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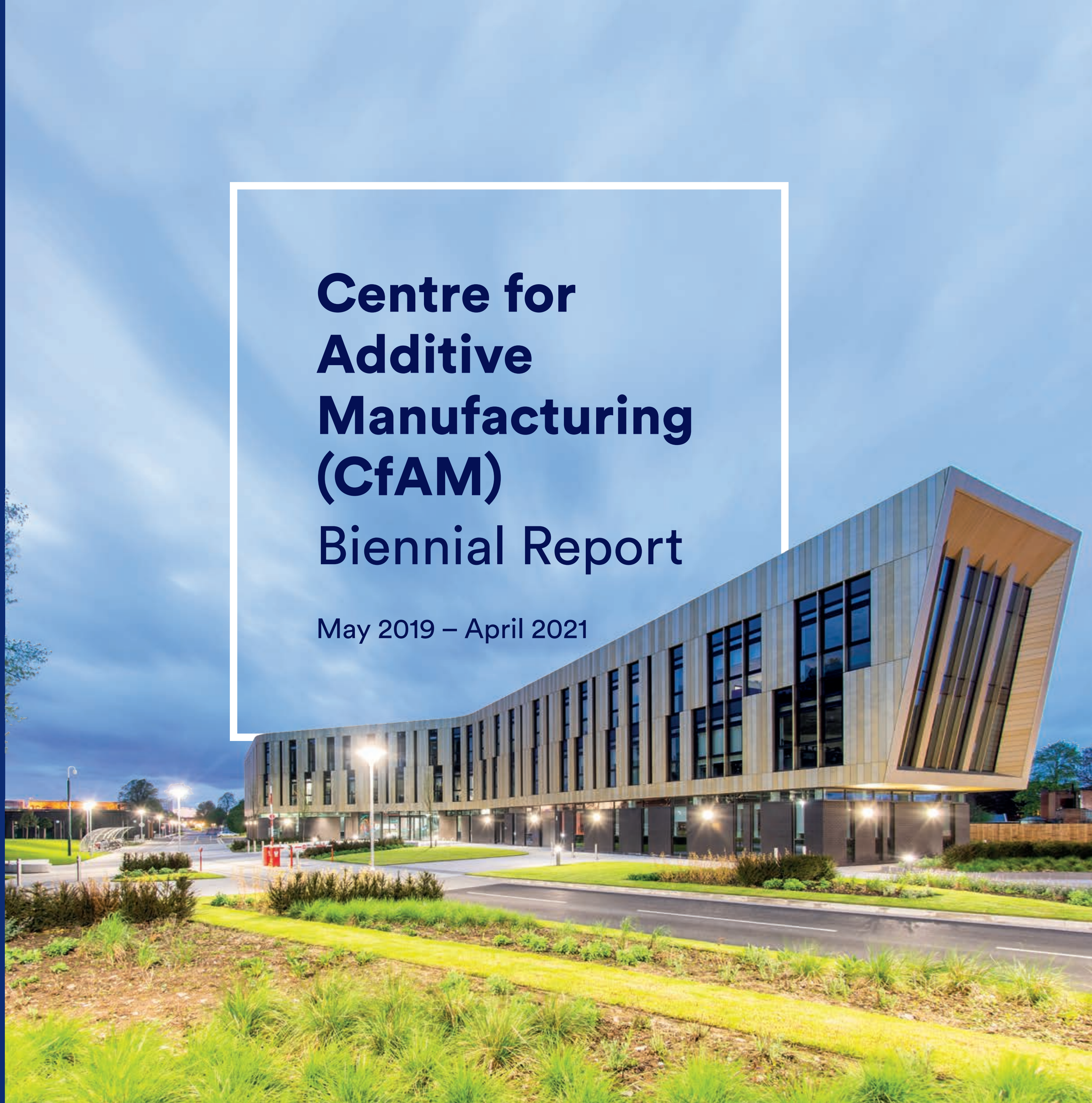
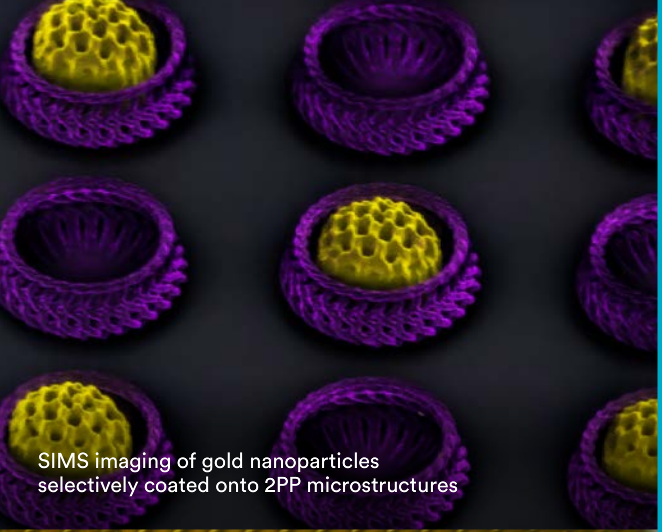


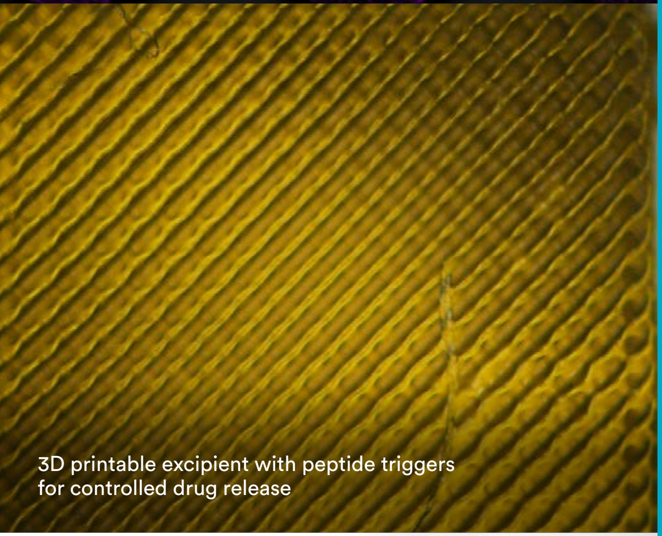
Centre for Additive Manufacturing (CfAM)

Biennial Report

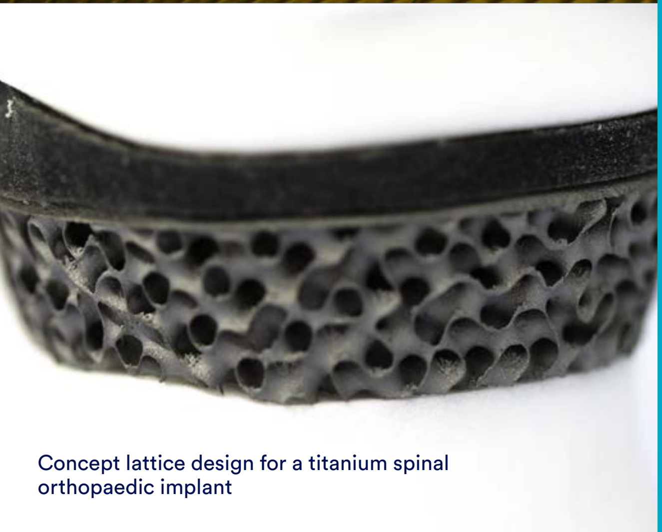
May 2019 – April 2021



SIMS imaging of gold nanoparticles selectively coated onto 2PP microstructures



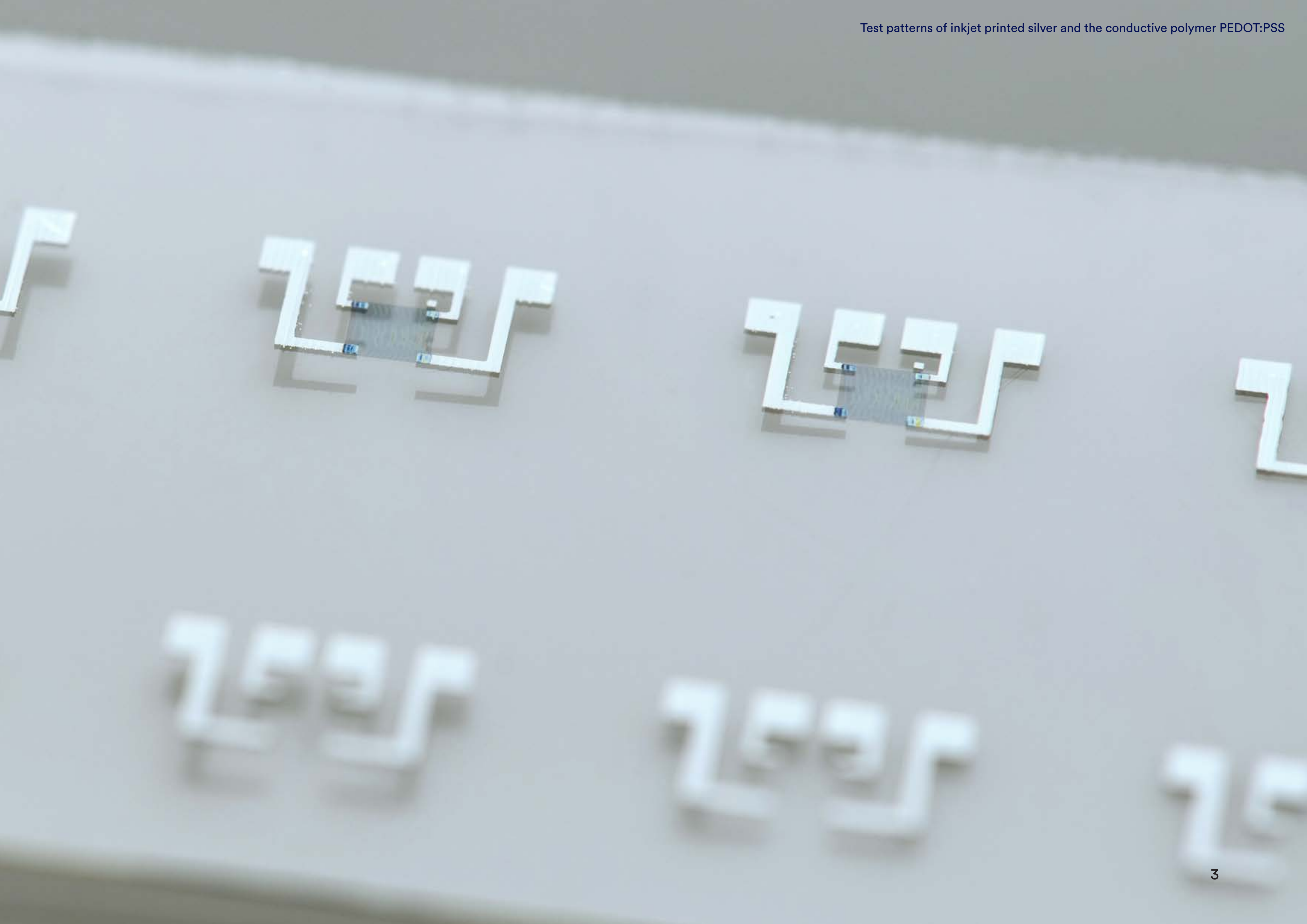
3D printable excipient with peptide triggers for controlled drug release



Concept lattice design for a titanium spinal orthopaedic implant

Contents

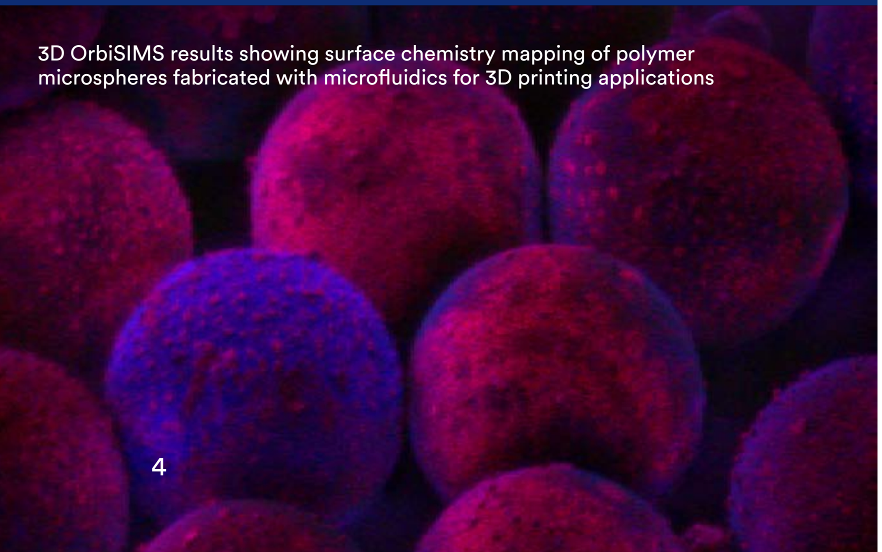
Cover: The Advanced Manufacturing Building, Jubilee Campus, University of Nottingham



Test patterns of inkjet printed silver and the conductive polymer PEDOT:PSS

Overview

The road ahead: Progress at the Centre for Additive Manufacturing



3D OrbiSIMS results showing surface chemistry mapping of polymer microspheres fabricated with microfluidics for 3D printing applications

The last two years have undoubtedly created a new reality for many people across the world. This applies to academic engineering research in the UK in particular. We now find ourselves at the confluence of major developments that have a significant bearing on how the field of manufacturing will evolve over the coming decade.

The first development is, of course, the global Coronavirus pandemic, which has significantly impacted all university activities, including engineering research, where we have had to adapt to a fundamental disruption to our ways of working and introduced many new working practices. However, I'm pleased to say that, as this report shows, the Centre for Additive Manufacturing (CfAM) is emerging from this challenge strengthened. We have demonstrated that many aspects of our research can be delivered in a decentralised manner with staff working from home and that it is possible to run a laboratory performing cutting-edge manufacturing research with resilience and responsibility. Going beyond our research mission, the pandemic has also allowed us to put our capabilities to use by performing emergency manufacturing services in collaboration with the Nottingham University Hospitals NHS Trust. All members of staff who have contributed to this essential effort deserve commendation. Moreover, the insights gleaned have allowed us to produce several innovative research proposals, focussing on Additive Manufacturing's strengths to build more resilient manufacturing capabilities.

Secondly, Brexit also clearly presents both challenges and potential opportunities for our research. Challenges include mobility of people and employment of staff alongside uncertainty about access to some funding streams; however, potential opportunities exist for digital manufacturing practices that further leverage the UK's strength in high value manufacturing and academic engineering research, particularly in the field of Additive Manufacturing (AM).

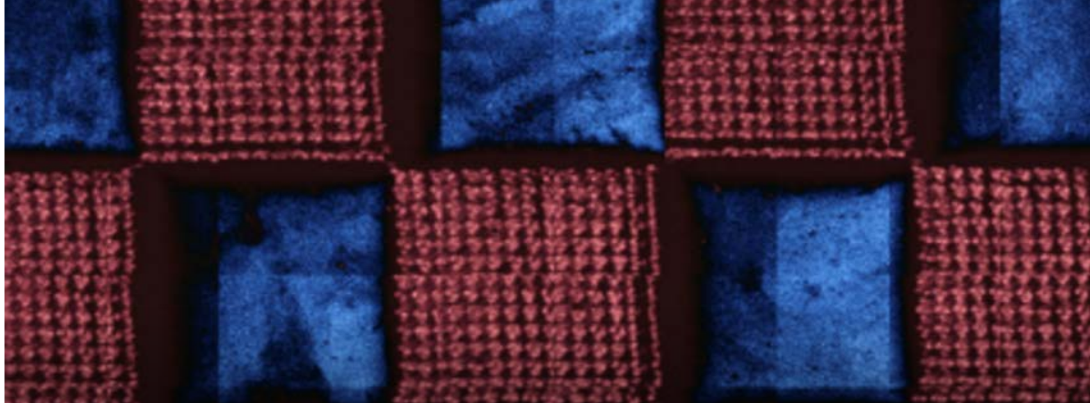
The third development that has come to the fore in the recent years is the global climate emergency. With the UN Climate Change Conference UK 2021 in Glasgow looming, the consumption and provision of goods is under renewed scrutiny. As our research track record shows, AM has the potential to make a real difference, where it can positively affect existing trade-offs in manufacturing that are responsible for significant environmental impacts. For example, AM's considerable freedom of geometry has been shown to allow the realisation of aerospace componentry featuring far lower whole life energy consumption and longer service lives. Moreover, several new application areas for AM promise significant environmental benefits. These include the manufacture of plant based proteins as a replacement for meat and the environmentally benign manufacture of pharmaceutical products.

CfAM addresses research challenges by combining several strands of engineering activity in pursuit of high calibre fundamental and translational research. Our method of operation interlinks progressive programmes of research in different areas, including the investigation of new material deposition processes, the formulation and selection of novel materials, the exploration of computation based design philosophies and novel approaches to deployment and operations for a wide range of industrial sectors. Our research position is unique because our activities straddle both single material processes, the adoption of which in mainstream manufacturing is now well under way, as well as multimaterial AM processes promising the deposition of innovative multimaterial structures (both functional and structural). The complementarity inherent to our activities, made possible through a closely knit team, is the basis for our recognised position of global leadership in multiple areas of AM related research.

Industrial applicability is and remains the ultimate yardstick for any manufacturing technology and CfAM has always focused on what lies ahead of the current status quo. Over the last two years, our vision has guided a thriving global research community. This community features prominent industrial and academic stakeholders, including AstraZeneca, AWE, BAE Systems, GSK, PPG, Texas Instruments, Lawrence Livermore National Laboratory, Karlsruhe Institute of Technology, and the Universities of Birmingham, Oxford, Stanford and Warwick. This has helped us establish a recognised track record of translating research through to commercial use and to sustain close engagement with the aerospace, automotive, defence, pharmaceutical, biotechnology and electronic industries. This crucial activity is supported through a dedicated contract research organisation, Added Scientific Ltd.

In this report, we summarise the activities of CfAM over the past two years. We are engaged in six complementary but interacting fields of research, each of which has led to significant theoretical contributions and avenues for new industrial systems and associated intellectual property. These areas encompass:

- innovative and industrially deployable single material AM processes
- multimaterial AM processes at different scales
- tailored materials for pairing with specific AM processes
- innovative computational design systems capable of leveraging novel geometries
- applications level research to further establish the industrial validity of AM
- organisational and managerial processes for the exploitation of AM-based supply chains



ToF-SIMS chemical mapping of a chequered pattern of silver printed on copper using MetalJet

We are pleased to report that in the period covered in this report, our early career fellows have further established their activities at CfAM, where they have now become full academic members. We congratulate Ruth Goodridge to her promotion to full professor in the Faculty of Engineering. With regret, CfAM has also seen the departure of two valued colleagues over this time period. Professor Phill Dickens, who has helped shape the entire field of AM and pushed for the use of additive techniques in manufacturing applications, has now taken his well-deserved retirement. Dr Nesma Aboulkhair has left our group to take up an exciting position in AM research in the United Arab Emirates. We wish both Phill and Nesma all the best for their future undertakings.

As with any collective endeavour, the continuing success of CfAM is sustained through the hard work and innovative ideas of all members and contributors, past and present. Especially, in light of the challenges and disruptions of the last year, we would like to gratefully thank all of our postdoctoral researchers, doctoral students, industrial partners, academic collaborators, technical team and our support staff for the dedication and professionalism with which they have handled this situation. We also thank our funders and the members of our Advisory Boards for supporting us in our ambitious activities. Without this support, our considerable progress would have been unthinkable and CfAM would not be able to confront the significant technological challenges ahead.

Professor Richard Hague, Director of CfAM

Key research areas include:

- Design systems and software tools for both single and multifunctional AM
- Modelling of AM processes
- High throughput materials discovery for organic materials
- New alloy development for Selective Laser Melting, including both structural materials as well as functional materials (e.g. hard / soft magnetic materials, copper and tungsten-carbide)
- Reactive jetting of engineering polymers including syntactic foams and silicones
- Multimaterial jetting of functional nano-particulate inks and dielectrics
- Drop-on-demand jetting of high temperature metallic materials-metal jetting
- Micro and nano scale multifunctional AM utilising photoreactive polymerisation
- Next generation biomaterials
- Pharmaceutical 3D printing: solid dosage forms and devices
- 3D printing of conductive and low-dimensional electronics materials
- Development of nano / microscale analysis methods of AM printed constructs
- AM management and implementation
- Clinical adoption of AM technologies
- Production of complex glass structures using AM

Centre highlights:

Producing a PPE face shield with CE approval for use in the NHS.

One of the first laboratories at the University of Nottingham to open up in summer 2020 after the first pandemic lockdown. CfAM laboratories have since continued to operate in a Covid-safe manner.

£1.8m EPSRC strategic equipment award led by Prof Chris Tuck for a facility to unlock the ability to understand, control and manipulate metal components that are manufactured by a metallic laser powder bed fusion.

Welcome to Dr Lyudmila Turyanska who joins the investigator team of CfAM.

Congratulations to Ruth Goodridge on being promoted to Professor of Additive Manufacturing.

Promotion of CfAM research staff – after being awarded a prestigious Anne MacLaren Fellowship, two Nottingham Research Fellowships and two Transitional Assistant Professorships, five of CfAM's postdoctoral research fellows are now progressing to academic positions.

We say a fond farewell to Professor Phill Dickens as he retires from the University of Nottingham. Phill founded this group in the early 1990s and was a major player in the field of AM research. His experience will be missed.

Dr Ali Sohaib setting up CfAM’s custom built micro SLA machine

“Industrial applicability is and remains the ultimate yardstick for any manufacturing technology and CfAM has always focused on what lies ahead of the current status quo of AM.”

Professor Richard Hague

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

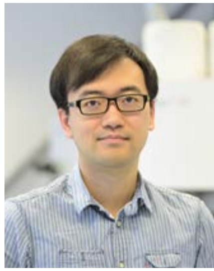
Professor Derek Irvine
Professor of Materials Chemistry, Faculty of Engineering, University of Nottingham

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
Assistant Professor, Faculty of Engineering, University of Nottingham

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



Dr Yinfeng He
Transitional Assistant Professor, Faculty of Engineering, University of Nottingham

Dr Ian Maskery
Nottingham Research Fellow, Faculty of Engineering, University of Nottingham

Dr Laura Ruiz-Cantu
Transitional Assistant Professor, Faculty of Engineering, University of Nottingham

Dr Marco Simonelli
Nottingham Research Fellow, Faculty of Engineering, University of Nottingham

Key individuals **Research fellows**

Dr Nesma Aboulkhair
Visiting Academic (Assistant Professor), Faculty of Engineering, University of Nottingham

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

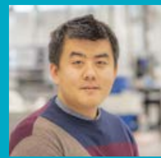
Dr Le Ma
Research Fellow, School of Pharmacy, University of Nottingham

Dr Gustavo Ferraz Trindade
Research Fellow, School of Pharmacy, University of Nottingham

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

Leonidas Gargalis
Research Associate, Faculty of Engineering, University of Nottingham

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

Dr Cordula Hege
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Ali Sohaib
Research Fellow, Faculty of Engineering, University of Nottingham

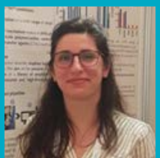
Dr Kaiyang (Scott) Wang
Research Fellow, Faculty of Engineering, University of Nottingham

Dr Masoomeh Bazzar
Research Fellow, Faculty of Engineering, University of Nottingham

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

Dr Amy Stimpson
Research Fellow, Faculty of Engineering, University of Nottingham

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



Valentina Cuzzucoli Crucitti
Research Associate, Faculty of Engineering, University of Nottingham

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

Dr Adja Touré
Research Fellow, Faculty of Engineering, 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

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

Dr Harinee Selvadurai
Programme Manager, EPSRC Programme Grant: Enabling Next Generation Additive Manufacturing, Faculty of Engineering, University of Nottingham

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

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

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

CfAM renewal

Group founder retires

“It has been a great pleasure working with so many great people on a fascinating subject. It may have been going for over 30 years, but the technology is just getting going and there will be lots of interesting work to do for many years to come.”

Professor Phill Dickens

At the start of his academic career at the University of Nottingham in 1990, Phill Dickens was first introduced to Rapid Prototyping by Rolf Husemann of Ford, Germany. This radically different approach to make things promised exciting new possibilities and so Phill latched onto it with enthusiasm.

Leading a group of junior academic colleagues at Nottingham, there was insufficient money available in the beginning to buy a rapid prototyping machine. So Phill initiated research through experimentation with available technologies. His first step was to try plasma spraying of powder to build up metal and he then attempted to use multiple-pass MIG welding. Following these initial steps, the nascent research group organised the first European Conference on Rapid Prototyping in 1992 and started the first EPSRC funded research project in 1993. The inaugural conference featured contributions on the finishing of stereolithography parts by Phil Reeves and using copper coated stereolithography parts as EDM electrodes by Alan Arthur. Having acquired research funding, the group purchased a stereolithography machine (SLA 250) in 1994. During this period Richard Hague joined as the first PhD student to investigate cracking of investment casting shells when using SL patterns.

The new group quickly attracted significant attention and growth ensued. An initial idea pursued systematically by the new group was the use of AM technologies for the manufacture of tooling, known as rapid tooling. A further breakthrough occurred around the year 2000 when the researchers in the group finally decided that AM technologies would become accepted manufacturing processes for final products in their own right. In turn, this led to the technology becoming known as rapid manufacturing, with the AM community latterly adopting the label Additive Manufacturing.

We thank Phill for all of his contributions and wish him all the best for his well-deserved retirement.

New investigator joins

University of Nottingham logo printed using caesium lead halide perovskite nanocrystal ink

Solutions of caesium lead halide perovskite nanocrystals with different halide contents

Dr Lyudmila Turyanska (Lyuda) joined CfAM in 2019 and has already had a big impact on our work, ranging from being an investigator on our EPSRC Programme Grant: Enabling Next Generation Additive Manufacturing (Next Gen AM - EP/P031684/1) where she has contributed across the research challenges, to taking a leading role in the delivery of the AM Masters course.

Her research is focused on the study of functional low-dimensional materials, which crosses the boundaries between Physics, Chemistry and Pharmacy. She has successfully developed research projects on the growth and fundamental properties of 0D and 2D materials; hybrid low dimensional composites for optoelectronic devices; and multifunctional nanoprobes for medical imaging and nanomedicine. She has an MSc in Chemistry and PhD in Physics, which has enabled her to successfully develop interdisciplinary projects. Lyuda has been the recipient of several prestigious awards and fellowships including an Anne McLaren Fellowship, MRC Discipline Hopping Fellowship and a Commendation Award at the House of Commons Britain's Early-Stage Researchers reception.

Since joining CfAM, her research has focused on the development of novel nanomaterials, including the synthesis of perovskite nanocrystals and their exploitation in devices, fundamental studies of graphene and graphene-based heterostructures, and the application of nanoscale materials for drug delivery. She has been contributing to the work of Next Gen AM's Research Challenge 4, mostly providing expertise on material characterisation and their integration into electronic devices. She also collaborates with colleagues in Research Challenges 2 and 3. Her current research focus is on the integration of nanomaterials within AM processes, which could offer opportunities for in situ and post-deposition control of material properties, as well as design freedom. This could provide a route to the up-scalable fabrication of multimaterial structures with properties tailored for specific applications.

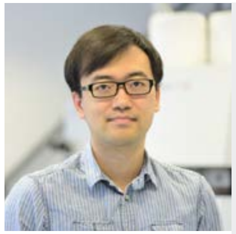
Developing a wave of future leaders

“Succession planning is critical for the continued success of CfAM”

At CfAM we have always seen the development of the next generation of academics in this field as a key priority. We understand that achieving continuity forms a vital part of developing and expanding the work of CfAM. This is why we are extremely proud that in addition to Ruth Goodridge being promoted to Professor, five CfAM researchers who were awarded prestigious fellowships and transitional posts, have now started to move to their new academic positions.

Transitional Assistant Professorships

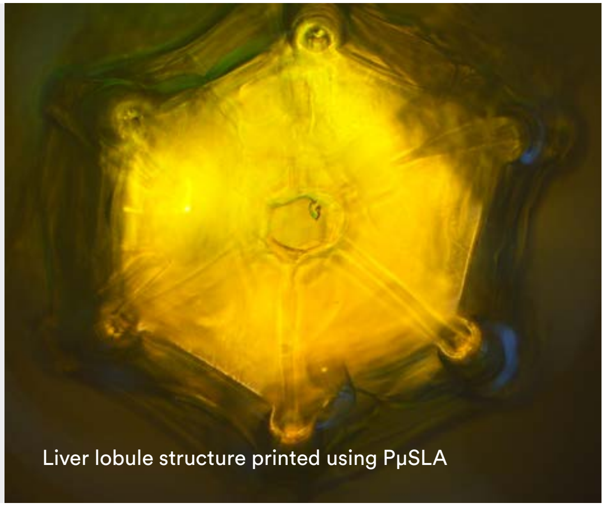
Transitional Assistant Professorships provide a pathway to a permanent academic position for early career researchers. Following an initial stage concentrating on research with a minimal teaching load, by the end of the scheme the post holder becomes a permanent member of academic staff within CfAM and the Faculty of Engineering.



Dr Yinfeng He started his PhD study at CfAM in 2011 and has since focused on advanced photoreactive materials development and their applications in multimaterial 3D printing. His current role as a Transitional Assistant Professor offers him an ideal opportunity to carry on his research and establish his research impact on multimaterial inkjet 3D printing and projection micro stereolithography (PμSLA) processes. He is currently part of the EPSRC ‘Enabling Next Generation Additive Manufacturing’ Programme Grant exploring functional polymeric materials and their interactions in multimaterial 3D printed devices, in order to boost their performance in 3D printed multi-functional devices. Yinfeng aims to utilise multimaterial 3D printing techniques to provide non-trivial solutions to manufacturing smart products. The ultimate goal of Yinfeng’s research is to pursue the production of next-generation biomedical and electronic devices that are more reliable, intelligent, and compacted.

Finger joint implant with customised mechanical performance and bacterial biofilm resistance (see page 17)

Dr Laura Ruiz-Cantu is paving her way towards becoming a leader in the area of 3D Bioprinting and Regenerative Medicine. She has been working closely with two international leading centres in AM and Translational Regenerative Medicine, the Lawrence Livermore National Laboratory and Wake Forest Institute for Regenerative Medicine. Her research involves the development of biomaterials and the use of four AM technologies, including inkjet printing, computer axial lithography, micro stereolithography and extrusion printing to initially create bone and cartilage tissues. Her vision is to expand the use of these technologies for the fabrication of more complex tissues such as liver and kidney. Laura has been awarded three pump priming grants as a co-I and is also now an Associate Fellow of Advance HE.



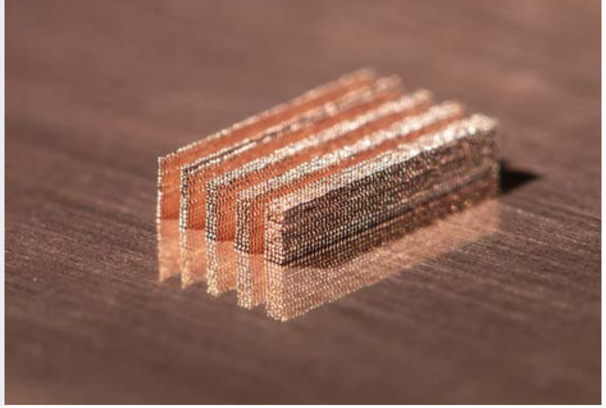
Liver lobule structure printed using PμSLA

Anne McLaren Fellowship

Dr Nesma Aboulkhair embarked on an ambitious career path by being awarded the prestigious Anne McLaren Fellowship quite early in her research career. Her three-year project focused on high temperature metal AM using the novel droplet-on-demand technology. Referred to as 'MetalJet', this technology is exclusively available at CfAM. Nesma's research includes the optimisation of the jetting process to print high-temperature metals, controlling droplet deposition, and characterising the 3D printed structures. The ultimate aim of this programme of research is to demonstrate the capability to produce fully 3D-printed microelectronic components. In 2020, Nesma was promoted to a full-time Assistant Professor. Recently, she has taken on a new role as the Additive Manufacturing Lead at the Technology Innovation Institute (UAE), whilst maintaining a visiting position at the University of Nottingham to continue working on her research activities at CfAM.

We thank Nesma for her hard work and wish her all the best for her new position.

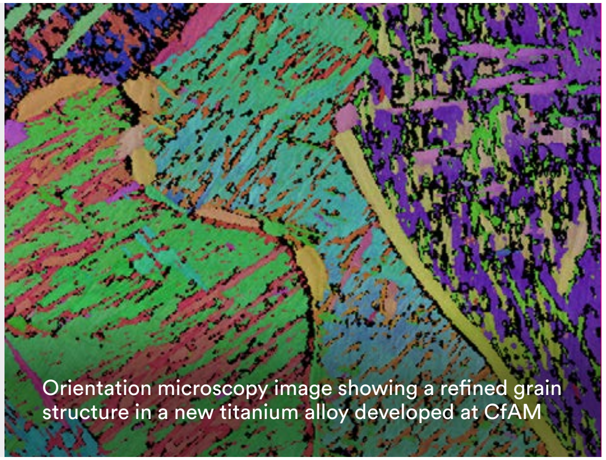
Thin walls of pure copper printed using the drop-on-demand MetalJet technology



Nottingham Research Fellowships

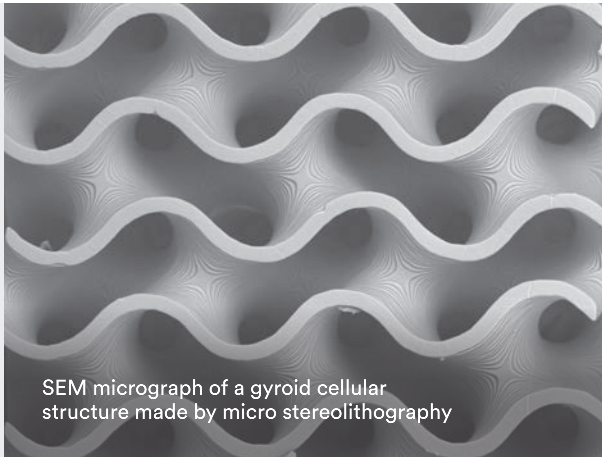
Nottingham Research Fellowships are competitively awarded internal fellowship schemes designed to enable the realisation of the University of Nottingham's Research Vision for a period of three years. Dr Marco Simonelli and Dr Ian Maskery are now progressing to full time academic roles.

Dr Marco Simonelli joined CfAM as a PhD student in 2010. After being involved in a number of research projects which provided him with extensive international experience, he successfully sought a Nottingham Research Fellowship to study new materials in metal AM. Marco's research addresses the issue that most of the readily available alloys are not printable, leading to components with non-desirable properties. He aims to develop a new supporting methodology to design and validate novel alloy compositions, specifically for use in metal AM. With this new set of improved materials, Marco aims to significantly advance the state-of-the-art of metal AM, benefitting applications in the aerospace and medical sectors primarily. In September 2021, Marco will transition to an Assistant Professor (lecturer) within the Faculty of Engineering.



Orientation microscopy image showing a refined grain structure in a new titanium alloy developed at CfAM

Dr Ian Maskery joined CfAM in 2013 after obtaining a PhD in Physics, and was excited to bring his knowledge and skills to a new area of research. He became interested in extending the use of AM cellular structures, or lattices, beyond their current applications. Ian's ongoing Nottingham Research Fellowship project investigates the use of AM lattices for thermal management, impact protection and nuclear fusion applications. Other promising research avenues include new lightweight alloys for AM, as well as the development of computational design tools (including CfAM's in-house lattice design software, FLatt Pack). Ian looks forward to building on his fellowship position to establish a successful academic career within CfAM, beginning later in 2021.



SEM micrograph of a gyroid cellular structure made by micro stereolithography

Responsive manufacturing

Certified 3D printed face shields for the NHS

In spring 2020 as the UK went into the first national lockdown, CfAM researchers and colleagues from the University of Nottingham Faculty of Engineering designed a PPE face shield with CE approval, which were 3D printed at scale for healthcare workers to use in the fight against Covid-19.

Using CfAM's latest AM technology and materials alongside key contributions from external collaborators – particularly Matsuura UK – the team delivered 5,000 face shields to Nottingham's NHS and community healthcare workers.

Building on an open-source headband design originally from HP, the team made modifications to ensure the face shield could pass a regulatory test by BSI, the UK's national standards body, to meet its essential health and safety requirements which ensures the highest level of protection is provided. The face shields successfully passed the BSI tests and were CE approved for use as part of PPE for healthcare workers' protection against Covid-19 in both hospital and community environments. They were provided in packs to the NHS, with five replacement visors per face shield, as well as instructions for use.

The team made the design and its accompanying documents 'open-source' to enable other manufacturers to produce the face shields: however, manufacturers needed to submit their product for testing to the BSI to obtain their own CE certification.

"We are extremely grateful to the University of Nottingham for developing and supplying the visors which will make a real difference to thousands of healthcare staff working on the frontline of the coronavirus outbreak [...] I think this is a really positive example of talented professionals working across normal boundaries in order to support our local communities in what is an unprecedented and very challenging time."

Dr James Hopkinson, Local GP and Joint Clinical Chair of NHS Nottingham and Nottinghamshire CCG

Design modifications were made by the team to conform to the BSI's PPE regulations in order to obtain CE marking; this involved making the wrap-around visor element wider, as well as other alterations to improve comfort for users. The HP design was chosen as it incorporates a cover at the top of the face shield which prevents fluid from entering the eyes from above – deemed critical by healthcare professionals.

The face shield comprises a 3D printed headband, a laser cut PET visor (with anti-fog coating) and is kept in place with a laser-cut adjustable strap. As well as using our own EOS Laser Sintering equipment, the team were supported by Matsuura UK to produce the 3D printed element, using their HP MultiJet Fusion process. The visor element was made with the help of local firm, Prime Group, and Nottingham Trent University produced the laser-cut strap.

Consultants at Queen's Medical Centre, Nottingham, (L-R) Surajit Basu and Stuart Smith, wear 3D printed face shields manufactured by University of Nottingham

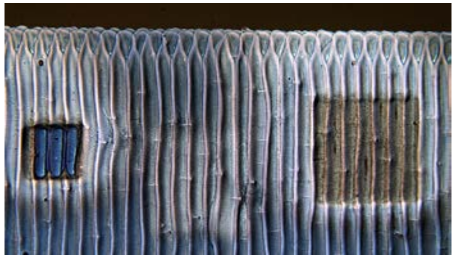


Fig1: Surface of an inkjet printed silver material with two craters from the chemical depth profiling analysis.

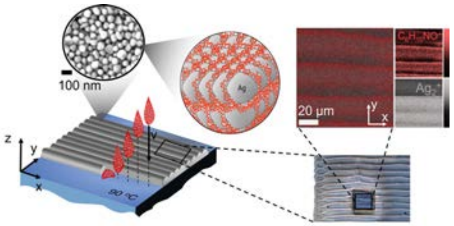


Fig2: (Left) Digital inkjet printing of inks containing metal nanoparticles with in-situ solvent evaporation (pinning). (Right) Optical and chemical images of a printed layer of silver nanoparticles showing organic residues at the surface.

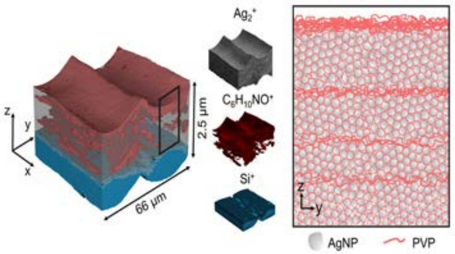


Fig3: Distribution of organic stabiliser residues within 3D printed layers of silver nanoparticles.

Case study 1 Anisotropic electrical conductivity during inkjet printing of metal nanoparticles

Background

Inkjet printing of metal nanoparticles for electronics allows for design flexibility, rapid processing and large scale production (Fig1). It also enables the 3D printing of functional devices through the co-deposition of multiple materials. However, the performance of printed devices is lower than those made by traditional manufacturing methods and is not fully understood. In particular, anisotropic conductivity is a long-standing problem for printed electronics that prevents their uptake in advanced applications. So far, the cause of this anisotropy has only been speculated. Understanding the causes for degraded and anisotropic functionality in inkjet printed nanoparticles is essential to enable the technology to compete with conventional manufacturing, ultimately impacting areas from photovoltaic devices to wearable electronics.

Key finding 1: Anisotropic electrical conductivity of printed metal nanoparticles is caused by organic residues from their inks (Fig2).

Key finding 2: Residues of a polymer stabiliser tend to concentrate in between stacked layers of inkjet printed metal nanoparticles (Fig3).

Results

We revealed that anisotropic electrical conductivity of printed metal nanoparticles is caused by organic residues from their inks.

We employed a combination of electrical and morphological characterisation and novel 3D nanoscale chemical analysis of printed devices produced using silver nanoparticle inks to show that residues of the polymer stabiliser polyvinylpyrrolidone tend to concentrate between vertically stacked ink layers as well as at dielectric/conductive interfaces. The work used the latest advances in mass spectrometry chemical imaging enabled by the University of Nottingham's novel 3D OrbiSIMS instrument.

Next steps

With a clearer understanding of the distribution of residual organic stabiliser within the printed layers, it is possible to consider optimisation strategies to overcome the functional anisotropy of inkjet-based 3D printed electronics. These include novel ink formulation routes with different stabilisers that can either be removed at lower temperatures or break down upon excitation using ultraviolet or infrared light sources. Our methodology is transferable to other nanomaterial-based inks and relevant for the development and exploitation of both 2D and 3D printed electronics.

Publication

Trindade, G.F., Wang, F., Im, J., et al. Residual polymer stabiliser causes anisotropic electrical conductivity during inkjet printing of metal nanoparticles. Commun Mater 2, 47 (2021)

Case study 2 **Voxel-based manufacturing via multimaterial AM techniques**

Background

Voxel-based manufacturing is a very powerful tool that is enabled by multimaterial AM techniques such as inkjet based 3D printing or vat polymerisation. It allows unrivalled design freedom for manufacturing electronic and healthcare devices.

Key finding 1: Inkjet based 3D printing is a powerful tool for voxel-based manufacturing that can allow the user to combine different functional materials in a single device.

Key finding 2: With the help of modelling and optimisation algorithms, voxel-based manufacturing enables the user to achieve highly customised functions not possible by traditional manufacturing processes.

Results

We have successfully developed novel formulations that are compatible with inkjet based 3D printing processes and applicable for voxel-based manufacturing processes. These new formulations enable the users to print healthcare devices not only with bespoke geometries, but also with either controlled drug releasing behaviours (Fig1 (top)) or with designed bio-instructive properties such as bacterial biofilm inhibition, which are customisable according to the needs of the patient (Fig1 (bottom)). By implementing a generative algorithm, we demonstrated that the voxel-based manufacturing technique can be empowered by machine learning to guide and help the user in designing their device. Our work also revealed the interaction between different materials during the voxel-based manufacturing process, which will help us to predict the performance of printed multimaterial, multi-functional devices and therefore guide us during process and formulation optimisation. Currently, different research challenges within the Programme Grant: Enabling Next Generation Additive Manufacturing are collaborating to look into these interactions at the interfaces and establish a predictive model to help the user optimise interface properties and guide the user when choosing different materials for this voxel-based manufacturing process.

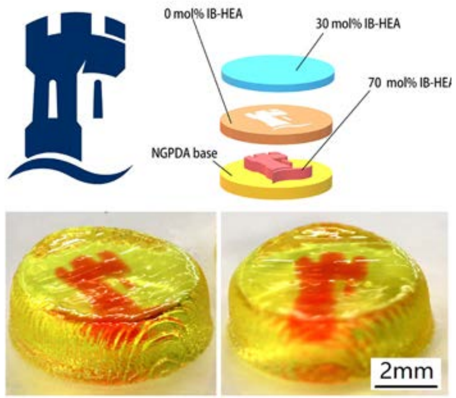
Next steps

We aim to also start looking into micro stereolithography based multimaterial AM techniques for voxel-based manufacturing to achieve material designing at the scale of a few microns. Also with the help of advanced characterisation techniques and modelling, we will further investigate the interface interactions in voxel-based manufacturing
processes to achieve advanced devices for electronics and healthcare applications.

Publication

He Y., Foralosso R., Trindade G.F., et al. A Reactive Prodrug Ink Formulation Strategy for Inkjet 3D Printing of Controlled Release Dosage Forms and Implants. Advanced Therapeutics 3, 6 (2020)

He Y., Abdi M., Trindade G.F., et al. Exploiting Generative Design for 3D Printing of Bacterial Biofilm Resistant Composite Devices.
Advanced Science, 2021: 2100249



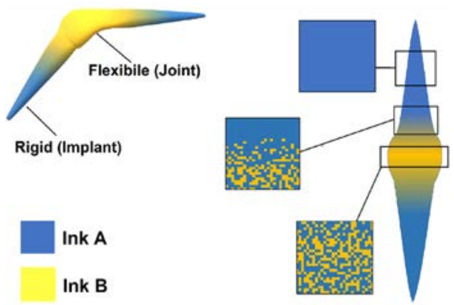


Fig1 (top): Devices for healthcare applications manufactured by voxel-based manufacturing: a compacted controlled releasing pill made from a novel reactive prodrug ink that contains four different regions, each with distinct releasing behaviours.
Fig1 (bottom): Schematic of a finger joint implant with customised mechanical performance in different regions, also using a bacterial biofilm inhibiting formulation to suppress infections (also image on page 12).

Case study 3 **Additive Manufacturing of 2D materials**

Background

Work on the Additive Manufacturing of 2D materials has been particularly successful for our EPSRC Programme Grant: Enabling Next Generation Additive Manufacturing. 2D materials have unique structural and electronic properties with the potential for transformative device applications. AM with inks containing 2D material flakes is a promising solution for producing high-quality large area hetero structures and for integrating these new materials with conventional electronics.

Key finding 1: Inkjet deposited 2D materials can be used as conductive and insulating layers in heterostructure based devices, such as field effect transistors and photon sensors.

Key finding 2: Theoretical models of charge transport through the 2D networks are developed to explain the properties of the inkjet printed 2D layers and to inform future work.

Results

We have developed successful deposition of electrically conductive graphene and insulating hexagonal boron nitride layers using inkjet printing and demonstrated the application of these layers in functional devices, such as field effect transistors and photon sensors (Figs 1-3). We have also, for the first time, reported on the use of inkjet printed graphene to replace single layer graphene as a contact material for 2D metal chalcogenides in a photodetector device. The experimental results obtained are supported by theoretical models of flake-to-flake charge transport. The properties of interfaces in 2D based hetero structures require particular attention as the sequential deposition of layers can result in the intermixing of materials, as was revealed by our ToF-SIMs studies. Pristine, encapsulated and quantum dot functionalised graphene sheets can have differing electrical properties, due to the nature of the neighbouring layer. We found that there was a universal connection between the carrier mobility and the variation of electrical conductivity with carrier density. Phenomenological relations provide a way to predict a priori all key transport parameters of graphene devices. First principles-based simulations, which considered the altered electrostatic environment induced by surrounding materials, were used to verify the resulting relations, and understand their origin.

The experimental results and models developed here inform our current work on the additive manufacture of low dimensional materials, in which we aim to produce inkjet printed flexible/stretchable 2D electronics and, in combination with novel optically active nanomaterials, develop optoelectronic devices.

Next steps

We aim to use these insights into the behaviour of 2D materials to develop other electronic and optoelectronic applications such as digital processors with multiple vertically stacked 2D material layers and healthcare devices.

Publications

Wang F., Gosling J.H., Trindade G.F., et al. Inter-Flake Quantum Transport of Electrons and Holes in Inkjet-Printed Graphene Devices. Advanced Functional Materials 31, 5 (2021)

Gosling J.H., Makarovsky O., Wang F., et al. Universal mobility characteristics of graphene originating from charge scattering by ionised impurities. Communication Physics 4, 30 (2021)

Cottam N.D., Zhang C., Wildman J.L., et al. Light-Induced Stark Effect and Reversible Photoluminescence Quenching in Inorganic Perovskite Nanocrystals. Advanced Optical Materials 2021: 202100104

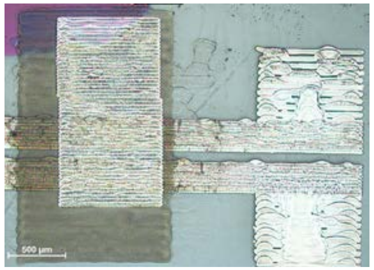


Fig1: Optical microscopy image of a field effect transistor containing an inkjet printed graphene channel.

Fig2: Graphene layers printed on a flexible substrate.

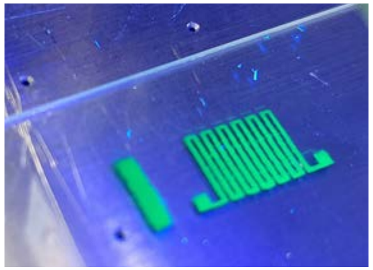


Fig3: Graphene layers photosensitised with perovskite nanocrystals under UV light.

Case study 4 **Additive Manufacturing of glass**

Background

Glass is a desirable material for many industrial applications, offering unique properties such as transparency, chemical durability, and high thermal stability. However, the high melting temperature of glass requires energy-intensive manufacturing procedures that create large temperature gradients within the built parts, generating residual stresses that can trigger thermal cracking. Additionally, the high transmittance in the visible and near-infrared range of the electromagnetic spectrum impedes the processing of glass with lasers operating in this range, while any microcracks or porosity introduced within the built structures diminish their optical quality and lead to opaque surfaces. The aim of this work has been to develop processing strategies to allow successful processing of soda lime silica glass using two laser-based AM techniques: powder bed fusion (PBF) and powder-fed Direct Energy Deposition (DED). This project has been carried out in collaboration with Glass Technology Services.

Key finding 1: Direct PBF can be used to produce complex multilayer glass structures with channel diameters of 2mm.

Key finding 2: Powder-fed DED is a promising technique for glass-on-glass processing.

Results

Using direct PBF, we have successfully produced a range of glass structures including lattice structures (Fig1a), narrow channels (Figs1b and 1d), and 20 mm^3 gyroid network structures (Fig1c). Optimisation of the processing strategy allowed us to produce parts with a fully amorphous structure; no post-processing was required and thus no shrinkage occurred. Powder-fed DED (Fig2) was successfully used for glass-on-glass processing, with consistent glass tracks and structures on glass substrates of varying thicknesses. Consideration of processing surface conditions and reduction of laser transmission through transparent substrates was necessary to allow consolidation of the glass powder. The effect of design geometry on the required processing strategy was also established.

Next steps

We are focusing our research on the applications of customised flow reactors, structured catalysts and high value glass décor, translating our understanding of laser-based AM of soda lime silica to other types of glass to enable wider and more advanced applications.

Publication

Datsiou, K.C., Spirrett, F., Ashcroft, I., Goodridge, R., et al. Laser powder bed fusion of soda lime silica glass. Additive Manufacturing 39, 2021: 101880

Datsiou, K.C., Spirrett, F., Goodridge, R., Ashcroft, I., et al. Additive Manufacturing of glass with laser powder bed fusion. J. American Ceramic Society 102(8) (2019)

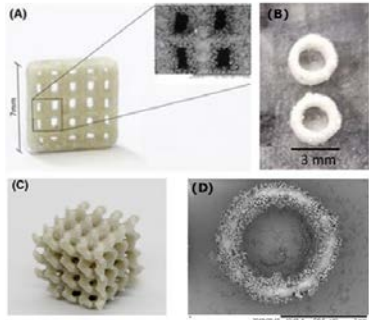


Fig1: Glass structures produced by powder bed fusion.

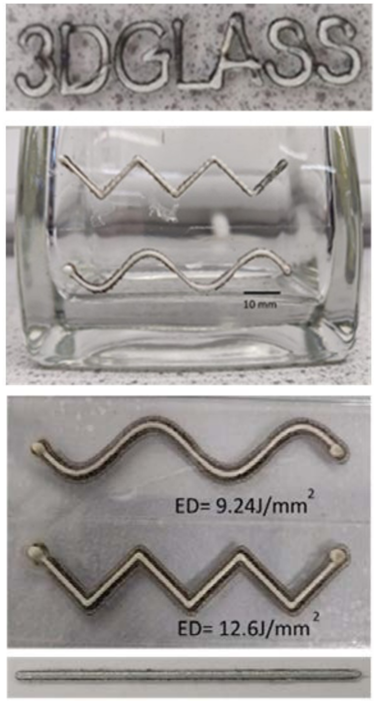


Fig2: Glass-on-glass powder DED.

Dr Adja Touré using the BMF nanoArch™ S130 PμSLA system

Facilities

CfAM's laboratories boast a unique portfolio of developmental and commercially available AM processes, and a state-of-the-art suite of analytical devices in a dedicated materials characterisation laboratory. This laboratory forms a vital tool that facilitates new avenues of both academic and industrially-focused research.

Among a large research portfolio of commercially deployed AM systems, the laboratory houses specialist and bespoke AM systems that are not available elsewhere in the world. These include experimental multimaterial 3D inkjetting systems, ranging from small scale exploratory research platforms to large scale systems such as the PiXDRO and Toucan, high-temperature liquid metal jetting systems (MetalJet) and custom built multimaterial high resolution AM systems.

In addition, our clean room facility (supported by the Wolfson Foundation) widens the palette of materials for 3D inkjet and extrusion printing platforms, and is used primarily for pharmaceutical, biological and electronics orientated research, which needs to be conducted in a setting with a low level of environmental pollutants, or where light sensitive materials are used. The clean room is equipped with a comprehensive suite of 3D inkjetting and analysis equipment, alongside pharmaceutically focused material extrusion systems.

Recent developments include:

Purchase of a BMF nanoArch™ 130 which is based on PμSLA (projection micro stereolithography) and a bespoke Integrity dual head powder bed inkjet printer.

Development of a multi-printhead (Xaar) reactive jetting system which is being manufactured externally, and is due to be installed in the lab soon.

Funding from the EPSRC for a facility to unlock the ability to understand, control and manipulate metal components that are manufactured by metallic laser powder bed fusion. The two instruments will provide a degree of flexibility not found in commercially available equipment.

Major grant successes at CfAM

Dial-up Engineered Microstructures for Advanced Additively Manufactured Metals (DEMAMM)

Funder EPSRC, £1.8m (grant ref: EP/V029010/1)

Led by Professor Chris Tuck

This recently awarded strategic equipment bid was for a facility to unlock the ability to understand, control and manipulate metal components that are manufactured by metallic laser powder bed fusion. The two instruments will provide a degree of flexibility not found in the commercially available equipment currently used in a wide range of industries, including healthcare (i.e. hip implants) or aerospace components, (i.e. fuel injectors on GE Leap engines).

The flexibility offered enables scientists and engineers to change parameters to modify how the metal powders within the machine heat up and solidify. Controlling the heat treatment within the machine provides further control on how the metal performs later in service, through controlling the metal grain size, shape and direction, otherwise known as its microstructure. Small fine grains characterise hard, strong materials, whereas larger grain sizes provide greater toughness and ductility. Coupling this ability to modify the heating and cooling of components with the ability to add in other materials through inkjet printing, we can also control the component's composition. Again, this provides more control to the engineer, giving the ability to change the material's crystal structure, its constituents and even to produce nano-composites within a metal framework. The final element of this bid is that of monitoring the build during manufacture, which can provide real time information on the component's structure as it's being built, enabling a feedback loop to control any defects that might occur within the build, and therefore make sure that everything coming off the machine is within specification.

Enabling Next Generation Additive Manufacturing Programme Grant

Funder EPSRC, £5.85m (grant ref: EP/P031684/1)

Led by Professor Richard Hague, this Programme is a collaboration between the universities of Nottingham, Birmingham and Warwick.

Our 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, we aim to move 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, our primary challenge is at the interface of the deposited materials.

The Programme submitted a mid-term review to the EPSRC in July 2020. The reviewers' and panel's comments were overwhelmingly positive and we were awarded a score of 9/10 ("very strong").

Formulation for 3D printing: Creating a plug and play platform for a disruptive UK industry

Funder: EPSRC, £3.84m

Led by Professor Ricky Wildman, this project is a collaboration between the universities of Nottingham, Birmingham and Reading.

By using high throughput methods and approaches to identify materials and formulations suitable for AM and 3D printing, this grant aims to solve the long standing problem of how to formulate products with the properties required for their proper performance. Working together in a multidisciplinary team, materials scientists, chemists, pharmacists, manufacturing engineers and chemical engineers will establish a library of materials that will free industry in the future from time consuming formulation problems, break the process and material links that slow progress and allow a focus on the exploitation of the key benefits of 3D printing: freedom of design, complexity and personalised manufacture.

This high throughput method has been used to rapidly identify suitable materials for various biomedical applications such as implants for drug delivery, tissue regeneration and bacteria resistant devices.

Future Additive Manufacturing Platform Grant

Funder: EPSRC, £1.73m (grant ref: EP/P027261/1)

Led by Professor Richard Hague

The Future Additive Manufacturing Platform covers research activities that are common to both single and multimaterial AM.

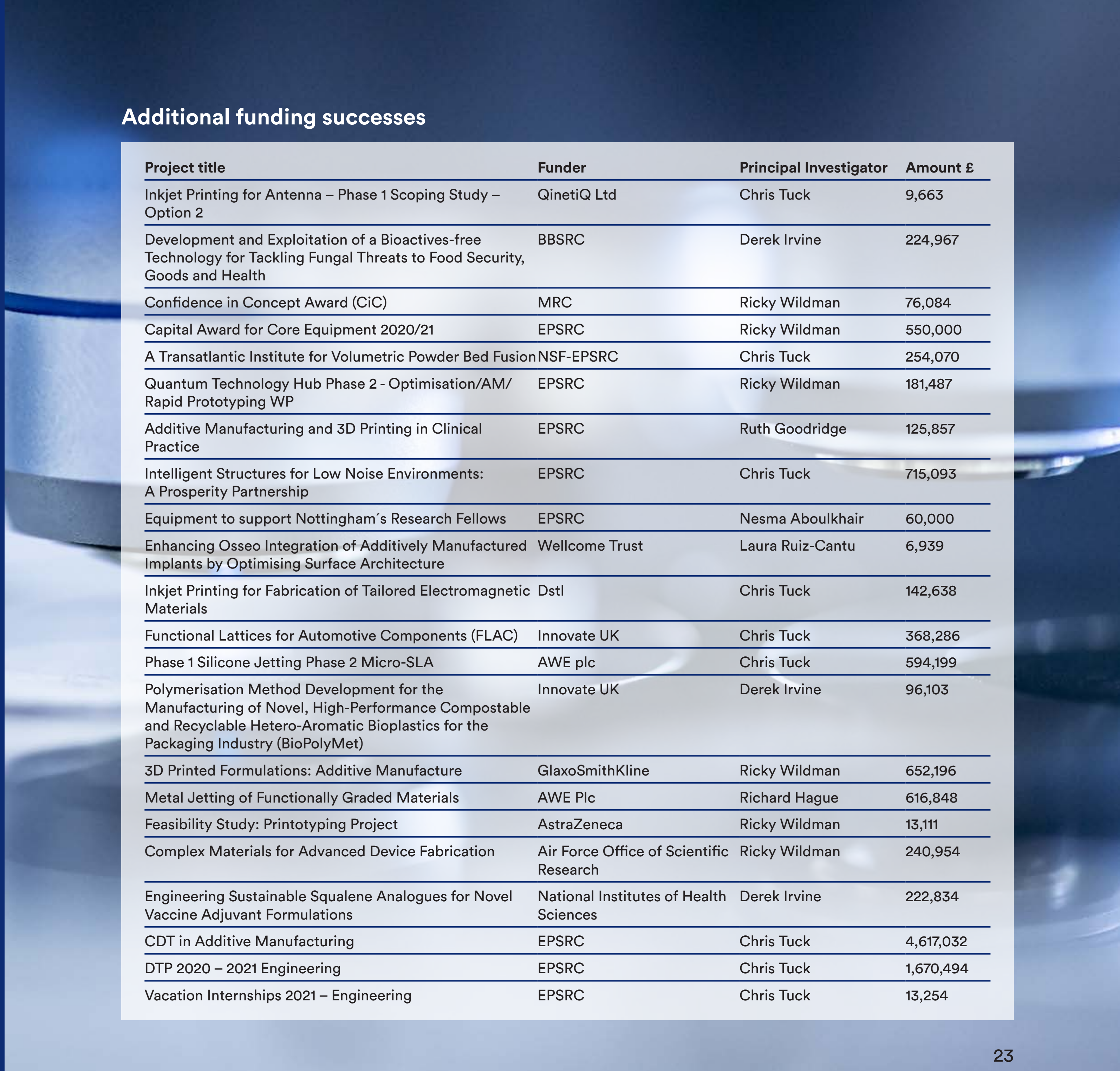
The vision driving this platform proposal is to discover, understand and enable industrial implementation of AM solutions to address the issues of productivity and industrial scalability, coupled with the ambition that this will strengthen engagement across the full value chain from discovery to deployment. As such, the platform enables CfAM to achieve its long-term ambitions and maintain international leadership through:

- flexibility in the deployment of funds for short term ('jump-start') studies which often lead to new project-based funding
- responsiveness to emerging industrial and scientific problems and opportunities
- bridging and retention of key research staff
- staff development
- long term planning activities

The Platform Grant has supported various projects ranging from 'Machine learning as a design tool for Additive Manufacturing solutions' to 'Development of a reactive inkjet powder bed printing process'.

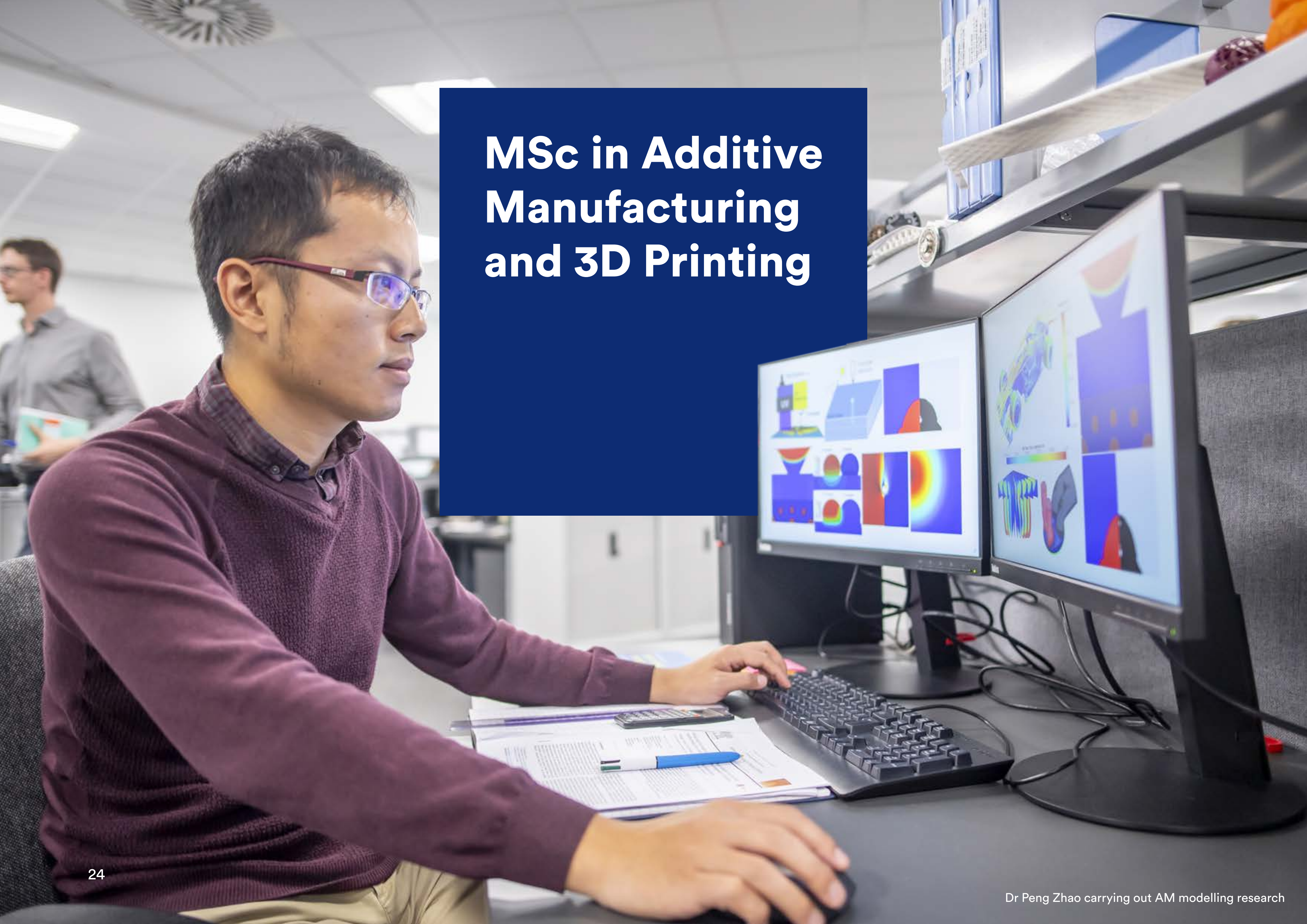
Additional funding successes

Project title	Funder	Principal Investigator	Amount £
Inkjet Printing for Antenna – Phase 1 Scoping Study – Option 2	QinetiQ Ltd	Chris Tuck	9,663
Development and Exploitation of a Bioactives-free Technology for Tackling Fungal Threats to Food Security, Goods and Health	BBSRC	Derek Irvine	224,967
Confidence in Concept Award (CiC)	MRC	Ricky Wildman	76,084
Capital Award for Core Equipment 2020/21	EPSRC	Ricky Wildman	550,000
A Transatlantic Institute for Volumetric Powder Bed Fusion	NSF-EPSRC	Chris Tuck	254,070
Quantum Technology Hub Phase 2 - Optimisation/AM/ Rapid Prototyping WP	EPSRC	Ricky Wildman	181,487
Additive Manufacturing and 3D Printing in Clinical Practice	EPSRC	Ruth Goodridge	125,857
Intelligent Structures for Low Noise Environments: A Prosperity Partnership	EPSRC	Chris Tuck	715,093
Equipment to support Nottingham´s Research Fellows	EPSRC	Nesma Aboulkhair	60,000
Enhancing Osseo Integration of Additively Manufactured Implants by Optimising Surface Architecture	Wellcome Trust	Laura Ruiz-Cantu	6,939
Inkjet Printing for Fabrication of Tailored Electromagnetic Materials	Dstl	Chris Tuck	142,638
Functional Lattices for Automotive Components (FLAC)	Innovate UK	Chris Tuck	368,286
Phase 1 Silicone Jetting Phase 2 Micro-SLA	AWE plc	Chris Tuck	594,199
Polymerisation Method Development for the Manufacturing of Novel, High-Performance Compostable and Recyclable Hetero-Aromatic Bioplastics for the Packaging Industry (BioPolyMet)	Innovate UK	Derek Irvine	96,103
3D Printed Formulations: Additive Manufacture	GlaxoSmithKline	Ricky Wildman	652,196
Metal Jetting of Functionally Graded Materials	AWE Plc	Richard Hague	616,848
Feasibility Study: Printotyping Project	AstraZeneca	Ricky Wildman	13,111
Complex Materials for Advanced Device Fabrication	Air Force Office of Scientific Research	Ricky Wildman	240,954
Engineering Sustainable Squalene Analogues for Novel Vaccine Adjuvant Formulations	National Institutes of Health Sciences	Derek Irvine	222,834
CDT in Additive Manufacturing	EPSRC	Chris Tuck	4,617,032
DTP 2020 – 2021 Engineering	EPSRC	Chris Tuck	1,670,494
Vacation Internships 2021 – Engineering	EPSRC	Chris Tuck	13,254



Microscope lenses in operation on the Buehler Wilson VH3100 Automated Hardness Tester

MSc in Additive Manufacturing and 3D Printing



Dr Peng Zhao carrying out AM modelling research

Whether it is creating advanced engineering components, new kinds of prosthetic limbs, or complex pharmaceutical devices, AM gives engineers and scientists the ability to build structures with unprecedented degrees of complexity. This leads to the emergence of conceptually new products and transformative technologies. The digital and tool-less nature of AM offers a range of new opportunities that are very exciting to today's engineers. However, there is a need to train a new generation of engineers able to operate in and lead this new area.

The Additive Manufacturing and 3D Printing MSc programme offered at the University of Nottingham has been developed as a bespoke postgraduate taught course offering to address this requirement. In this 12-month course, students are taught by the researchers at CfAM, who are world-leading experts and have access to CfAM's laboratory. The course is currently in its third year of operation.

The course aims to give students in-depth knowledge and understanding of Additive Manufacturing and 3D printing technology. Students will 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

Batch of 3D printed bacterial biofilm resistant materials for *in vitro* testing

MSc alumni Alex Christie

" As an undergraduate student I was always fascinated with the amazing possibilities presented by Additive Manufacturing (AM) and its unique ability to rapidly produce complex 3D models. I heard about the Nottingham AM Masters course as an undergraduate student at Loughborough University and was immediately interested because of the university's reputation and the speciality of the course.

As a taught course, the modules covered a wide range of topics and provided a full coverage of the AM technologies, whilst still leaving space for students to research and develop skills in their areas of interest. This meant that I could specialise my Individual Postgraduate Project on the production of Damascus Steel, using multimaterial metal AM.

As a university with global connections, the course gave me a great opportunity to work with international students from different backgrounds and cultures. The lecturers at the university create a fun working environment and support you in your work whilst still encouraging you to push yourself. They go above and beyond to make sure that all students are accommodated and supported. With the onset of the pandemic the remaining modules on the course were quickly adapted to accommodate virtual learning under the government's guidelines, allowing for a smooth transition into remote learning.

My time at the University of Nottingham provided me with both the skills and confidence to go on to work as an Additive Manufacturing Designer at Sartorius, an international biotechnology company. My role at the company is to support the creation and adoption of additively manufactured parts for small batch production, prototyping and eventually mass production. "

Doctoral research

CfAM has a wide range of doctoral research projects ranging from mechanical engineering and materials development to biochemistry and pharmacy. The PhD student recruitment has gone well, with 24 new PhD students recruited since October 2019.

The EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing and 3D printing (4-year programme) led by the University of Nottingham in collaboration with the Universities of Liverpool, Loughborough and Newcastle started in 2014 and finished recruitment of the last cohort of CDT students in 2019.

Cohorts 2014 and 2015 have already finished or are in process of being awarded their PhDs. Cohort 2016 are in the process of finalising their theses and students from the last CDT cohort (2018/19) are expected to finish their PhDs in 2023.

In 2020, CfAM was awarded EPSRC studentships for two Thematic Doctoral Training Programmes (DTPs). The 4-year Thematic DTP studentships, funded by the EPSRC with match funding from industrial sponsors are:

- Science-informed manufacturing for scientific discovery (led by Prof Chris Tuck): five PhD studentships
- Novel complementary diagnostics for improved therapeutics/theranostics (led by Prof Derek Irvine): four PhD studentships (two studentships at the University of Nottingham and two studentships at the University of Queensland).

CfAM has continued its collaboration with other University of Nottingham schools (e.g. Pharmacy, Chemistry and Physics) and industrial partners (e.g. AstraZeneca, MTC, Siemens, Oerlikon, Liberty Powder Metals) to supervise and support its PhD students.

The Centre has continued to develop its training programme and introduce a range of new activities. All CfAM PhD/CDT students are brought together through team building events, training, regular seminars and talks by external speakers and alumni. Since the start of the pandemic, these activities are continuing to run virtually. For example, the Nature Masterclass workshop designed to help to improve researchers' scientific writing skills and give them first-hand insight into the publishing process at top-tier journals, has been delivered in a digital format. The CDT continued offering training in project management (PRINCE2) and some PhD students have started the Postgraduate Teaching Programme.

CDT Manager Mirela Axinte with the 2018-19 cohort of postgraduate students

Public engagement

We understand the importance of an effective portfolio of outreach and public engagement activities in supporting the delivery of our research vision. CfAM researchers and PhD students have taken part in a variety of outreach activities to engage with schools, undergraduate students, businesses, government and the wider community. As with many areas, our outreach and public engagement has been disrupted since March 2020 due to the pandemic, but activities have since started to resume online.

Outreach events

- Pint of Science 'Tech Me Out', Parliament Bar and Kitchen, Nottingham
- Pint of Science Creative Reactions, Canalhouse, Nottingham
- SoapBox Science, Riverside Festival, Leicester
- IntoUniversity – Mentoring Graduation, University of Nottingham
- 3D Printed City, Cheltenham Science Festival (supporting the Sustainable Chemistry CDT)
- 3D Printing Learning Journey, Glade Hill Primary School, Nottingham
- Archway STEM Festival, Bluecoats Beechdale Academy, Nottingham
- Wonder, University of Nottingham
- IntoUniversity – Family Learning Graduation, University of Nottingham
- Young Persons Advisory Group, Nottingham University Hospitals (NUH)
- Sunnyside Spencer Academy, Nottingham
- Christmas Lecture 2019, University of Nottingham
- Festival of Science and Curiosity, Victoria Centre Market, Nottingham
- Brilliant Club, George Spencer Academy, Nottingham
- Soapbox Science Nottingham, online
- Inspiring Women in STEM, University of Nottingham, online
- The Importance of STEM outreach, the University of Nottingham, online

Royal Society Summer Science

We were delighted to have been selected to present at the Royal Society's prestigious Summer Science Exhibition in July 2020. Due to the Covid-19 pandemic the Royal Society postponed their Summer Science Exhibition until July 2021 when it will run as a digital event, and we look forward to taking part.

We will demonstrate how we can use 3D printing 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 in e.g. war zones and low income countries where transport links can be limited.

The team from CfAM and the University of Nottingham School of Pharmacy will present a short video, an interactive game, and a lightning lecture, as well as taking part in a 'meet the researcher' event for school students.

Influencing Policy

POSTnote – March 2020

Dr Jin Ding was invited to review the POSTnote about '3D Bioprinting in Medicine', which gives an overview of 3D bioprinting in regenerative medicine and the associated biological, manufacturing, regulatory and ethical implications. The POSTnote is a summary of public policy issues published by the Parliamentary Office of Science and Technology (POST). It is based on literature reviews and interviews with a range of stakeholders and is externally peer-reviewed. The objective of this POSTnote was to inform parliamentarians about the key issues in the area of 3D bioprinting before upcoming parliamentary debates.
It was published on 13 March 2020 on the UK Parliament website:
post.parliament.uk/research-briefings/post-pn-0620/

'3D Printing – tool or toy?' April 2019. Ingenuity Breakfast event for local business development agencies and industry.

'Overcoming Policy Roadblocks in the Application of 3D Printed Pharmaceutical Innovation', July 2019. Workshop for the pharmaceutical industry and regulators discussing the social, ethical and economic implications of 3D printed medicines.

Summer studentships

We run summer internship projects as part of the University of Nottingham NSERP scheme. Due to the Covid-19 pandemic NSERP didn't run in 2020, but we have recruited four students for summer 2021 and they will complete their projects in our Covid-safe labs.

2019 Summer Studentships

Student	Project
Guy Lawrence	Improving carbon fibre composite manufacturing processes by characterisation of composite preforms stabilised by inkjet printing methods
Eoin O'Connor	Formulation of graphene containing ink for 3D printing and electronic devices
Adam Balogh	3D printed flexible electronic devices: optimisation of the in-line sintering process for 3D inkjet printed silver nanoparticles
Sylvia Tan	Exploring routes to overcome functional anisotropy in two-photon lithography based 3D micro/nano fabrication
Varinder Panesar	Development of a new manufacturing protocol for the production of a carbon fibre composite: integration of inkjet in carbon fibre composites manufacturing
Joni Wildman	Optimisation of the printing parameters of water-soluble polymers for the development of micro vascular channels

3D printed polypills with controlled distribution and release of medication

Publication highlights

1. Aboulkhair, N.T., et al., Progress in Materials Science 106 (2019)
2. Aboulkhair, N.T., et al., Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing 765 (2019)
3. Aboulkhair, N.T., et al., Journal of Manufacturing Processes 55 (2020)
4. Al-Thamir, M., et al., Materials 13 (2020)
5. Araujo, L.J.P., et al., International Journal of Production Research 57 (2019)
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7. Askari, M., et al., Additive Manufacturing 36 (2020)
8. Askari, M., et al., Journal of Laser Micro Nanoengineering 14 (2019)
9. Baumers, M., et al., Journal of Operations Management 65 (2019)
10. Baumers, M., et al., Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture 233 (2019)
11. Baumers, M., Cost Implications of Precision Additive Manufacturing. Precision Metal Additive Manufacturing, ed. R. Leach and S. Carmignato (2020).
12. Bouzinab, K., et al., Acs Applied Materials & Interfaces 12 (2020)
13. Cader, H.K., et al., International Journal of Pharmaceutics 564 (2019)
14. Catchpole-Smith, S., et al., Additive Manufacturing 30 (2019)
15. Clare, A.T., et al., Cirp Annals-Manufacturing Technology 69 (2020)
16. Clark, E.A., et al., International Journal of Pharmaceutics 578 (2020)
17. Cooper, N., et al., Additive Manufacturing 40 (2021)
18. Cottam, N.D., et al., ACS Applied Electronic Materials 2 (2020)
19. Dalleywater, W.J., et al., Journal of Pathology 249 (2019)
20. Datsiou, K.C., et al., Journal of the American Ceramic Society 102 (2019)
21. Datsiou, K.C., et al., Additive Manufacturing 39 (2021)
22. de Macedo, R.Q., et al., Additive Manufacturing 40 (2021)
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24. Dundas, A.A., et al., Advanced Functional Materials 30 (2020)
25. Dundas, A.A., et al., Advanced Materials 31 (2019)
26. Ferreira, R.T.L., et al., Structural and Multidisciplinary Optimization 61 (2020)
27. Foerster, A., et al., Current Market for Biomedical Implants. Polymer-Based Additive Manufacturing: Biomedical Applications, ed. D.M. Devine. (2019)
28. Foerster, A., et al., Materials & Design, 205 (2021)
29. Gargalis, L., et al., IEEE Access 8 (2020)
30. Garibaldi, M., et al., Journal of Mechanical Design 141 (2019)
31. Gasper, A.N.D., et al., Powder Technology 354 (2019)
32. Gherardi, F., et al., ACS Applied Bio Materials 2 (2019)
33. Giuri, A., et al., Nanomaterials 9 (2019)
34. Gosling, J.H., et al., Communications Physics 4 (2021)
35. Harvey, H.J., et al., Soil Biology & Biochemistry 148 (2020)
36. He, Y.F., et al., Advanced Therapeutics 3 (2020)
37. Henning, I., et al., Advanced Functional Materials 30 (2020)
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39. Jain, A., et al., Journal of Colloid and Interface Science 587 (2021)
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41. Jiang, T., et al., Nanoscale 13 (2021)
42. Kabir, S.F., et al., Journal of Applied Polymer Science 137 (2020)
43. Kalamiotis, A., et al., Sensors and Actuators B-Chemical 290 (2019)
44. Knott, A., et al., Building Simulation 12 (2019)
45. Kuhnl, A., et al., British Journal of Haematology 189 (2020)
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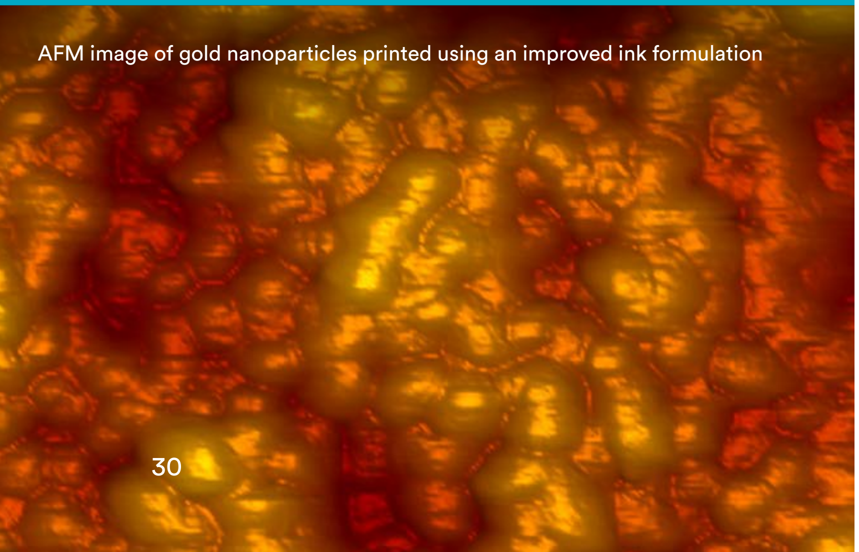
AFM image of gold nanoparticles printed using an improved ink formulation

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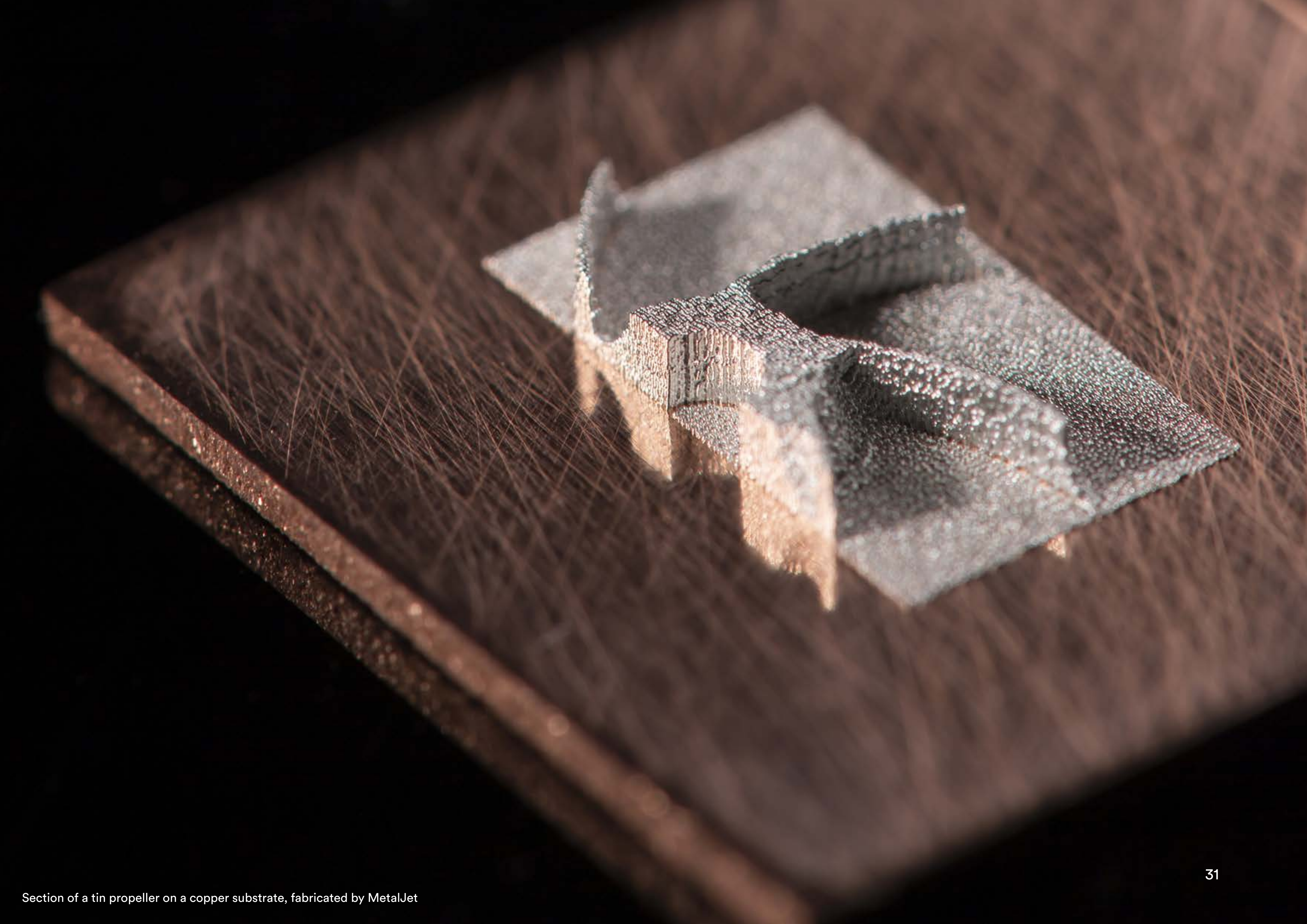

Section of a tin propeller on a copper substrate, fabricated by MetalJet

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