purpose of electronics packaging
Mohga Yousif	Investigating TPMS scaffold design using SLA for facial reconstruction
William Pritchard	3D printing proteins for continuous flow biocatalysis and bioabsorption
Yassin Ziar	Modular Additive Manufacturing for next-generation hydrogen storage
Alya Alhammadi	Sustainable feedstock for metal additive manufacturing
Tien Thuy Quach	Novel micro/nano scale characterisation of interfaces in multimaterial Additive Manufacturing
Han Wang	Workflow optimisation to release environmental network effects in AM
Ellie Ward	Targeted near-infrared quantum dots for next generation health diagnostics
Thomas Smith	Enhancing magnetic shielding using the design freedom of Additive Manufacturing
Oliver Nelson-Dummett	3D inkjet printing for electronic materials
Diego Della Crociata	Creating new energy-absorbing structures for automotive applications using Additive Manufacturing of lightweight steels
Charles Heaton	Inkjet deposition of low dimensional materials for flexible healthcare devices
Daniel Padrao	Thermofluid optimisation of AM high heat flux components for fusion
Doa'a Ismail	Felodipine bioavailability enhancement through polymeric-lipid extrusion 3D printing
Binsha Ollekkatt Sivadas	3D printing with 1D functional nanomaterials
Xiao Yuan Wang	Synthesis and continuous manufacture of novel, high performing polymeric lubricants for next-generation electric transportation
Kristian Plender	Implementing 3D printing for the long-term release of biomacromolecules
Bethany Husband	Inkjet printing of polyimide replacement materials
Valeria Gonzalez Abrego	3D printing of complex anatomical features in tissue models through MM- PμSLA
Jordan Hill	Integrating molecular self-assembly with Additive Manufacturing for biomedical applications
Shreeja Basak	The impact of process planning on cost and production losses in Additive Manufacturing
Arielle Torres	Fabrication of polyurethane composites via reactive binder jetting using a dual-ink binding system
Mostafa Mohamed	Development and experimental validation of children's biomimetic adaptive myoprosthetic hand with sensory feedback
Alasdair Bulloch	Design of metal structures of custom composition using Additive Manufacturing

AM MSc course



Students on the 2022-23 cohort of the AM MSc course together with the Course Directors.

The capabilities enabled by AM are opening up a new world of advanced engineering components. Such components include new kinds of lightweight structures for transport applications, novel prosthetic limbs, and complex pharmaceutical products. As the activities outlined in this report show, engineers and scientists are benefitting from the ability to create unprecedented degrees of complexity and are grasping this by developing conceptually new products and transformative manufacturing approaches.

The Additive Manufacturing and 3D Printing MSc programme at the University of Nottingham is available as a bespoke postgraduate taught opportunity for those interested in gaining in-depth knowledge and understanding of Additive Manufacturing and 3D printing technology. As a 12-month course, students are taught by career researchers at CfAM, who are world-leading experts and have access to CfAM's laboratory. Students gain the skills needed to:

- evaluate the application of AM technologies
- apply methods in a project context
- design additively manufactured devices
- undertake individual research projects
- critique, analyse, and communicate research findings

The course is delivered in a one-year, full-time format, starting each September. Entry requirements for this course are a 2:1 undergraduate degree (or international equivalent) in a relevant subject such as engineering, maths, physics, chemistry, pharmacy, design or any science-related discipline. For more information, please visit our website.

Starting with the academic session 2022-2023, the course is led by its new Programme Director Dr Lyudmila Turyanska. We thank the outgoing Programme Director Dr Martin Baumers for leading the course successfully in its first five years and wish the new Programme Director all the best for her tenure.

What our alumni say:

> **"As an international graduate and passionate about 3D printing, I found a life-changing experience in the Additive Manufacturing and 3D Printing MSc course, which is designed by renowned researchers. I can proudly say it has enhanced my personal growth, soft skills and facilitated in-depth knowledge on the techniques currently adopted in industry and current research [...]. In my professional day-by-day life, I use the knowledge I have gained to help customers from the sectors of TV and film production, food processing, AI training, aerospace and defence to adopt and use AM technology in the best possible way for each application."**
>
> Moisés Arturo Clemente Guzman (graduated 2022)

> **"Attending the Additive Manufacturing and 3D Printing master's programme at the University of Nottingham has been one of the best decisions I have ever made. The programme exceeded my academic expectations with a well thought through course structure, up-to-date course material, engaging lectures and tutors, and second-to-none facilities. Perhaps more importantly, the University of Nottingham and the Centre for Additive Manufacturing have cultivated a warm and welcoming environment emphasising personal development, building relationships, and having fun."**
>
> Magnus Kristensen (graduated 2022)

For more information, please visit the AM MSc course website:

Aerosint powder recoating system permitting the selective deposition of two distinct metallic materials.

AM facilities

CfAM's laboratories host a globally unique portfolio of developmental and commercially available AM systems. This is supported by a state-of-the-art suite of analytical devices in a dedicated materials characterisation laboratory. Together, our laboratories form a vital tool for establishing new avenues of academic and industrially focused research.

Among our large portfolio of research and commercially deployed AM systems, CfAM's main laboratory in the Advanced Manufacturing Building on Jubilee Campus boasts specialist and bespoke systems that are not available elsewhere. These include experimental multimaterial 3D ink jetting systems, ranging from small exploratory research platforms to large systems such as our PiXDRO Toucan and Notion jetting systems, high-temperature liquid metal jetting systems (MetalJet), and custom-built multimaterial high-resolution AM systems. We are also proud to have recently installed the Aconity metallic powder bed fusion system, which is an open architecture system permitting the processing of multiple metals in a single powder bed process.

This is complemented by our clean room facility (supported by the Wolfson Foundation) which provides a setting in which processes are shielded from environmental pollutants and light sources. This environment considerably widens the palette of materials for 3D inkjet and extrusion printing platforms and is used primarily for pharmaceutical, biological, and electronics-oriented research. It is equipped with a comprehensive suite of 3D ink jetting and analysis equipment, alongside pharmaceutically focused material extrusion systems.

Recent developments include:

- Installation of the Aconity metallic powder bed fusion system in conjunction with the Aerosint powder deposition system (pictured on page 22)
- Installation of the Notion/ Xaar jetting platform
- We congratulate our Trainee Technician Adam Whitbread to passing his NVQs in Engineering in September 2022
- We have now made our laboratories available in a virtual lab tour which you can visit here:

The new Additive Biofabrication Laboratory.

Additive Biofabrication Laboratory

The Additive Biofabrication Laboratory located within the Biodiscovery Institute is a joint venture between the School of Pharmacy and the Faculty of Engineering at the University of Nottingham. Additive biofabrication is the use of 3D printing technologies to create structures that can direct the behaviour of biological systems. This facility is unrivalled in the UK in its consolidation of the latest technologies and boasts a plethora of bioprinting equipment, including a unique portfolio of the latest light-based biofabrication technologies for high-resolution AM for healthcare applications, all of which are housed within a dedicated cell culture suite where live biological materials can be used.

Technologies available span from small scale exploratory systems to develop new materials to cutting edge commercial equipment and bespoke systems built in-house. They include multiphoton lithography/ two-photon polymerisation (MPL/2PP), projection microstereolithography (pμSLA) and computed axial lithography/volumetric additive manufacturing (CAL/ VAM). With these, cell scale (10s microns) to sub-cell scale (<1 micron) resolutions can be achieved at the high fabrication rates needed for live cell printing. By housing this equipment within biological safety cabinets, cell-laden bioprints can be manufactured in a sterile environment in a clinically relevant manner.

AM laboratory in Clinical Engineering

In 2022, we established a new AM laboratory at Queens Medical Centre (QMC), in a joint venture with the Clinical Engineering department at Nottingham University Hospitals NHS Trust (NUH). The lab, which includes HP Multijet Fusion 580, Ultimaker S7, and Formlabs Form3B systems, provides a central facility for NUH staff who would like to explore the use of AM in clinical applications. This venture is designed to aid translation of research from CfAM and the wider AM community into hospitals, identifying current opportunities and future research needs. For further information, please contact Prof Ruth Goodridge.

Detail of a nylon test specimen created via the Jet Fusion process.

Engaging the public

Outreach events

- Success in the Ingenuity Programme with two projects being selected as finalists (“Improve Health” and “Build Community”)
- Participation in the 2021 Women in Engineering Day by Masoomeh Bazzar and Salomé Sanchez
- Participation in the Annual Engineering Research Showcase in the Pitch Perfect, Poster and Three Minute Thesis competitions
- Winner of the Tri-Campus Awards in the Covid-19 Impact category
- Media interviews on 3D-printed personalised pills at BBC Radio 4, BBC Radio Nottingham and Aljazeera English TV by Dr Laura Ruiz Cantu, Dr Yinfeng He and Prof Ricky Wildman
- Continued school outreach activity at Woodthorpe School
- Participation in the Real Science in Schools Symposium as part of the Nottingham Festival of Science and Curiosity (FOSAC)
- Contributions to the IntoUniversity Mentoring Celebration programme
- Supporting the Three Minute Wonders 2022 initiative – East Midlands Branch
- Mentoring role in the Able Orchestra Project, which won Project of the Year at the Final Showcase

Royal Society Summer Science Exhibition

We were honoured to be able to present our research at the Royal Society’s prestigious Summer Science Exhibition in July 2021, which was run as a digital event. We are delighted to again present our research at the Royal Society Summer Science Exhibition in 2023

Our contribution in the form of online lectures, video clips, and interactive content demonstrated the use of AM technology to print personalised ‘polypills’. Polypills can be particularly helpful, for example, for the very young or the elderly who find it difficult to swallow pills, which is often made worse by having to take many different medications. The polypill can be loaded with several different medications and can be personalised to deliver a patient-specific combination of medication at just the right dose depending on the patient’s weight, sex, ethnicity and genetic factors etc. 3D printing of polypills can also enable the local manufacture of medication at community pharmacies, so revolutionising the supply chain and could be especially useful, for example, in war zones and low income countries where transport links can be limited.

Future scalability of AM event

Academic and industry-focused workshop held on 10 November 2022.

CfAM was delighted to host an agenda-building workshop focussing on the operations management of AM technology. Co-hosted by Dr Martin Baumers and Shreeja Basak from the University of Nottingham and Prof Matthias Holweg from the University of Oxford, this workshop was attended by a range of industrial and academic stakeholders.

The workshop investigated the role of the operations managers in the context of AM technology, the possibility of Lean approaches, and whether production losses represent a barrier to the adoption of AM technology. Moreover, data-driven methods and metrics to improve AM operations were evaluated.

For more information, please see the article here:

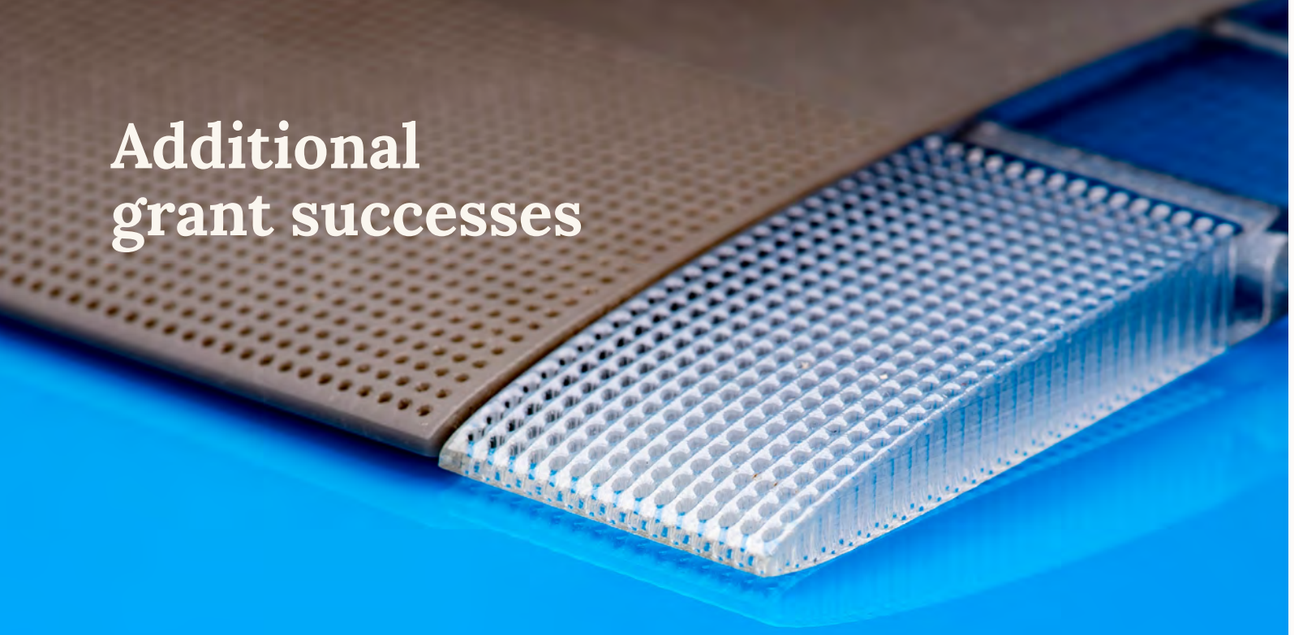
Selected publication highlights

Kong, L., et al.	2023	A Spacer Cation Assisted Nucleation and Growth Strategy Enables Efficient and High-Luminance Quasi-2D Perovskite LEDs	Advanced Functional Materials
Vassey, M., et al.	2023	Innate immune cell instruction using micron-scale 3D objects of varied architecture and polymer chemistry: The ChemoArchiChip	Matter
Gosling, J.H., et al.	2023	Graphene FETs with high and low mobilities have universal temperature-dependent properties	Nanotechnology
Goodridge, R.D., et al.	2023	Adding functionality to powder bed fusion materials: Creating magnetic polymers using hybridized hollow carbon nanofibres	Additive Manufacturing
Zhang, C., et al.	2023	Highly Controlled Zigzag Perovskite Nanocrystals Enabled by Dipole-Induced Self-Assembly of Nanocubes for Low-Threshold Amplified Spontaneous Emission and Lasing	Advanced Functional Materials
Chen, M., et al.	2023	A quantitative study of thermal cycling along the build direction of Ti-6Al-4V produced by laser powder bed fusion	Materials and Design
Spirrett, F., et al.	2023	Powder-fed directed energy deposition of soda lime silica glass on glass substrates	Journal of the American Ceramic Society
Cottam, N.D., et al.	2023	Magnetic and Electric Field Dependent Charge Transfer in Perovskite/Graphene Field Effect Transistors	Advanced Electronic Materials
Del Guercio, G., et al.	2023	Increasing the build rate of high-strength aluminium alloys produced by laser powder bed fusion	Optics and Laser Technology
Préve, D., et al.	2023	A comprehensive characterization of fracture in unit cell open foams generated from Triply Periodic Minimal Surfaces	Engineering Fracture Mechanics
Fan, M., et al.	2023	Efficient All-Perovskite White Light-Emitting Diodes Made of In Situ Grown Perovskite-Mesoporous Silica Nanocomposites	Advanced Functional Materials
Im, J., et al.	2023	Strategies for Integrating Metal Nanoparticles with Two-Photon Polymerization Process: Toward High Resolution Functional Additive Manufacturing	Advanced Functional Materials
Cuzzucoli Crucitti, V., et al.	2023	Predictive Molecular Design and Structure-Property Validation of Novel Terpene-Based, Sustainably Sourced Bacterial Biofilm-Resistant Materials	Biomacromolecules
Reyes-Luna, J.F., et al.	2023	A surrogate modelling strategy to improve the surface morphology quality of inkjet printing applications	Journal of Manufacturing Processes
Du, X., et al.	2023	Facile manipulation of mechanical properties of Ti-6Al-4V through composition tailoring in laser powder bed fusion	Journal of Alloys and Compounds
Bastola, A.K., et al.	2023	Magnetorheological brushes – Scarcely explored class of magnetic material	Journal of Magnetism and Magnetic Materials
Wang, K., et al.	2023	Ring opening polymerisation of ε-caprolactone with novel microwave magnetic heating and cyto-compatible catalyst	Frontiers in Bioengineering and Biotechnology
Rivers, G., et al.	2023	Stable large area drop-on-demand deposition of a conductive polymer ink for 3D-printed electronics, enabled by bio-renewable co-solvents	Additive Manufacturing
Del Guercio, G., et al.	2022	Cracking behaviour of high-strength AA2024 aluminium alloy produced by Laser Powder Bed Fusion	Additive Manufacturing
Kong, L., et al.	2022	Light-emitting field-effect transistors with EQE over 20% enabled by a dielectric-quantum dots-dielectric sandwich structure	Science Bulletin
Hu, Q., et al.	2022	The influence of printing parameters on multi-material two-photon polymerisation based micro additive manufacturing	Additive Manufacturing
Maskery, I., et al.	2022	FLatt Pack: A research-focussed lattice design program	Additive Manufacturing
Groth, J.-H., et al.	2022	Five simple tools for stochastic lattice creation	Additive Manufacturing
Zhuo, P., et al.	2022	Continuous fibre composite 3D printing with pultruded carbon/PA6 commingled fibres: Processing and mechanical properties	Composites Science and Technology
Gilani, N., et al.	2022	From impact to solidification in drop-on-demand metal additive manufacturing using MetalJet	Additive Manufacturing
Im, J., et al.	2022	Functionalised Gold Nanoparticles with a Cohesion Enhancer for Robust Flexible Electrodes	ACS Applied Nano Materials
Dewi, S.R., et al.	2022	Investigating the role of solvent type and microwave selective heating on the extraction of phenolic compounds from cacao (Theobroma cacao L.) pod husk	Food and Bioproducts Processing
Chen, M., et al.	2022	Microstructural engineering of a dual-phase Ti-Al-V-Fe alloy via in situ alloying during laser powder bed fusion	Additive Manufacturing
Hill, J., et al.	2022	Exploiting the fundamentals of biological organization for the advancement of biofabrication	Current Opinion in Biotechnology
Malas, A., et al.	2022	Reactive Jetting of High Viscosity Nanocomposites for Dielectric Elastomer Actuation	Advanced Materials Technologies
Speidel, A., et al.	2022	The interaction of volatile metal coatings during the laser powder bed fusion of copper	Journal of Materials Processing Technology
Speidel, A., et al.	2022	Chemical recovery of spent copper powder in laser powder bed fusion	Additive Manufacturing
Sanjuan-Alberte, P., et al.	2022	Printing biohybrid materials for bioelectronic cardio-3D-cellular constructs	iScience
Dubrovka, R., et al.	2022	Additive Manufacturing of a Terahertz Back-to-Back Horn Antenna for Use in Life Sciences	IEEE Transactions on Components, Packaging and Manufacturing Technology
Abuzaid, H., et al.	2022	Apoferritin-Encapsulated Jerantinine A for Transferrin Receptor Targeting and Enhanced Selectivity in Breast Cancer Therapy	ACS Omega
Dundas, A.A., et al.	2022	A new particle mounting method for surface analysis	Surface and Interface Analysis
Qian, Q., et al.	2022	3D reactive inkjet printing of bisphenol A-polycarbonate	Additive Manufacturing
Basak, S., et al.	2022	Reducing production losses in additive manufacturing using overall equipment effectiveness	Additive Manufacturing
Alvarez, E., et al.	2022	Electrochemical Oscillatory Baffled Reactors Fabricated with Additive Manufacturing for Efficient Continuous-Flow Oxidations	ACS Sustainable Chemistry and Engineering
Kuruppu, A.I., et al.	2022	Apoferritin and Dps as drug delivery vehicles: Some selected examples in oncology	Biochimica et Biophysica Acta - General Subjects
He, Y., et al.	2022	Ink-jet 3D printing as a strategy for developing bespoke non-eluting biofilm resistant medical devices	Biomaterials

Alruqi, M., et al.	2022	The Challenge of Deploying Failure Modes and Effects Analysis in Complex System Applications—Quantification and Analysis	Sustainability (Switzerland)
Bai, B., et al.	2022	Atomically flat semiconductor nanoplatelets for light-emitting applications	Chemical Society Reviews
Monaghan, O.R., et al.	2022	A self-crosslinking monomer, α-pinene methacrylate: understanding and exploiting hydrogen abstraction	Polymer Chemistry
Larder, R.R., et al.	2022	Antimicrobial 'inks' for 3D printing: block copolymer-silver nanoparticle composites synthesised using supercritical CO2	Polymer Chemistry
Goodwin, S.R., et al.	2022	Facile Synthesis of Functionalised Hyperbranched Polymers for Application as Novel, Low Viscosity Lubricant Formulation Components	Polymers
Groth, J.-H., et al.	2022	Stochastic design for additive manufacture of true biomimetic populations	Additive Manufacturing
Elsmore, M.T., et al.	2022	Sustainable terpene triblock copolymers with tuneable properties for pressure sensitive adhesive applications	Polymer Testing
Atkinson, R.L., et al.	2022	Sustainable ABA triblock methacrylate copolymers incorporating both high and low Tg terpene-derived monomers	European Polymer Journal
Marsh, G.E., et al.	2022	Utilising micron scale 3D printed morphologies for particle adhesion reduction	Powder Technology
Austin, J.S., et al.	2022	Photosensitisation of inkjet printed graphene with stable all-inorganic perovskite nanocrystals	Nanoscale
Berumen, G., et al.	2022	Data as a Resource for Designing Digitally Enhanced Consumer Packaged Goods	Multimodal Technologies and Interaction
Wang, H., et al.	2022	The impact of the risk of build failure on energy consumption in additive manufacturing	Journal of Industrial Ecology
Baumers, M., and Dominy, J.	2022	Practical management for the digital age: An introduction for engineers, scientists, and other disciplines	
Sanchez, S., et al.	2022	On the thermomechanical aging of LPBF alloy 718	Materials Science and Engineering A
Jodeiri, K., et al.	2022	Additively Manufactured 3D Micro-bioelectrodes for Enhanced Bioelectrocatalytic Operation	ACS Applied Materials and Interfaces
Birchall, L., et al.	2022	An inkjet-printable fluorescent thermal sensor based on CdSe/ZnS quantum dots immobilised in a silicone matrix	Sensors and Actuators A: Physical
Harvey, H.J., et al.	2022	Application of microfluidic systems in modelling impacts of environmental structure on stress-sensing by individual microbial cells	Computational and Structural Biotechnology Journal
Latif, A., et al.	2022	Microparticles Decorated with Cell-Instructive Surface Chemistries Actively Promote Wound Healing	Advanced Materials
Contreras, J., et al.	2022	Developing Echogenic Materials as Catheters for Use with Ultrasound	ACS Biomaterials Science and Engineering
Sanchez, S., et al.	2021	Powder Bed Fusion of nickel-based superalloys: A review	International Journal of Machine Tools and Manufacture
Zhang, C., et al.	2021	Core/Shell Metal Halide Perovskite Nanocrystals for Optoelectronic Applications	Advanced Functional Materials
Gosling, J.H., et al.	2021	Universal mobility characteristics of graphene originating from charge scattering by ionised impurities	Communications Physics

Sanchez, S., et al.	2021	The creep behaviour of nickel alloy 718 manufactured by laser powder bed fusion	Materials and Design
Pu, J., et al.	2021	Understanding mechanical properties in fused filament fabrication of polyether ether ketone	Additive Manufacturing
Gargalis, L., et al.	2021	Determining processing behaviour of pure Cu in laser powder bed fusion using direct micro-calorimetry	Journal of Materials Processing Technology
Ding, J., et al.	2021	The economics of additive manufacturing: Towards a general cost model including process failure	International Journal of Production Economics
Robinson, A.J., et al.	2021	Toward Hijacking Bioelectricity in Cancer to Develop New Bioelectronic Medicine	Advanced Therapeutics
Alogla, A.A., et al.	2021	The impact of additive manufacturing on the flexibility of a manufacturing supply chain	Applied Sciences (Switzerland)
Sanchez, S., et al.	2021	Multi-laser scan strategies for enhancing creep performance in LPBF	Additive Manufacturing
Cooper, N., et al.	2021	Additively manufactured ultra-high vacuum chamber for portable quantum technologies	Additive Manufacturing
Jain, A., et al.	2021	Modulating the biological function of protein by tailoring the adsorption orientation on nanoparticles	Journal of Colloid and Interface Science
Gilani, N., et al.	2021	Insights into drop-on-demand metal additive manufacturing through an integrated experimental and computational study	Additive Manufacturing
Trindade, G.F., et al.	2021	Residual polymer stabiliser causes anisotropic electrical conductivity during inkjet printing of metal nanoparticles	Communications Materials
Lion, A., et al.	2021	Customisable tablet printing: The development of multimaterial hot melt inkjet 3D printing to produce complex and personalised dosage forms	Pharmaceutics
Datsiou, K.C., et al.	2021	Laser powder bed fusion of soda lime silica glass: Optimisation of processing parameters and evaluation of part properties	Additive Manufacturing
Bhuwal, A.S., et al.	2021	Localization and coalescence of imperfect planar FCC truss lattice metamaterials under multiaxial loadings	Mechanics of Materials
Foerster, A., et al.	2021	UV-curable silicone materials with tuneable mechanical properties for 3D printing	Materials and Design
Cuzzucoli Crucitti, V., et al.	2021	Generation and Characterization of a Library of Novel Biologically Active Functional Surfactants (Surfmers) Using Combined High-Throughput Methods	ACS Applied Materials and Interfaces
He, Y., et al.	2021	Exploiting Generative Design for 3D Printing of Bacterial Biofilm Resistant Composite Devices	Advanced Science
Alruqi, M., et al.	2021	A Structured Approach for Synchronising the Applications of Failure Mode and Effects Analysis	Management Systems in Production Engineering
Ashcroft, I.A., and Mubashar, A.	2021	Fatigue	Adhesive Bonding: Science, Technology and Applications
Ruiz-Cantu, L., et al.	2021	Bespoke 3D-Printed Polydrug Implants Created via Microstructural Control of Oligomers	ACS Applied Materials and Interfaces
He, Y., et al.	2021	Inkjet 3dprinting of polymers resistant to fungal attachment	Bio-protocol
Alogla, A., et al.	2021	Analysis of the effects of operator experience and learning in laser sintering	International Journal of Mechatronics and Manufacturing Systems

Additional grant successes



Advanced multimaterial wing structure created with AM.

Title	Sponsor	Principal Investigator	Budget
Dialling Up Performance for On Demand Manufacturing	EPSRC	Ricky Wildman	£5,865,536
Enabling Next Generation Additive Manufacturing	EPSRC	Richard Hague	£5,852,466
Dial-up Engineered Microstructures for Advanced Additively Manufactured Metals (DEMAMM)	EPSRC	Chris Tuck	£1,809,056
Future Additive Manufacturing Platform Grant	EPSRC	Richard Hague	£1,733,623
Next Generation Rehabilitation Technologies	EPSRC	Ruth Goodridge	£831,040
Intelligent Structures for Low Noise Environments	EPSRC	Chris Tuck	£715,093
AIM3: Additive and intelligent manufacturing of multi-functional membranes	EPSRC	Ricky Wildman	£711,336
Metal Jetting of Functionally Graded Materials	AWE	Richard Hague	£618,848
Accelerated Discovery and Development of New Medicines: Prosperity Partnership for a Healthier Nation	EPRSC	Ricky Wildman	£563,445
Quiet aerofoil with adaptive porous surfaces (QUADPORS)	EPSRC	Chris Tuck	£531,142
Silicone Jetting Micro-SLA	AWE	Chris Tuck	£356,477
IDR-Engineering sustainable squalene analogs for novel		Derek Irvine	£327,390
Next Generation Biomaterials Discovery	EPSRC	Ricky Wildman	£257,328
Savi: NSF-EPSRC A Transatlantic Institute for Volumetric Powder Bed Fusion	EPSRC	Chris Tuck	£254,070
Development and exploitation of a bioactives-free technology for tackling fungal threats to food security, goods and health	BBSRC	Derek Irvine	£224,976
AI Synthesis of Structures for Additive Manufacturing	EPSRC	Ian Maskery	£202,419
AM and 3DP in Clinical Practice		Ruth Goodridge	£158,815
A biopesticidal lease of life for crop protection : additive manufacturing for tailored timing of biopesticide release by natural triggers	BBSRC	Ricky Wildman	£129,319
Quantum bio-sensing for next generation health diagnostics		Lyudmila Turyanska	£114,725
Low-cost Titanium for Combat Protective Equipment via Laser-Powder Bed Fusion	U.S. Army Research Office	Marco Simonelli	£75,000
Second line materials for reactive jetting	IAA	Ricky Wildman	£56,265
Polymerisation method development for the manufacturing of novel, high-performance, compostable and recyclable hetero-aromatic bioplastics for the packaging industry (BioPolyMet)	IUK	Derek Irvine	£35,700
Accelerated commercialisation of the Nottingham reactive 3D printing process	IAA	Yinfeng He	£24,868

Funders, partners and collaborators

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3D LifePrints UK Ltd
Airforce Office of Scientific Research
Arkema
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Arthritis Research UK Tissue Engineering Centre
AstraZeneca
AWE
BBSRC
BMF
BMW
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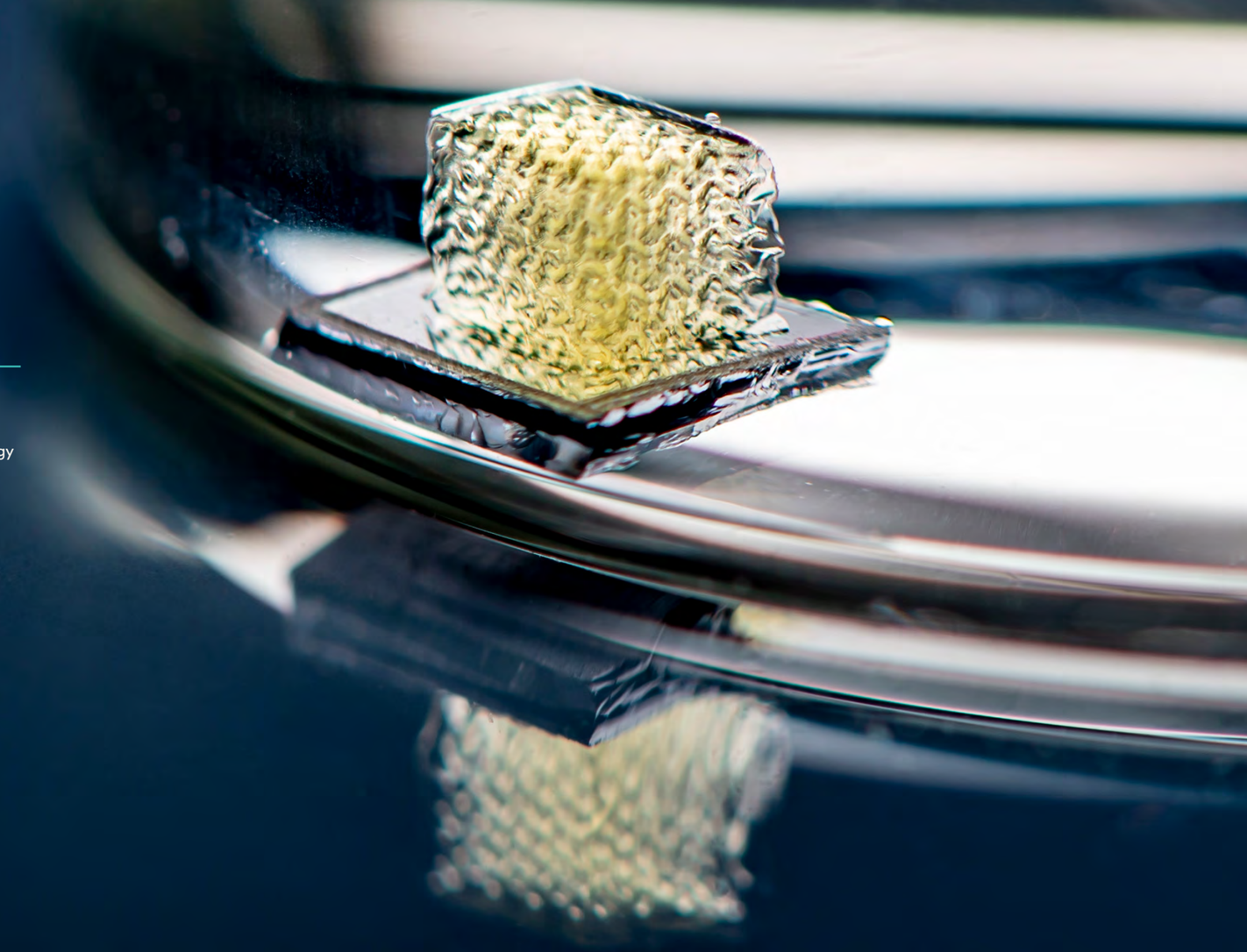

Biofunctionalised gyroid test specimen made via photopolymeric AM.

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Engineering and Physical Sciences Research Council

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