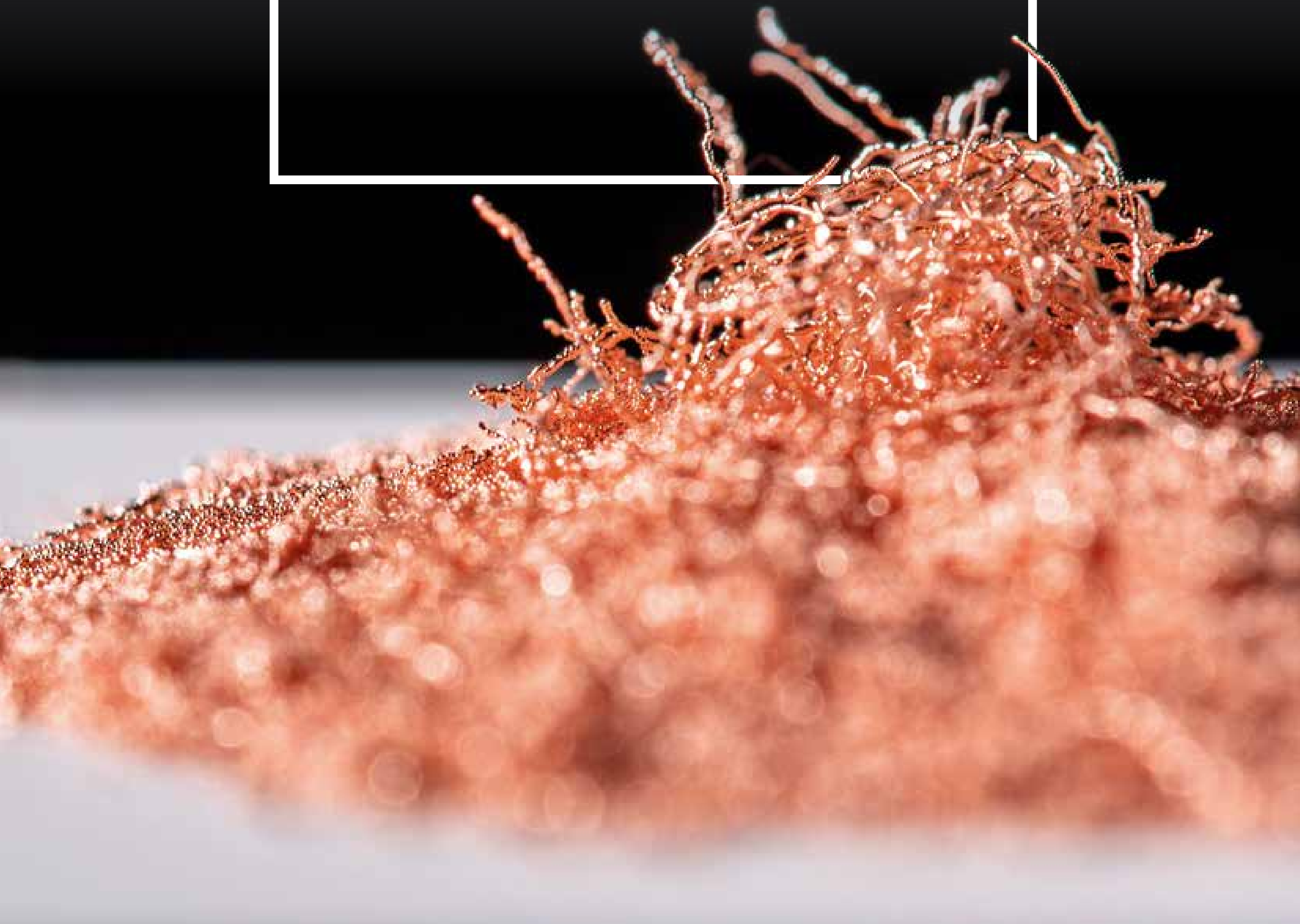
University of Nottingham
UK | CHINA | MALAYSIA

Centre for Additive Manufacturing (CfAM)

Biennial report

May 2017 – April 2019



Summary: building our additive future

Additive Manufacturing (AM) technologies, also known as 3D printing, continue to evolve rapidly into crucial 21st Century manufacturing practices. At the University of Nottingham, the Centre for Additive Manufacturing (CfAM) is at the forefront of this development. To address the exciting engineering research challenges arising from this, CfAM combines several innovative strands of engineering research to span fundamental and translational research. Implemented as an interlinked and progressive programme of research projects, our activities include the investigation of underpinning material deposition processes, the formulation and selection of entirely new materials, the exploration of new computation-based design philosophies and novel deployment approaches for a wide range of industrial sectors.

The recent years of intense public interest in AM have shown that the possibilities afforded by the technology can be confounding, even for seasoned technologists and manufacturing experts. While the potential of single material AM is seemingly well-understood in particular industries, especially in aerospace and the medical domain, there are still many open issues and obstacles that stand in the way of truly manufacturing-compatible AM technology. As our research portfolio demonstrates, these may be located upstream of the AM process, encompassing novel computational design techniques and new raw material provision, or downstream for example in post-processing, product qualification and supply chain integration tasks.

Our research over the recent years has further shown that the engineering challenges faced by multi-functional AM processes, which are capable of depositing multiple materials in unison, are markedly distinct from those faced by their single-material cousins. The broad and interlinked structure of our research activities, supported by a closely-knit team, forms the basis for our position of global leadership in multiple areas of AM-related research.

Whilst always keeping a keen eye on industrial implementation, the vision guiding CfAM has always had its focus ahead of the current state of the art of AM technological capability. Throughout the last two years, this vision has helped sustain a thriving international research community, featuring both industrial and academic collaborators, such as, amongst significant others: Astra Zeneca, AWE, BAE Systems, GSK, PPG, Texas Instruments (industrially) and Lawrence Livermore National Laboratory, Karlsruhe Institute of Technology and the Universities of Birmingham, Oxford, Stanford and Warwick (academically).

By engaging closely with the aerospace, automotive, defence, pharmaceutical, biotechnology and electronic industries, CfAM has a recognised track record of translating its research through to commercial use. To support this activity, the members of CfAM have established a dedicated contract research organisation (addedscientific.com) to engage with partners in the industrial ecosystem. By also engaging with international AM research groups and the UK academic science and engineering community (with a focus on involving stakeholders in other EPSRC funded research groups) our work has helped progress different aspects of AM technology from engineering research stages towards truly manufacturing-ready processes. Our highly successful and influential Additive International conference is testament to our role in bringing together various industrial and academic stakeholders to help shaping progress in the development of AM technology.

Cover: Pure copper jetted using CfAM's exclusive MetalJet technology.

This report outlines six complementary but interacting fields of research we are engaged in, each of which has created significant theoretical contributions and avenues for new industrial systems, and associated intellectual property. These fields are:

- 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

Corresponding to our pursuit of these interconnected strands of research, the period covered in this report, 2017-2019, has been marked by the emergence of a new group of early career academics within CfAM. Enabled by one Anne McLaren Fellowship, two Nottingham Research Fellowships, and two Transitional Assistant Professorships, all of which will lead to permanent academic posts at Nottingham, as well as the very recent addition of a new Assistant Professor to support the delivery of our new postgraduate taught course, the group of core academics supporting CfAM is currently in the process of expanding and renewing itself.

Strengthened by our new members and underpinned by our extensive portfolio of research, we are in an excellent position to continue delivering our progressive programme of complementary research over the coming years. This is set to continue, facilitating the technology readiness of exciting new engineering approaches and value-creating process implementation. In this we will draw on the world-unique and diverse mix of AM equipment we have at our disposal here at the Advanced Manufacturing Building at Nottingham.

As with any collective endeavour, our success rests on the shoulders of all our members and contributors, past and present. In particular, we would like to thank our postdoctoral researchers, doctorate students, industrial partners, academic collaborators, technical team and our support staff for their hard work. Additionally, we would like to use this opportunity to express gratitude towards our funders and the members of our Advisory Boards for supporting us in our ambitious project of establishing AM technology as a dominant manufacturing approach for the 21st Century.

Professor Richard Hague

> "The interlinked and closely-knit structure of our research activities forms the basis for our position of global leadership in multiple areas of AM-related research."

Overview of the Centre

In addition to the extensive polymeric and metallic single material activity undertaken within the CfAM, we are excited to also be continuing our research efforts into next generation multifunctional AM, where both functional and structural materials are co-deposited for the generation of systems, as opposed to components. Such an approach allows us to investigate the engineering of high performance, durable and life-changing items such as prosthetic limbs, complex pharmaceutical devices and advanced electronic components.

Key research areas include:

- design systems and software tools for both single and multifunctional AM
- modelling of AM processes
- high throughput materials discovery for polymeric materials
- new alloy development for Selective Laser Melting, including both structural materials as well as functional materials (e.g. lightweight alloys, hard / soft magnetic alloys, copper and tungsten-carbide)
- reactive jetting of polymeric materials
- multimaterial jetting of functional nano-particulate inks and dielectrics
- jetting of syntactic foams and silicones
- drop-on-demand jetting of high temperature metallic materials
- micro and nano scale multifunctional AM utilising multiphoton 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

Centre highlights

- CfAM moved to the purpose built state-of-the-art Advanced Manufacturing Building (AMB) in December 2017 which includes new laboratories and a clean room facility for pharma-related activities.
- £5.8 million EPSRC award for the 'Enabling Next Generation Additive Manufacturing' Programme Grant, starting October 2017.
- promotion of CfAM research staff – a prestigious Anne McLaren Fellowship and two Nottingham Research Fellowships, as well as two Transitional Assistant Professorships were awarded to CfAM postdoctoral research fellows. All the awards will lead to permanent academic posts.
- the EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing and 3D Printing recruited its fifth and final cohort in 2018/19. Cohort 1 is in their final year.
- the annual Additive International conference now attracts over 370 delegates over the course of the three days, representing more than 200 institutions, and includes a parallel exhibition showcasing developments in AM and wider manufacturing industries.
- promotion of Professor Chris Tuck to Associate Pro-Vice Chancellor for Research and Knowledge Exchange for the Faculty of Engineering, University of Nottingham.

The Advanced Manufacturing Building, Jubilee Campus, Nottingham.

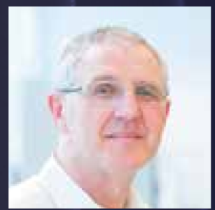
Key individuals

Investigators

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

Professor Chris Tuck
Professor of Materials Engineering,
Faculty Associate Pro-Vice Chancellor for Research and Knowledge Exchange and Director of the EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing

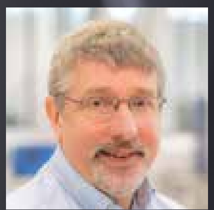
Professor Ian Ashcroft
Professor of Mechanics of Solids,
Faculty of Engineering,
University of Nottingham



Professor Phill Dickens
Professor of Manufacturing Technology,
Faculty of Engineering,
University of Nottingham

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

Dr Ruth Goodridge
Associate Professor,
Faculty of Engineering,
University of Nottingham



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

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

Research fellows

Dr Nesma Aboulkhair
Anne McLaren Fellow,
Faculty of Engineering,
University of Nottingham

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

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

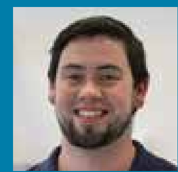
Dr Meisam Askari
Research Fellow,
Faculty of Engineering,
University of Nottingham

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

Amy Stimpson
Research Associate,
Faculty of Engineering,
University of Nottingham

Dr Adedeji Aremu
Research Fellow,
Faculty of Engineering,
University of Nottingham

Dr Qin Hu
Research Fellow,
Faculty of Engineering,
University of Nottingham



Dr Adam Thompson
Research Fellow,
Faculty of Engineering,
University of Nottingham

Dr Xuesheng Chen
Research Fellow,
Faculty of Engineering,
University of Nottingham

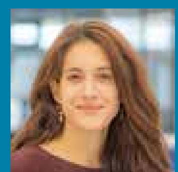
Dr Ian Maskery
Nottingham Research Fellow,
Faculty of Engineering,
University of Nottingham

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

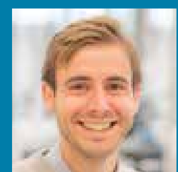
Dr Elizabeth Clark
Research Fellow,
School of Pharmacy,
University of Nottingham

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

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



Dr Kyriaki Corinna Datsiou
Research Fellow,
Faculty of Engineering,
University of Nottingham



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

Dr Zuoxin Zhou
Research Fellow,
Faculty of Engineering,
University of Nottingham

Research fellows (cont'd)

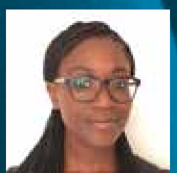
Dr Jin Ding
Research Fellow,
Faculty of Engineering,
University of Nottingham

Dr Xuesong Lu
Research Fellow,
Faculty of Engineering,
University of Nottingham

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

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

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



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

Support staff

Mirela Axinte
CfAM Research Co-ordinator,
Faculty of Engineering,
University of Nottingham

Dr Harinee Selvadurai
Programme Manager – EPSRC 'Enabling Next Generation Additive Manufacturing' Research Programme,
Faculty of Engineering, University of Nottingham

Romina Davoudi
CDT Operations and Development Manager,
Faculty of Engineering,
University of Nottingham

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

Mark Hardy
Technician,
Faculty of Engineering,
University of Nottingham

Joe White
Technician,
Faculty of Engineering,
University of Nottingham

Developing a wave of future leaders

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 five CfAM researchers have been awarded prestigious fellowships and transitional posts, all of which lead to permanent new academic positions over the coming years.

We are delighted to report that Dr Nesma Aboulkhair was awarded an Anne McLaren Fellowship, Dr Marco Simonelli and Dr Ian Maskery were both awarded Nottingham Research Fellowships, and Dr Yinfeng He and Dr Laura Ruiz-Cantu successfully obtained Transitional Assistant Professorships.

> "Establishing the next generation of thought leadership at CfAM."

Anne McLaren Fellowship

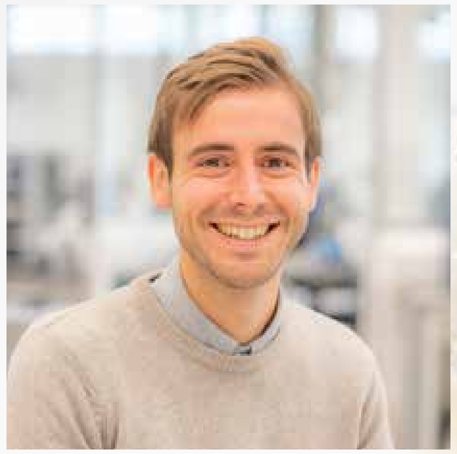
We are extremely pleased that Dr Nesma Aboulkhair, who first joined CfAM as a PhD student in 2013, was awarded an Anne McLaren Fellowship in 2017.

In the early phases of her activities as a post-doctoral research fellow, **Dr Aboulkhair** embarked on an ambitious career path by successfully applying for this prestigious opportunity. Her three year project focusses on high temperature metal AM using the novel droplet-on-demand technology. Referred to as 'MetalJet', this technology is exclusively available at CfAM. Dr Aboulkhair's research includes the optimization of the jetting process to print pure copper and other metals, controlling droplet deposition, studying the effect of using metallic and dielectric substrates, and characterising the 3D printed structures. The ultimate aim of this programme of research is to demonstrate the capability of producing fully 3D printed micro-electronic components. Dr Aboulkhair's current role as an Anne McLaren Fellow at CfAM offers an ideal starting point for a successful academic career in this field.

Contact between copper droplets deposited by MetalJet

Nottingham Research Fellowships

At CfAM we are delighted that Dr Marco Simonelli and Dr Ian Maskery were both awarded prestigious Nottingham Research Fellowships in 2018. Nottingham Research Fellowships are competitively awarded internal three year fellowship schemes designed to enable the realisation of the University of Nottingham's Research Vision.

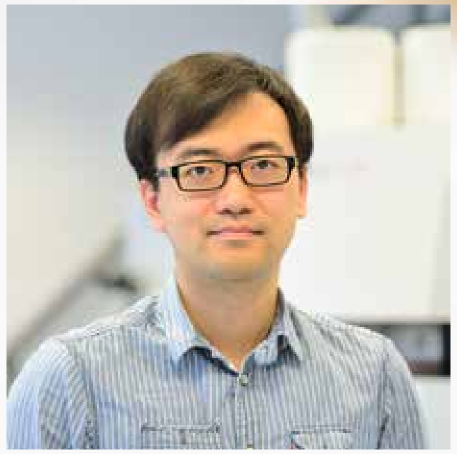


Dr Marco Simonelli joined CfAM as a PhD student in 2010. After being involved in a number of research projects which provided him with extensive international experience, he successfully sought a Nottingham Research Fellowship to explore the new horizons offered by metal AM. Dr Simonelli's research addresses 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, Dr Simonelli aims to significantly advance the state-of-the-art of this technology, benefitting applications in the aerospace and medical sectors. However, Dr Simonelli anticipates that the discovery-led nature of this research will provide foundations for broad industrial applications over the years to come.

Dr Ian Maskery joined CfAM in 2013 after obtaining a PhD in Physics, and was excited to bring his knowledge and skills to a completely new area of research. He quickly became interested in extending the use of AM cellular structures, or lattices, beyond their current applications. This became the focus of his successful Nottingham Research Fellowship proposal. Dr Maskery's three-year project will investigate the use of AM lattices for thermal management, vibration isolation and dynamic impact protection. Other promising research avenues include new lightweight alloys for metal AM, as well as the development of computational design and optimisation tools (including CfAM's in-house lattice design software, FLatt Pack). A combined approach of experimental and computer simulation will enable the creation of advanced AM components, those which incorporate much greater functionality than is currently available. Dr Maskery looks forward to building on his Fellowship position to establish a successful academic career within CfAM.

Transitional Assistant Professorships

We are proud that Dr Yinfeng He and Dr Laura Ruiz-Cantu have both been promoted to Transitional Assistant Professor roles. Transitional Assistant Professorships provide a pathway to a permanent academic position for early career researchers. In the initial stage, the posts will concentrate on research with a minimal teaching load, while by the end of the scheme the workload is evenly distributed between research and teaching and the post holder will become a permanent member of CfAM, and the Department within the Faculty of Engineering.



Dr Yinfeng He joined CfAM in 2011 as a PhD student, and has since focused on advanced materials development for inkjet 3D printing. In 2018, he was awarded a Transitional Assistant Professorship to work on functional polymerisable formulations for inkjet based multimaterial 3D printing processes. He is currently part of the EPSRC 'Enabling Next Generation Additive Manufacturing' Programme to study inkjet printable smart materials and interaction between different materials during multimaterial inkjet 3D printing processes. Dr He's research in multimaterial inkjet 3D printing will open up the capability to design and produce more intelligent, complex and compacted devices that are hard to achieve with traditional manufacturing techniques. The ultimate aim of his research agenda is to pursue the production of next generation biomedical or electronic devices, at smaller scales with more functional complexities, but without sacrificing customisation and production speed.

Dr Laura Ruiz-Cantu joined the University of Nottingham in 2012 to study for a masters degree in Stem Cell Technologies and Regenerative Medicine, followed by a PhD in 3D Bioprinting in the Tissue Engineering group. After completing her PhD, Dr Ruiz-Cantu joined CfAM as a post-doctoral research fellow. Joining CfAM offered her the opportunity to pursue her own research plans, leading to her successful application for a Transitional Assistant Professorship. Her research involves the use of multimaterial ink jet printing technology to create biodegradable implants. These implants resemble the architecture of bone tissue and also deliver biopharmaceuticals to help with the regeneration of bone defects. This technology could in future be adapted to target other types of body tissues. Dr Ruiz-Cantu's new position at CfAM will offer her the opportunity to become an academic leader in the area of Bioprinting and Regenerative Medicine.

Next generation glass structures fabricated by AM.

Facilities

In December 2017 CfAM moved to the purpose-built Advanced Manufacturing Building (AMB) on the University of Nottingham's Jubilee Campus. Also housing the Institute for Advanced Manufacturing and the Composites Research Group, this impressive building provides an inspiring environment for research and teaching.

Contained in a large section on the ground floor of the building, CfAM's new 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 special and bespoke AM technologies that are not available elsewhere in the world. These include experimental multimaterial 3D ink jetting systems, ranging from small scale exploratory research platforms to large scale systems such as the PiXDRO Toucan, high-temperature liquid metal jetting systems (MetalJet) and custom-built multimaterial micro-additive systems based on multi-photon lithography technology.

We are pleased to report that an additional £1 million from the Wolfson Foundation was secured by CfAM and the School of Pharmacy to incorporate a clean room in the laboratory. This new facility widens the palette of materials for 3D ink jet 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 ink-jetting and analysis equipment, alongside a pharmaceutically focused liquid extrusion printer system.

> “Moving to a bespoke new building has allowed us to expand our unique portfolio of AM processes and devices, with the addition of a clean room facility.”

Dr Laura Ruiz-Cantu working in the new clean room facility. The yellow tint is due to a film added to the window to prevent UV light entering.

Major grant successes at CfAM

Enabling Next Generation Additive Manufacturing Programme Grant

Funder: EPSRC, £5.85 million

Project Team: Professor Richard Hague, Professor Chris Tuck, Professor Ricky Wildman, Professor Derek Irvine, Professor Ian Ashcroft, Professor Clive Roberts (School of Pharmacy), Professor Mark Fromhold (School of Physics and Astronomy), Dr James Sprittles (University of Warwick), Professor Yulii Shikhmurzaev (University of Birmingham), Dr Gustavo Ferraz Trindade (School of Pharmacy), Dr Mykyta Chubynsky (University of Warwick), Dr Peng Zhao, Dr Xuesheng Chen, Dr Qin Hu, Dr Feiran Wang (School of Physics and Astronomy), Dr Yinfeng He, Dr Laura Ruiz-Cantu, Dr Nesma Aboulkhair, Dr Marco Simonelli, Amy Stimpson.

Led by Professor Richard Hague, this Programme is a collaboration between the universities of Nottingham, Birmingham and Warwick. Major external partners include the Lawrence Livermore National Laboratory, National Physical Laboratory, Karlsruhe Institute of Technology, Dstl, AWE, AstraZeneca, Océ-Technologies BV, and Texas Instruments.

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. To achieve the integrity and functionality of the separate, but combined, structural and functional materials over many thousands of deposited layers, this research addresses the following objectives:

- develop understanding at the droplet, voxel and layer levels of how multimaterials interact as they progress through the various states and stages of deposition for 3D ink-jetting, high-viscosity jetting, metal-jetting and multi-photon fabrication.
- generate new predictive modelling capability for multimaterial coalescence where we may want materials to remain discrete, or may require mixing, inter-diffusion or chemical reactions for the in-process formation of new materials.
- find strategies to overcome inter and intra layer functional anisotropy for electronic and healthcare materials.
- identify key strategies to control the material deposition and dynamically change layer interfaces and interphases between multiple structural and functional materials in 3D.

The Programme has got off to a strong start with two journal papers already published during year one. In the year ahead the Programme will focus on new developments in 3D nanoscale mass spectrometry by exploring a state-of-the-art hybrid ToF-SIMS Orbitrap instrument recently acquired by the University of Nottingham. We will exploit the computational model to discover the physical mechanisms governing the MetalJet process and hence optimise its performance, identify low dimensional materials and devise a methodology for printing. We will continue to investigate the influence of scan strategy, co-polymer and solvent on 2PP connectivity. Additionally, the Programme will characterise and optimise current devices, especially the study of voxel size (layer thickness) to reveal the subtle chemical mechanism of layer deposition. This will help to improve the piezo jetting process and device functionality, thus permitting a mature deposition strategy.

Single chip with hundreds of 3D architecture patterns fabricated by two-photon lithography for high throughput screening.

Formulation for 3D Printing: Creating a Plug and Play Platform for a Disruptive UK Industry

Funder: EPSRC, £3.53 million

Project team: Professor Ricky Wildman, Professor Clive Roberts (School of Pharmacy), Dr Tom Mills (University of Birmingham), Professor Derek Irvine, Professor Morgan Alexander (School of Pharmacy), Professor Richard Hague, Professor Chris Tuck, Professor Ian Ashcroft, Professor Tim Foster (School of Biosciences), Professor Simon Avery (School of Life Sciences), Professor David Amabilino (School of Chemistry), Professor Ian Norton (University of Birmingham), Dr Fotios Spyropoulos (University of Birmingham), Dr Zuoxin Zhou, Dr Elizabeth Clark (School of Pharmacy), Dr Shaban Khaled (School of Pharmacy), Dr Saumil Vadodaria (University of Birmingham), Dr Azarmidokht Gholamipour-Shirazi (University of Birmingham), Dr Vincenzo di Bari (School of Biosciences), Dr Lewis Hart (University of Reading), Dr Lea Santu (School of Chemistry).

Led by Prof Ricky Wildman, this project is a collaboration between the universities of Nottingham, Birmingham and Reading. External partners inlcude GSK, Malvern Instruments, Syngenta, Unilver and PPG Industries.

By using high throughput methods and approaches to identify materials and formulations suitable for Additive Manufacturing and 3D Printing, the Formulation for 3D printing 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, 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 exploitation of the key benefits of 3D printing: freedom of design, complexity and personalised manufacture.

The project is organised in four overlapping and intersecting research challenges:

- building a sector specific materials library
- researching formulations for multiactive compartmentalisation and delivery
- formulating materials for structure and texture via the medium of 3D printing
- feeding the pipeline for high throughput formulation

The project recently had a very positive mid-term review and has so far published five journal papers, with a further six submitted. One of our remaining challenges is to capture and securely store all the data generated, whilst still ensuring that the data is able to be shared and be effectively available.

3D inkjet printed tablets cured with UV light.

Future Additive Manufacturing Platform Grant

Funder: EPSRC, £1.73 million

Project Team: Professor Richard Hague, Professor Chris Tuck, Professor Ian Ashcroft, Professor Ricky Wildman, Professor Phill Dickens, Dr Ruth Goodridge, Dr Martin Baumers, Dr Xuesheng Chen, Dr Adedeji Aremu, Dr Aleksandra Foerster, Dr Jayasheelan Vaithilingam, Dr Corinna Kyriaki Datsiou, Mark East, Joseph White.

The Future Additive Manufacturing Platform covers research activities that are common to both single and multimaterial AM. 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 formulation problems, break the process and material links that slow progress and allow a focus on exploitation of the key benefits of 3D printing: freedom of design, complexity and personalised manufacture. 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 to explore speculative ideas emanating from emerging research within CfAM and elsewhere. Such studies often lead to new project-based funding.
- responsiveness to emerging industrial and scientific problems and opportunities, and opportunistic support for developing new collaborations, deployment of available skilled researchers, and responding to calls for proposals from EPSRC, industry and other funding providers.
- bridging and retention of key research staff, where the grant is used as bridging funding to support researchers between contracts, enabling employment on short-term feasibility and industrial projects.
- staff development, focussed particularly on broadening the multidisciplinary skills base, translational skills, national and international networking.
- long-term planning activities, implemented as a structured programme of engagement and consultation with stakeholders, debating of new directions, and renewal of the research agenda in line with national priorities.

The Platform Grant has supported 13 projects ranging from 'Machine learning as a design tool for additive manufacturing solutions' to 'Development of a reactive inkjet powder bed printing process'.

PhD student David Pervan operating the Realizer 50 Selective Laser Melting system.

Additional funding successes

3D glass laser-sintered structures (3D GLaSS)

Project team: Dr Kyriaki Corinna Datsiou, Fiona Spirrett, Professor Ian Ashcroft, Dr Ruth Goodridge

Funder: Innovate UK, £164,000

A laser powder bed fusion method has been successfully developed in this project for soda lime silica glass. Glass feedstock, laser powder bed fusion set-up and processing parameters have been optimised enabling the formation of glass structures with micro- / macro-scale resolution and high levels of complexity in design that cannot be achieved with conventional glass-forming methods. These findings provide the stepping stone for the formation of a new generation of glass structures for a wide range of applications from chemistry and bio-medical to decorative glass industries.

Engineering sustainable squalene analogues for novel vaccine adjuvant formulations

Project team: Dr Cordula Hege, James Summers (School of Chemistry), Professor Derek Irvine, Professor Steven Howdle (School of Chemistry), Dr Christopher Dodds, Dr Christopher Fox (Infectious Disease Research Institute, Seattle, USA)

Funder: National Institutes of Health Sciences, £121,000

This multidisciplinary project will develop the additive manufacturing production of squalene analogues using synthesis chemistry / chemical engineering approaches, and prove their efficacy by emulsion formulation development and biological evaluation for adjuvant activity in *in vitro* human and *in vivo* mouse and ferret models.

3D printed formulations: Additive Manufacturing

Project team: Dr Elizabeth Clark, Dr Xuesheng Chen, Dr Jin Ding, Dr Jayasheelan Vaithilingam (CfAM alumni), Dr Shaban Khaled (School of Pharmacy), Professor Ricky Wildman, Dr Martin Baumers

Funder: GlaxoSmithKline, £366,300

This project looks at the feasibility of manufacturing drug release solid dosage forms (tablets) using inkjet, SLA and extrusion printing. These AM platforms offer geometric flexibility and additional control over dosage design, which may allow for the production of personalised medicines.

Jetting of silicones and phase 2 micro-SLA cellular structures

Team members: Dr Aleksandra Foerster, Professor Derek Irvine, Professor Ricky Wildman, Professor Richard Hague, Professor Chris Tuck

Funder: AWE, two awards totalling £818,500

This project developed a novel Additive Manufacturing (AM) system based on material jetting and the processing parameters for printing highly viscous polysiloxanes that could be processed by both thermal and UV curing techniques.
A continuation of this project focuses firstly on developing a library of material formulations for UV curable silicone showing variation in extensibility, compressive properties for ink jet printing and potential for conformal printing. Secondly, it looks at printing a representative design to demonstrate the capability of photocurable formulations using Micro Stereolithography.

Complex materials for advanced device fabrication

Project team: Dr Qin Hu, Professor Ricky Wildman, Professor Derek Irvine, Professor Richard Hague and Professor Chris Tuck

Funder: Air Force Office of Scientific Research, £155,400

Two photon polymerisation capability in CfAM was extended to include multibeam capability through the use of diffractive optics. This work was complemented by studies exploring how photoreduction can be used to understand how metal based nanoparticles can be used to create composites on the nanoscale.

Optimisation of the patented reactive inkjet powder bed Additive Manufacturing technology

Project team: Dr Yinfeng He, Dr Kaiyang Wang, Professor Richard Hague, Professor Ricky Wildman, Professor Chris Tuck, Professor Derek Irvine

Funder: Nottingham Impact Accelerator, £35,000

We are carrying out further development and optimization work on a new powder bed based reactive inkjet printing technique, which has been patented by CfAM, to generate chemically 'sintered' structures with more homogeneous spatial properties and better inter-particle binding than traditional laser or IR sintering processes.

A transatlantic institute for volumetric powder bed fusion

Project team: Dr Ali Sohaib, Professor Ian Ashcroft, Professor Phil Dickens, Professor Richard Hague, Professor Ricky Wildman, Professor Chris Tuck

Funder: National Science Foundation and EPSRC, £254,000

Electromagnetic energy in the microwave and/or radio frequency (RF) spectrum is used to volumetrically solidify selective regions of a polymer powder bed. This volumetric sintering approach has the potential to produce parts with better mechanical properties, along with a reduction in product development cycle time relative to commercial Laser Sintering.

Wearable soft robotics for independent living

Project team: Dr Asish Malas, Dr Ehab Saleh (both CfAM alumni), Professor Ian Ashcroft, Professor Chris Tuck and Dr Ruth Goodridge

Funder: EPSRC, £318,000

Targeted materials development for aerosol and material jetting was undertaken in order to develop new compliant smart materials and structures for fabrication into soft robotic components. We also worked to improve the dielectric constant of base elastomers and combined with the jetting of conducting electrode materials to produce soft stacked actuators.

Metal jetting of functionally graded materials

Project team: Dr Marco Simonelli, Dr Nesma Aboulkhair, Mark East, Professor Ricky Wildman, Professor Chris Tuck, Professor Richard Hague

Funder: AWE, £618,800

A unique droplet-on-demand (DOD) technology 'MetalJet', which is equipped with four print-heads capable of ejecting and depositing tens-of-microns-sized droplets of high temperature (up to 2,000°C) conductive metals, is used to fabricate multimaterial three-dimensional structures with unprecedented precision. State-of-the-art characterisation techniques are used to investigate the interfaces of dissimilar materials printed using this bespoke technology.

Functional lattices for automotive components (FLAC)

Project Team: Dr Ian Maskery, Professor Chris Tuck, Professor Ian Ashcroft, Professor Richard Leach, Professor Adam Clare, Professor Ricky Wildman, Professor Richard Hague.

Funder: Innovate UK, £368,300

In addition to developing metal AM as an advanced production tool with FLAC's industrial partners, the project resulted in multiple journal publications detailing lattice structure design and performance. CfAM looks forward to participating in future research and development projects with the other FLAC partners.

Foresight fellowships in manufacturing – The future of Additive Manufacturing

Fellow: Professor Phill Dickens

Funder: EPSRC, £198,300

This fellowship scoped the possibilities to see UK academics inventing entirely new AM processes that are orders of magnitude faster than current processes, and helped to establish a UK Strategy for Additive Manufacturing that enables and accelerates UK industry to be world-leading at exploiting the technology. The fellowship brought together academics from different disciplines with the existing AM community in the UK to explore the potential for volume processing of materials at high speed.

Single layer of silver droplets deposited by MetalJet.

Processes

Existing AM technology operates on the principle of adding material in a sequential process, which is captured in the word ‘additive’. It affords an ability to manufacture parts and products directly from raw materials in powder, liquid, sheet or filament form using digital 3D design data. A central characteristic of Additive Manufacturing is that the process operates by depositing material, usually layer-by-layer, without the need for moulds, tools or dies of any kind.

Within CfAM, we are taking a broad multidisciplinary approach to investigating the ways of evolving Additive Manufacturing to the next technological level. This may be in the form of new, more effective or better integrated single material technology, or through technology capable of depositing multiple dissimilar materials within a single build procedure to print distinct functional structures, or entire working systems.

A spotlight on material jetting technology

Material jetting, a drop-on-demand processing technique, has been widely recognised as one of the most promising AM approaches for the production of multimaterial and multi-functional devices. However, understanding the mechanisms behind jetting-based multimaterial 3D printing is still in its infancy. At CfAM, we are carrying out a range of fundamental research activities to generate insight into how multimaterial AM can be implemented.

This research includes the simulation of droplet impact and coalescence under extreme temperatures (>1,000°C) or UV radiation; solidification of deposited droplets by either cooling or photopolymerisation; chemical and physical interactions between droplets and layers from the same and different materials. With the help of advanced characterisation techniques (TOF-SIMS, Orbi-SIMS, Confocal Raman Microscope, FIB-SIMS, FIB-SEM etc.) available at the University of Nottingham and from other collaborators, we have succeeded in, for the first time, tracking and characterising the interactions between droplets at micron or sub-micron level.

On the basis of such characterisation, data and cooperation with our simulation team, models are being built including: high temperature metal melt droplets impact and solidification, prediction of spatial reactive monomer conversion during UV curing based jetting process, understanding of droplet spreading and coalescence under UV curing conditions. All these elements yield insights into the jetting process which then allows an optimisation of product properties and processes, in order to achieve our final goal of producing reliable multi-functional devices that can be applied in real life.

Negar Gilani using a drop-watcher camera during a MetalJet experiment.

Materials

Materials research at CfAM encompasses a wide range of areas from improving and better understanding existing formulations or alloys, to developing new materials in order to expand the library of AM processable materials; this materials research is undertaken for polymeric and metallic structural materials, as well as a range of functional materials for biological, pharmaceutical and electronic applications.

Alongside a strong pedigree and expanding portfolio of work investigating materials for single-material based AM (e.g. SLM, SLA, material jetting, multiphoton lithography), much of our materials work is also motivated by a strong drive towards understanding what interactions occur at the interface of dissimilar materials, e.g. polymeric and metallic, after AM processing. We are using this knowledge to improve the functionality of multimaterial printed articles by using methods or additives to improve adhesion between voxels / layers.

Among the avenues of research explored, we are developing new nanoparticulate formulations containing gold. Despite the high price of gold, there are benefits to making gold-based ink which are of particular interest in printed electronics. It has good chemical stability and a high work function, yet does not suffer from migration issues common to other metal nanoparticles which results in device failure. Materials based on gold nanoparticles will be used to print electrode structures with a synergistic effect in combination with organic / 2D materials.

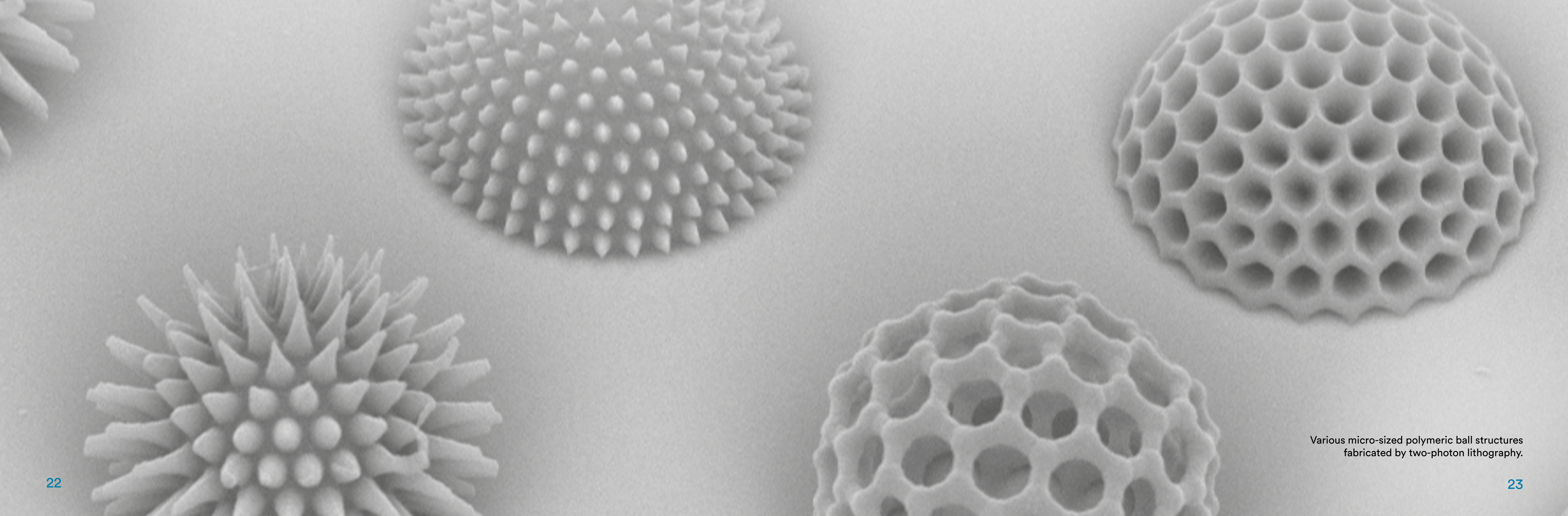
In collaboration with colleagues at Imperial College London, we are synthesising new graphene-loaded polymer resin for two-photon lithography based 3D printing at the micro / nano scale. Additionally, graphene is of interest for printed electronics, where we are looking to functionalise it with surfactants which allow the retention of graphene's conductivity, as well as improve the printing resolution. It is hoped a method of formulating and processing graphene containing inks can be applied to other low dimensional materials, such as hexagonal boron nitride and molybdenum disulfide.

Design systems and computational methods

Many of CfAM's projects are underpinned by computational methods, including some created within the group specifically to open up new areas of AM research and design. A principal example of this is the Functional Lattice Package (FLatt Pack), a program created at CfAM to explore the design and performance of a new range of AM cellular structures. This has been taken up by researchers and students throughout the group and is now used on projects spanning vehicle lightweighting, human bone implants, high-precision metrology instruments and the design of acoustic metamaterials. Other examples of our in-house software development include tools for AM build optimisation, to ensure that products are manufactured as efficiently, cheaply and quickly as possible, and another tool for placement and routing optimisation which is a special function required for the design of multifunctional AM components.

CfAM also draws on a range of numerical modelling techniques, including finite element analysis (FEA) and computational fluid dynamics (CFD) in its research. These are used to predict the mechanical performance of AM components and model their interactions with their environments. These are also often paired with topology optimisation, another computational method of high relevance in AM, in order to design components which far surpass the performance of those available by conventional manufacturing processes.

CfAM's development of these new design processes adds crucial support and complementarity to its other research endeavours, and ensures that the next generation of AM leaders are versed and highly skilled in the important aspects of AM design.



Various micro-sized polymeric ball structures fabricated by two-photon lithography.

AM management

Like all technologies aimed at industry, current and future AM systems must be successfully deployable in a commercial setting. As shown during the emergence of earlier kinds of digitally controlled manufacturing technologies, such as numerically-controlled machining systems in the second half of the 20th century, the effective use of new manufacturing technologies requires new complementary management approaches.

As a nascent field, AM management is concerned with creating, operating and controlling an AM transformation system that takes a variety of inputs and produces outputs needed by users, which may well be the consumer. One important objective of such a process is to allow the AM technology user to maximise profits or minimise cost, while at the same time generating the best possible product.

It is observable in the AM industry that distinct AM management methods are currently emerging. These methods need to deal with two special aspects of AM. First, AM is a digitally integrated 'parallel' manufacturing technology enabling the contemporaneous creation of different parts or products. Second, due to the absence of digital tooling AM allows the manufacture of highly complex or customised products at a relatively low unit cost.

Taking an operational view on AM management, research at CfAM is concentrating on tools and methods needed to utilise the technology in an efficient way. Linked to the computational-design tools supporting AM, our activities have shown that the processes needed to organise AM will require optimisation capability, for example to coordinate the work flow across multiple AM systems in multiple time periods or to control supply chains incorporating AM.

Through a series of research projects, the activities at CfAM have produced additional insight into the cost structure of AM, highlighting the role of so-called ill-structured costs related to build failure, process robustness and problems with the integration of AM with other manufacturing functions. In line with the theme of benefitting from a breadth of expertise, such knowledge greatly complements the engineering research carried out at CfAM and permits a qualification of CfAM's technological research products from the outset.

Customised biofilm inhibition devices manufactured by inkjet based 3D printing.

Applications-level research

The process of translating scientific discoveries into engineering applications, and ultimately productive processes available to industry, forms an important part of the work taking place at CfAM. This process is often described as "translational research" since different kinds of expertise and activities are involved in the progression of knowledge from our laboratory to industrial practice.

Following our research at low technology readiness levels, generating and verifying the operating principles of new additive manufacturing technology, the scope of our translational research includes the exploration of proposed applications as well as research into technical suitability and efficiency. This leads to proven applications and finally to implementation and adoption of new AM technologies. Our applications-level research is undertaken either as part of larger research projects, for example in the form of dedicated work packages aiming to establish the value proposition of new AM approaches, or as specific research projects set up to generate application-ready research outputs.

Within this 'zone of translation' CfAM engages with a wide range of industrial partners looking to understand and implement AM within their value chains. Our collaborators include high profile organisations such as Philips, GSK, Astra Zeneca and EON, amongst many significant others. In some cases, our engagement takes the form of simply facilitating visits to the CfAM laboratories and meetings with academics and researchers, or hosting ideation sessions workshops and training sessions with industry. In other cases we engage in industry funded translational research projects with our industry partners.

Networking at a CDT Industry Day.

Doctoral research

CfAM has a wide range of doctoral research projects ranging from mechanical engineering and materials development to biochemistry and pharmacy. We recruited 40 doctoral research students during 2017/18 and 2018/19, which includes PhD students and doctoral students who are part of our EPSRC Centre for Doctoral Training (CDT).

Training future research leaders in Additive Manufacturing, the EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing and 3D printing continues to be an integral part of CfAM. The CDT is led by the University of Nottingham in collaboration with the Universities of Liverpool, Loughborough and Newcastle and offers a 4 year PhD programme. Cohorts 4 and 5 were recruited in 2017-19, and we are proud to report that students from Cohort 1, who were recruited in 2014/15 have either been awarded their doctorate or are about to submit their theses.

The CDT has continued to develop its training programme and introduce a range of new activities. A new Biomedical Additive Manufacture and Biofabrication module delivered by colleagues from the University of Newcastle was launched in 2017/18, and we organised and hosted a number of visits and events including a discussion with the National Defence University, USA, 'Women in 3D Printing' and 'Multidisciplinary Collaboration'.

Our Annual Industry Visit Days attracted over ninety delegates from industry, academia and CDT students, and the CDT's Annual *Nature* Publication Masterclasses, which are designed to teach research staff and students how to write high-quality scientific manuscripts and optimise their chances of being published in high impact journals, has been getting very good feedback from participants.

We have been building relationships with other CDTs, and now have formal links to both the Horizon CDT at Nottingham and the Risk CDT in Liverpool, with students working between them.

Creativity@Home events have encouraged students to explore different tools and techniques to unlock creative energies and remove the blocks and constraints associated with group thinking. Students have also been continuing their outreach activities, including Christmas Lectures and Pint of Science events.


CDT cohort 4.


CDT cohort 5.


Alex Gullane and Shreeja Basak in the laboratory.

Outreach activities @CfAM

At CfAM, we understand the importance of an effective portfolio of outreach activities in supporting the delivery of our research vision. CfAM researchers and students have taken part in a variety of outreach activities to engage with schools, undergraduate students, businesses and the wider community.

- STEM Club, St Edward's School, Liverpool
- Academic Support Family Leaning Club sessions, Nottingham
- Christ the King College visit, University of Nottingham
- Family Learning Graduation Day, Nottingham
- Shirebrook Academy Industry Day, Nottingham
- Starworks: Innovations in Prosthetics for Young People
- Christmas Lecture 2017, University of Nottingham
- Open-source Prosthetic Assistive, adaptive and rehabilitation Devices (OPAD) workshop for undergraduates, University of Nottingham
- Careers event, University of Nottingham
- Pint of Science 2018, Nottingham
- EDT Routes to STEM, University of Nottingham
- I'm an Engineer, get me out of here! University of Nottingham
- Nanoscience outreach days, University of Nottingham
- Year 10 girls physics taster days, University of Nottingham
- Engineering YES (Young Entrepreneur Scheme), University of Nottingham
- Christmas Lecture 2018, University of Nottingham
- Ingenuity Breakfast Event, "3D Printing – Tool or Toy?" Ingenuity Network, University of Nottingham


School students visit our facilities.

Additive International

Additive International, formerly The International Conference on Additive Manufacturing and 3D Printing, founded in 2006, takes place annually at the Belfry Hotel, Nottingham, UK each July. Over the years this two-day event has built a reputation as a leading technology transfer event for both academic and industrial experts in Additive Manufacturing and incorporates many networking opportunities where invaluable connections are made.

Aligned with Additive International, the event also hosts a pre-conference day, giving delegates the opportunity to attend for three days if desired. In July 2017, during the pre-conference day, talks were presented in the morning highlighting the more challenging aspects of AM entitled 'Industrial Realities of AM' and was followed in the afternoon by an update on the UK National Strategy for AM. In 2018, this day was hosted in partnership with the InnovateUK Knowledge Transfer Network, during which there was an update on the UK's AM Strategy, which has identified business opportunities of £3.5 billion per year.

Additive International now attracts over 370 delegates over the course of the three days, representing more than 200 institutions, and includes a parallel exhibition showcasing a number of organisations whose technology, expertise and products are driving development in AM and wider manufacturing industries.

Richard Hague, CfAM Director opening the 13th annual Additive International Summit in July 2018.

Added Scientific Ltd

Established in 2014 by a group of CfAM academics, Added Scientific Ltd (ASL) has combined expertise with innovative research and design to provide commercial research and development services for companies keen to push the boundaries of Additive Manufacturing.

ASL services include:

- **process development** – ASL can re-imagine and re-engineer hardware and processes to develop tailored solutions that can be integrated into manufacturing environments to make AM work for different businesses.
- **material development** – Materials are at the heart of this new technology so all projects should start with them. Whether high-performance alloys for the aerospace industry, biological and pharmaceutical materials, or something completely different is needed, ASL helps develop new materials optimised for individual needs, to enable the product to work perfectly.
- **design and software solutions** – ASL can help exploit the freedoms of AM by developing next-generation custom-made software and automated tools to improve and optimise the design of products, specifically made for commercial AM. Their modelling and simulation capabilities provide a cost-effective way of optimising process, materials and design.
- **training and strategy** – ASL provides education and training in AM, preparing businesses for the future of this evolving industry. They provide bespoke training delivered by staff with thousands of hours of teaching experience between them.

Whatever the requirement, ASL's experts can point establishments in the right direction, ensuring they get the help needed.

Find out more at **addedscientific.com**

Visiting researchers and summer studentships

Rafael Quelho de Macedo
April – December 2018

Rafael was a PhD student in Mechanical and Aeronautics Engineering at ITA (Institute Technological of Aeronautics), Brazil. He was funded through a FAPESP fellowship and spent 6 months here working on 'Mechanical properties optimization of parts built by FDM through micromechanical modelling', supervised by Professor Ian Ashcroft.

Dr Rafael Ferreira
January 2018 – December 2019

Dr Ferreira is an Assistant Professor at the Aeronautics Institute of Technology, Brazil. His research interests include cellular materials, FDM-composite structures and discrete material optimisation. He spent a year at CfAM collaborating on the hierarchical optimisation of structures with Professor Ian Ashcroft.

Max Wedekind
July – August 2018

Local school student Max Wedekind had a four-week summer placement with the group, which was organised in partnership with the Nuffield Foundation. Max was interested in replicating useful and unique biological forms with 3D printing. This led to his designing and producing several specimens based on turbulence-minimising shark skin riblets. Max was supervised by Dr Ian Maskery.

Antonella Giuri
April – May 2018

Antonella was a 3rd year PhD student in Materials Engineering, Structures and Nanotechnology at the University of Salento, Italy, in collaboration with CNR Nanotech (LECCE). She spent 10 weeks in our group on the Erasmus student exchange program, investigating the printability of perovskites-polymer photoactive composite by ink-jet printing technique. She was supervised by Professor Chris Tuck and Dr Ehab Saleh.

Megan Allpress
June – August 2017

Megan took part in the Nottingham Summer Engineering Research Programme (N-SERP) and her project researched the effects of spray coating aluminium alloy parts, made through Selective Laser Melting. Her supervisors were Dr Jayasheelan Vaithilingam and Professor Chris Tuck.

Metallic coil created by selective laser melting.

Publication highlights

1. Abdi, M. et al., Eng Optim 50, 1850-1870 (2018).
2. Abdi, M. et al., Int. J. Powertrains 7, 142-161 (2018).
3. Ampatzidis, T. et al., Compos Part B: Eng 153, 26-35 (2018).
4. Azam, A. et al., J. Adhes. Sci. Technol. 31, 2124-2138 (2017).
5. Baumers, M. et al., J. Ind. Ecol. 21, S9-S14 (2017).
6. Baumers, M. et al., Proc Inst Mech Eng Part B J Eng Manuf 233, 1235-1249 (2019).
7. Bourell, D. et al., CIRP Ann Manuf Technol 66, 659-681 (2017).
8. Capel, A. J. et al., Beilstein J. Org. Chem. 13, 111-119 (2017).
9. Catchpole-Smith, S. et al., Addit. Manuf. 15, 113-122 (2017).
10. Chen, C. et al., Opt. Express 27, 3682-3697 (2019).
11. Chen, M. et al., Compos. Sci. Technol. 150, 1-15 (2017).
12. Chen, X. et al., J Mater Res 32, 1407-1420 (2017).
13. Cheung, C. F. et al., CIRP Ann 67, 539-542 (2018).
14. Clare, A. T. et al., CIRP Ann 67, 205-208 (2018).
15. Clark, E. A. et al., Int. J. Pharm. 529, 523-530 (2017).
16. Colombi, A. et al., Sci. Rep. 7, (2017).
17. Datsiou, K.C. et al., J Am Ceram Soc, 102: 4410-4414 (2019).
18. Despeisse, M. et al., Technol. Forecast. Soc. Change 115, 75-84 (2017).
19. Diaz, M. et al., IEEE Trans Ind Electron 64, 8799-8810 (2017).
20. Ejaz, H. et al., Int J Adhes Adhes 81, 1-10 (2018).
21. Ekberg, P. et al., Opt. Express 25, 18703-18712 (2017).
22. Espinoza-B, M. et al., IEEE Trans Ind Electron 66, 2343-2354 (2019).
23. Espinoza, M. et al., IEEE Trans Ind Electron 64, 2620-2630 (2017).
24. Farr, E. M. et al., IEEE Trans Power Electron 33, 5641-5659 (2018).
25. Feng, X. et al., Opt. Express 26, 13927-13936 (2018).
26. Garibaldi, M. et al., Mater Charact 143, 144-151 (2018).
27. Garibaldi, M. et al., Scripta Mater 142, 121-125 (2018).
28. Gasper, A. N. D. et al., Addit. Manuf. 24, 446-456 (2018).
29. Gleadall, A. et al., Addit. Manuf. 21, 605-618 (2018).
30. Gomez, C. et al., Opt Eng 56, (2017).
31. Gurney-Champion, O. J. et al., Int. J. Radiat. Oncol. Biol. Phys. 100, 306-316 (2018).
32. He, Y. et al., J. Biomed. Mater. Res. Part B Appl. Biomater. 105, 1645-1657 (2017).
33. He, Y. et al., Addit. Manuf. 16, 153-161 (2017).
34. Hirsch, M. et al., Addit. Manuf. 19, 127-133 (2018).
35. Hirsch, M. et al., Addit. Manuf. 13, 135-142 (2017).
36. Hu, Q. et al., Sci. Rep. 7, (2017).
37. Hui, D. et al., Addit. Manuf. 22, 560-570 (2018).
38. Hüsler, A. et al., RSC Adv. 8, 15352-15357 (2018).
39. Karim, S. et al., Precis Eng 54, 182-197 (2018).
40. Karjalainen, E. et al., ACS Sustainable Chem. Eng. 6, 3984-3991 (2018).
41. Kellens, K. et al., J. Ind. Ecol. 21, S49-S68 (2017).
42. Khaled, S. A. et al., AAPS PharmSciTech 19, 3403-3413 (2018).
43. Khaled, S. A. et al., Int. J. Pharm. 538, 223-230 (2018).
44. Leach, R. et al., in 8th IFIP WG 5.5 International Precision Assembly Seminar, IPAS 2018, S. Ratchev, Ed. (Springer New York LLC, 2019), vol. 530, pp. 145-157.
45. Leach, R. et al., CIRP Ann 67, 599-602 (2018).
46. Lemke, J. N. et al., J Alloys Compd 722, 293-301 (2017).
47. Liu, M. Y. et al., Precis Eng 50, 99-106 (2017).
48. Louzao, I. et al., ACS Appl. Mater. Interfaces 10, 6841-6848 (2018).
49. Maskery, I. et al., Addit. Manuf. 16, 24-29 (2017).
50. Maskery, I. et al., Mater. Des. 155, 220-232 (2018).
51. Maskery, I. et al., Polymer 152, 62-71 (2018).
52. Mikulskis, P. et al., ACS Appl. Mater. Interfaces 10, 139-149 (2018).
53. Mitchell-Smith, J. et al., J Mater Process Technol 255, 364-372 (2018).
54. Mitchell-Smith, J. et al., J. Manuf. Processes 31, 273-285 (2018).
55. Mitchell-Smith, J. et al., Int J Mach Tools Manuf 122, 32-46 (2017).
56. Mubashar, A. et al., J Adhes. 93, 444-460 (2017).
57. Murray, J. W. et al., J Mater Process Technol 243, 143-151 (2017).
58. Murray, J. W. et al., Mater. Des. 155, 352-365 (2018).
59. Okafor, O. et al., React. Chem. Eng. 2, 129-136 (2017).
60. Oyelola, O. et al., Addit. Manuf. 24, 20-29 (2018).
61. Özel, T. et al., Int J Adv Manuf Technol 94, 4451-4458 (2018).
62. Parry, L. A. et al., Addit. Manuf. 25, 166-175 (2019).
63. Peris, E. et al., Green Chem. 19, 5345-5349 (2017).
64. Prina, E. et al., Stem Cell Rev. Rep. 13, 430-441 (2017).
65. Rojas, F. et al., IEEE Trans Energy Convers 32, 23-35 (2017).
66. Ruiz-Cantu, L. A. et al., Macromol. Chem. Phys. 220, (2019).
67. Saint, R. et al., Sci. Rep. 8, (2018).
68. Sanjuan-Alberte, P. et al., ACS Appl. Mater. Interfaces 11, 8928-8936 (2019).
69. Senin, N. et al., Meas. Sci. Technol. 28, (2017).
70. Sibianu, T. I. et al., Ind. Eng. Chem. Res. 56, 1940-1947 (2017).
71. Siepmann, J. et al., Int. J. Pharm. 558, 128-142 (2019).
72. Silbernagel, C. et al., Addit. Manuf. 21, 395-403 (2018).
73. Stavroulakis, P. et al., Opt Lasers Eng 114, 7-14 (2019).
74. Sturgess, C. et al., J. Mater. Chem. C 5, 9733-9745 (2017).
75. Su, R. et al., Opt. Lett. 43, 82-85 (2018).
76. Thompson, A. et al., Precis Eng 53, 54-64 (2018).
77. Townsend, A. et al., Addit. Manuf. 23, 422-432 (2018).
78. Vaithilingam, J. et al., Mater. Des. 139, 81-88 (2018).
79. Vaithilingam, J. et al., Sci. Rep. 8, (2018).
80. Vaithilingam, J. et al., ACS Appl. Mater. Interfaces 9, 6560-6570 (2017).
81. Wang, K. et al., Chem. Eng. Process.: Process Intensif. 122, 389-396 (2017).
82. Wang, M. et al., Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., (2018).
83. Xu, Z. et al., Addit. Manuf. 24, 486-497 (2018).
84. Zhang, F. et al., Addit. Manuf. 25, 477-484 (2019).
85. Zhang, Y. et al., Compos. Struct. 195, 45-59 (2018).
86. Zhao, G. et al., Mater. Des. 149, 63-72 (2018).

Funders, partners and collaborators

We thank all our partners who have supported the delivery of our research vision, including our industrial collaborators, allied research institutions and technology organisations and of course our funders. We look forward to an ongoing and fruitful future collaboration and are excited to see how our diverse partner network will grow as the technology in our shared focus matures and evolves.

³T
Airforce Office of Scientific Research
Akzo Nobel Coatings International BV
Alcyomics
AO Foundation
Astra Zeneca
AWE
Base Group Ltd
BMW
BMW AG, Bayerische Motoren Werke AG
Borg Warner
Croda
Dstl
EPSRC
Exova
Fluorocarbon
Fluorocarbon Company Ltd
Glass Technology Services Ltd
GlaxoSmithKline
GTS
Innovate UK
Johnson Matthey plc
Karlsruhe Institute of Technology (KIT)
Lawrence Livermore National Laboratory
Leonardo MW Ltd
Loughborough University
Lucite International
Malvern Instruments Ltd
Materialise
Materialise NV
MTC
National Institutes of Health Sciences
National Physical laboratory (NPL)
National Science Foundation
Newcastle University
Nikon
Nonoscribe GmbH
Océ-Technologies BV
Oerlikon
Pfizer
PPG
QuantuMD
Renishaw
Rogers Corporation
SABIC Innovative Plastics BV
Siemans
Stryker
Syngenta
TAC
Texas Instruments
Arthritis Research UK Tissue Engineering Centre
TWI
UKAEA
Unilever
University of Birmingham
University of Liverpool
University of Reading
University of Warwick
UTC Aerospace Systems
Wolfson Foundation

University of Nottingham
UK | CHINA | MALAYSIA

For general enquires please contact

The Centre for Additive Manufacturing
Faculty of Engineering
Advanced Manufacturing Building
Jubilee Campus
Nottingham
NG8 1BB

+44 (0) 115 84 66374

CfAM@nottingham.ac.uk

nottingham.ac.uk/CfAM

This publication is available in alternative formats:
+44 (0)115 951 5559

Printed July 2019.