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UKRI Engineering and Physical Sciences Research Council

EPSRC Programme Grant

Enabling Next Generation Additive Manufacturing

Annual report 2022

UNIVERSITY OF BIRMINGHAM

WARWICK
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Foreword

Professor Richard Hague
Principal Investigator

As 2022 draws to an end, we are now completing the fifth year of this EPSRC Programme Grant (PG), Enabling Next Generation Additive Manufacturing. After a one-year no-cost extension confirmed in 2022, we are pleased to present the progress of our Programme, that has been built upon the research developed throughout the past five years.

The Programme, based within the Centre for Additive Manufacturing (CfAM) at the University of Nottingham (UoN) with colleagues with the Schools of Pharmacy and Physics at Nottingham and Warwick University and the University of Birmingham as partner institutions, has been focussing on the development of next generation, multi-material additive manufacturing through strategic fundamental research. The engagement with other academic and industrial partners, either through advisory meetings, joint co-developed projects or knowledge exchange workshops, has facilitated the progress of our fundamental research and supported our vision to drive disruptive change, rapid development and adoption of next generation additive manufacturing. It has achieved this by establishing the fundamental knowledge and advanced methods of control to enable targeted 3D multifunctionality.

Although our team has worked hard to minimise the impact of COVID-19, inevitably some experimental results were delayed in past years. Nevertheless, in 2022 we were able to see much of this work coming to fruition where a strong team effort has ensured that the PG has maintained its strong momentum and success, as recognised by the overall score of nine out of ten in our earlier mid-term review.

As highlighted in our last report, we continue to see graduated PhDs become Post-Doctoral Researchers within the Programme as well as take up other exciting opportunities to develop their careers in academia and industry. The Programme has also been supporting the development of the Post-Doctoral researchers and early-career investigators by providing opportunities to continue to develop their skills through tailored workshops as well as increase their academic profiles and experience through high-impact journal publications and supervision of doctoral and master students aligned to the PG's vision. As a result, we have been achieving fantastic outcomes, for instance, Dr Jonathan Gosling, from the 2018 PhD cohort, was awarded a prestigious EPSRC Doctoral Prize and Dr Yinfeng He, co-investigator of the PG, has been appointed to a two-year secondment in UoN's China campus. These are two great examples of the recognition of the quality of research developed within the group.

For the final year of the PG, we will continue to work on the development of devices to further drive the direction of research, particularly focusing on 3D electronic devices, including memristors, wearable devices and batteries. Concurrently, we will continue to support biomedical and pharmaceutical based devices that are of relevance to our industrial and academic partners that is strongly linked to the research developed in the past years. These activities will be underpinned by the advancements made in materials analysis, modelling and processes that has been executed within our Research Challenges over the course of the PG. Overall, we continue to see our contribution as helping shape the future of UK additive manufacturing research strategy, where we are honoured to be acting on behalf of the UK academic science and engineering communities, whilst actively engaging with other EPSRC Centres and leading research groups across the UK and globally.

I would like to sincerely thank the investigators, researchers, PhD students and support team for their dedication in keeping up the momentum of the Programme, as well as our advisory board for their guidance and EPSRC for their continuous support and I invite you to look at our projects and achievements over the past year.

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Cover image: Dr Negar Gilani (Research Fellow) and Xiangyun Gao (PhD student) working in the MetalJet lab.

Meet the team

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Co-Investigator

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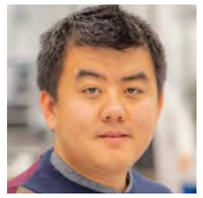

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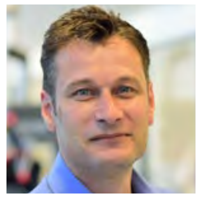
Professor Ian Gilmore

Head of Science, National Physical Laboratory (NPL)

Professional and managerial staff



Mark East

Senior Research Technician, Faculty of Engineering, University of Nottingham

Flavia Villarroel

Programme Manager, Faculty of Engineering, University of Nottingham

And leaving the group: Dr Laura Ruiz Cantu and Dr Carlos Galeano Rios, who have accepted industry positions. All the best in your new roles.

Technical highlights of year four

Research Challenge 01

The primary challenge for RC1 is to understand, at the micro and nano scales, the spatio-temporal interface/interphase evolution between successively deposited droplets or voxels.

Image: Interface patterns between water-soluble and structured inks were designed and inkjet printed before applying FIB-SEM and OrbiSIMS analyses.

One of the primary challenges in multi-material deposition is the potential difference in the co-deposited materials' physical state, chemistry and temperature at deposition or conversion. Through precision experiments and the development of new methodologies for ex situ materials analysis, we have been solving some of the challenges so that we understand how to enable the inter and intra layer coalescence/bonding of functional-structural or functional-functional materials.

In the first year, we established appropriate micro/nanoscale analytical methods for chemical and physical properties of interfaces within samples, in particular utilising the unique 3D OrbiSIMS facilities at NPL and the University of Nottingham that enables exceptional spatial and chemical resolution. In the following years, we have implemented and integrated these methods across the Programme, thereby informing the modelling with RC2 and build optimisation strategies of RC3/4. In the past year, we have increased our collaboration via a series of projects with the National Physical Laboratory (NPL) and other internal groups, including, the Nanoscale and Microscale Research Centre (NMRC), as well as international collaborations with University of Sao Paulo and CERN, the European Organization for Nuclear Research.

As part of our collaborations with other RCs within the Programme Grant and beyond, we have extended collaboration with RC2 researchers on the influence of UV curing strategies to optimise inkjet 3D printing of organic materials, where we utlised the 3D OrbiSIMS instrument and advanced data analysis to study the interface between organic materials in 3D inkjet-printed bacterial biofilm resistant composites from RC3. Additionally we used ToF-SIMS 3D chemical imaging to identify the distribution of polymers and drugs in 3D-printed polydrug implants developed and to understand the role of additives within a new bespoke gold nanoparticles ink formulation developed in RC4.

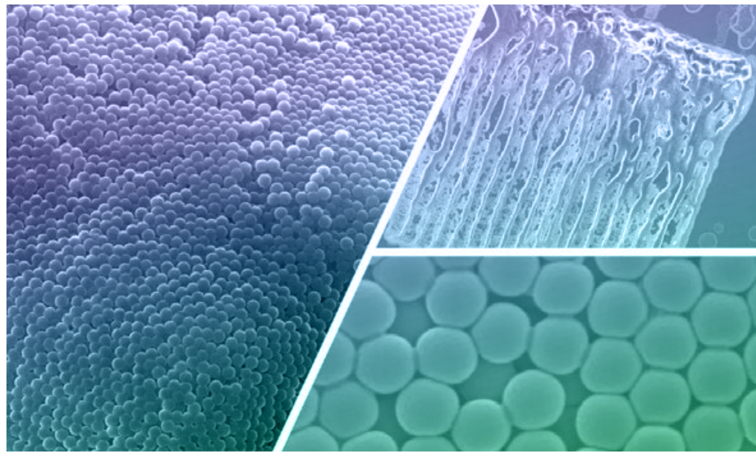


Image: SEM images of polystyrene nanoparticles after 3D-printing – average diameter around 240 nm ± 5 nm

Key findings and activities include:

- Evaluation of the interfaces formation between metallic droplets and dielectric substrate.
- Completed characterisation using dual-focused ion beam scanning electron microscopy (FIB-SEM), transmission electron microscopy (TEM) and electron backscatter diffraction (EBSD) to characterise the interfaces and microstructure of printed objects through the MetalJet platform.
- Benchmark definition for morphology analysis of printed tracks was undertaken using focused ion beam scanning electron microscopy (FIB-SEM), profilometry, atomic force microscopy (AFM), and other techniques, before investigating material/substrate interfaces with scanning/transmission electron microscopy (SEM/TEM).
- Development of a Matlab tool for the analysis of optical microscopy and optical profilometry data.
- Further collaboration work with NPL focussed on mapping the interface between inkjet printed materials for optoelectronic applications using ToF-SIMs, FIB-SEM and FIB-TEM.
- Development of an enhanced framework to study the biopharmaceutical multi-materials in additive manufacturing, by the building and developing the tailored analytical methodologies with variations of microscopy, spectroscopy and related techniques supported by optimised sample preparation strategies.
- Investigation the effects of printing strategies and UV-exposure time on the interface-interphase via Scanning Electron Microscopy (SEM) With Energy Dispersive X-Ray Analysis (EDX), and Time Of Flight Secondary Ion Mass Spectrometer (Tof-SIMS) With Hybrid Orbitrap (OrbiSIMS).

Ongoing projects

Detection of organic residues that hinder biocompatibility of stents printed via multi-material 3D inkjet printing

Support materials are an indispensable component for constructing complex 3D geometries within both single and multi-material 3D inkjet printing. Such supports are normally printed next to, or under, the structural and functional materials to provide temporary support for overhanging geometries and are washed away after processing is complete.

However, it is apparent that such support materials have the potential for surface contamination on the final product after removal and it is therefore necessary to investigate this to understand the influence on both mechanical and functional performance. For example, such contamination could impact on the printed functional devices of which its surface chemistry is important to its functionalities, e.g. bacterial biofilm resistance or biocompatibility of the printed medical devices. Therefore, we are deploying advanced characterisation techniques (e.g. 3D OrbiSIMS) to help investigate, understand and, therefore, solve such contamination issues, will help in the production of more reliably performing devices.

To investigate this, a UNICAS* funded project using the nmRC's 3D ToF-OrbiSIMS to identify the distribution of materials on the surfaces of specimens printed by CfAM's unique six-material 3D inkjet printer, the PiXDRO JETx, was undertaken. Investigations determined a correlation between the degree of intermixing at the flat layer interface of the two materials, which correlated with i) the order in which the materials were deposited, ii) the location on the specimen in relation to the print orientation, and iii) the washing procedure. These results demonstrate the importance of understanding the interface between differently deposited materials that, in this case, will enable the printing of additively manufactured medical devices with well-controlled surface chemistry.

Droplet formation in the MetalJet process

One of the primary challenges to be addressed in drop-on-demand devices is the generation of uniform, tuneable, stable, and repeatable droplets. Indeed, the resolution and consistency of printed parts is predicated on the precise control over the droplets' size, velocity, trajectory, and absence of satellite droplets. In this project, the formation of micro droplets were investigated at high temperatures (>1000 °C) under various jetting conditions for a range of metals (such as silver and copper) including jetting pulses and frequencies.

The in-situ drop formation, particularly the tail breaking behaviour, droplet speed, radius, and trajectory, were investigated using a stroboscopic camera. The main output of this investigation was to provide insights into the mechanism of producing satellite-free droplets through the MetalJet platform. This understating will enable the expansion of the range of printable materials by the system.

***UNICAS is the University of Nottingham Interdisciplinary Centre for Analytical Science, an internal sponsor of cross-disciplinary projects from across the university.**

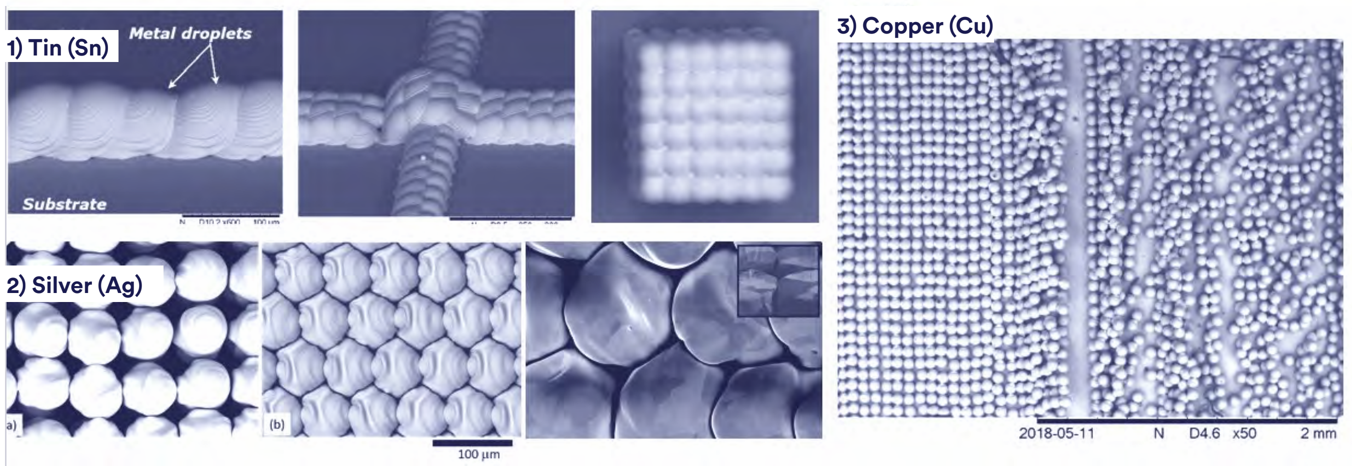


Image: Metal droplets in tin, silver and copper

Collaboration projects with the National Physical Laboratory (NPL)

In some recent investigations in collaboration with the National Centre of Excellence in Mass Spectrometry Imaging (NiCE-MSI) at NPL, 3D mass spectrometry imaging was used to map the interface between inkjet printed materials used in optoelectronic applications. These include conductive polymers and low-dimensional materials such as graphene, hexagonal boron nitride and perovskite nanocrystals. As these layers intermix and because the materials are dissimilar, methods that yield reliable results were developed to help improve ink formulations and device performance.

Previously published work by the University of Nottingham and NPL showed that these methods are able to detect and localise organic residues from inks, which often segregate to the interface of printed materials and may be deleterious for performance. Current ongoing projects include the characterisation of the interface for inkjet-printed novel functional electronic materials.

Materials interfaces in inkjet-printed electronic devices

Due to intermixing that occurs during the inkjet printing process, the interfaces of heterojunctions in electronic devices can have undesired thickness variations and material gradients, which result in a loss of efficiency and responsivity. In collaboration with Programme partner, National Physical Laboratory (NPL), we are investigating inkjet-printed interfaces of functional materials using ToF-SIMs, FIB-SEM, and FIB-TEM to excavate and map the printed interfaces at the sub-micron scale. Understanding how the ink formulation, printing strategies, and post-treatments interact to produce various interfaces is critical to the development of high efficiency digital and optoelectronic devices.

Following this phase, we will extend these protocols to the characterisation of inkjet-printed 3D circuits, in which digital devices are layered to increase device density; a challenging scenario for maintaining well-defined interfaces at all z-axis layers. Model interfaces between conductive polymers, low-dimensional (flake) materials and zero-dimensional nanocrystals are now being characterised. These results will inform the correct methods for accurately resolving each of these functional materials accurately and have already revealed unexpected inhomogeneity at the interfaces. In the coming months, we will use these techniques to investigate how the distribution of material at, and the uniformity of, the interfaces can be controlled through print strategies and treatments, leading to a demonstrator devices with improved functionality.

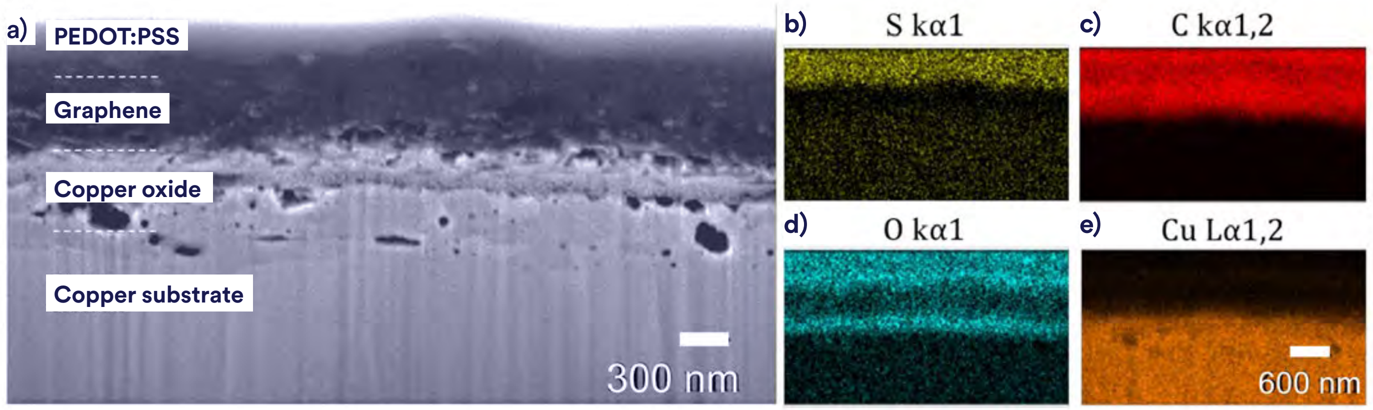


Image: a) FIB-SEM images of the cross-section of PEDOT: PSS deposited on inkjet printed graphene on a copper substrate, corresponding EDX maps confirm the presence of (b) sulfur, (c) carbon, (d) oxygen, and (e) copper.

Research Challenge 02

This Research Challenge aims to develop a multifunctional Additive Manufacture Computational Framework that will guide the manufacturing strategies to be employed to create functional objects and is delivered across all the academic partners at Warwick, Birmingham and Nottingham. Having a framework that provides an understanding across the processes leads to greater design capability for multifunctional additive manufacturing.

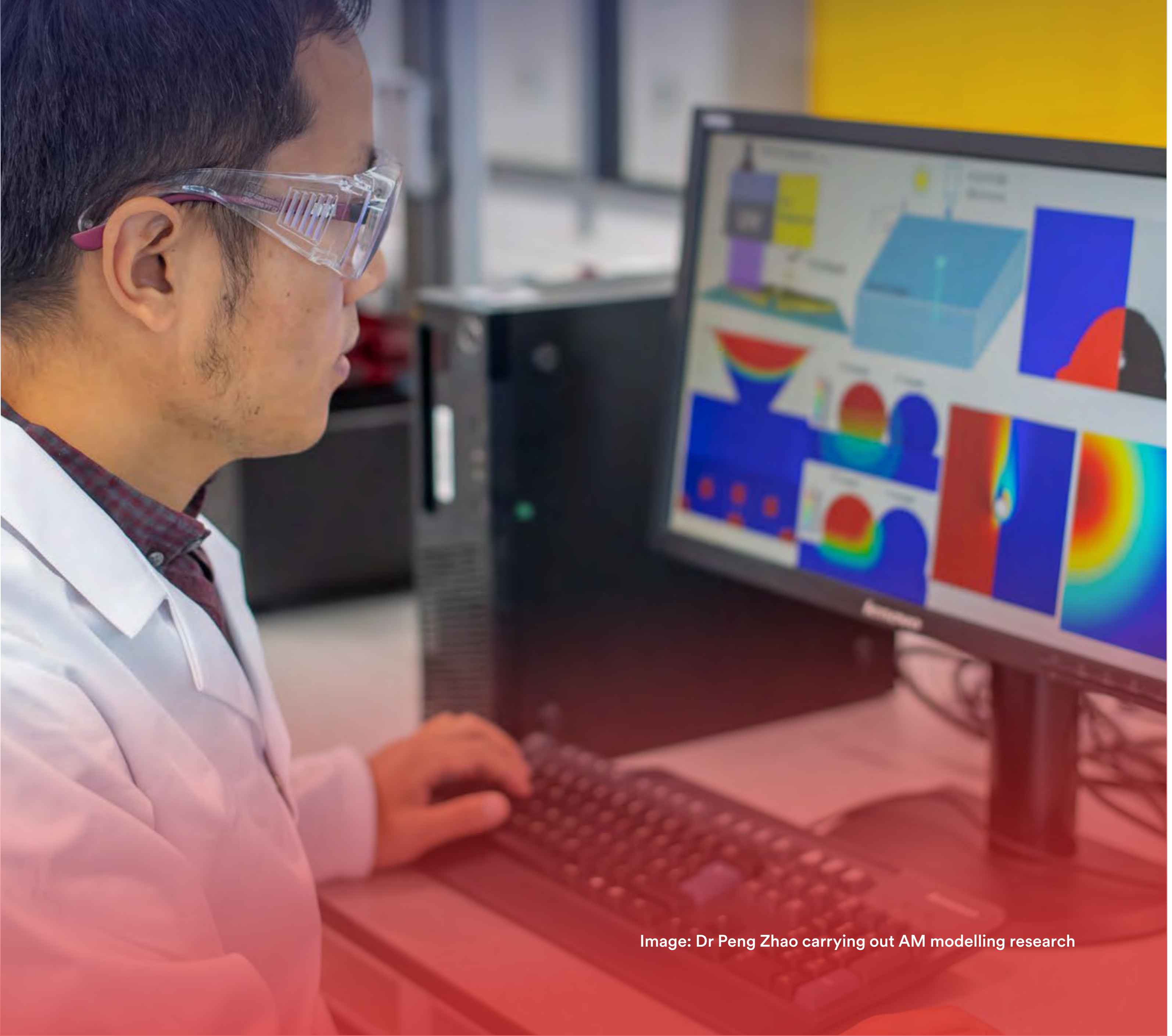


Image: Dr Peng Zhao carrying out AM modelling research

In the past year, RC2 teams have achieved significant progress in the model development for both inkjet and MetalJet, with further steps being validated with inputs from the other research challenges.

Progress on inkjet processes modelling:

- Progress on the development of a CFD computational framework for inkjet-based 3D printing aimed at optimising deposition. The development of all sub-models has been completed with the modelling team working towards validating their models across experimental inkjet platforms.
- Development of a novel technique for UV curing viscosity measurements alongside a study of oxygen inhibition for inkjet-based 3D deposition. The results of this work will be used for model validation and calibration.
- Development of a molecular dynamics model to predict the viscosity of 3D inkjetting inks based on non-equilibrium and equilibrium approaches.
- Development of a model of the coffee ring effect, relevant to inkjet printing of particle suspensions, including the surface capture effect

Progress on MetalJet processes modelling:

- Completion of the implementation of the Interface Formation Model for the spreading droplet problem in a finite element framework
- Development of a detailed study of the effect of the flow configuration on the wetting process highlighting non-uniqueness of the dynamic contact angle corresponding to the same contact-line speed
- The initial geometry of the drop has been shown to largely determine the short-term spreading dynamics, in particular resulting in highly nontrivial patterns in the contact angle-versus-contact line speed diagram
- Coupling the dynamic wetting and thermal phenomena in droplet spreading
- Extension of the MetalJet cooling-in-flight model to solidification, with the inclusion of drag within the model, alongside a systematic study of influence of assumptions about the effective size of the heated region around the MetalJet nozzle.

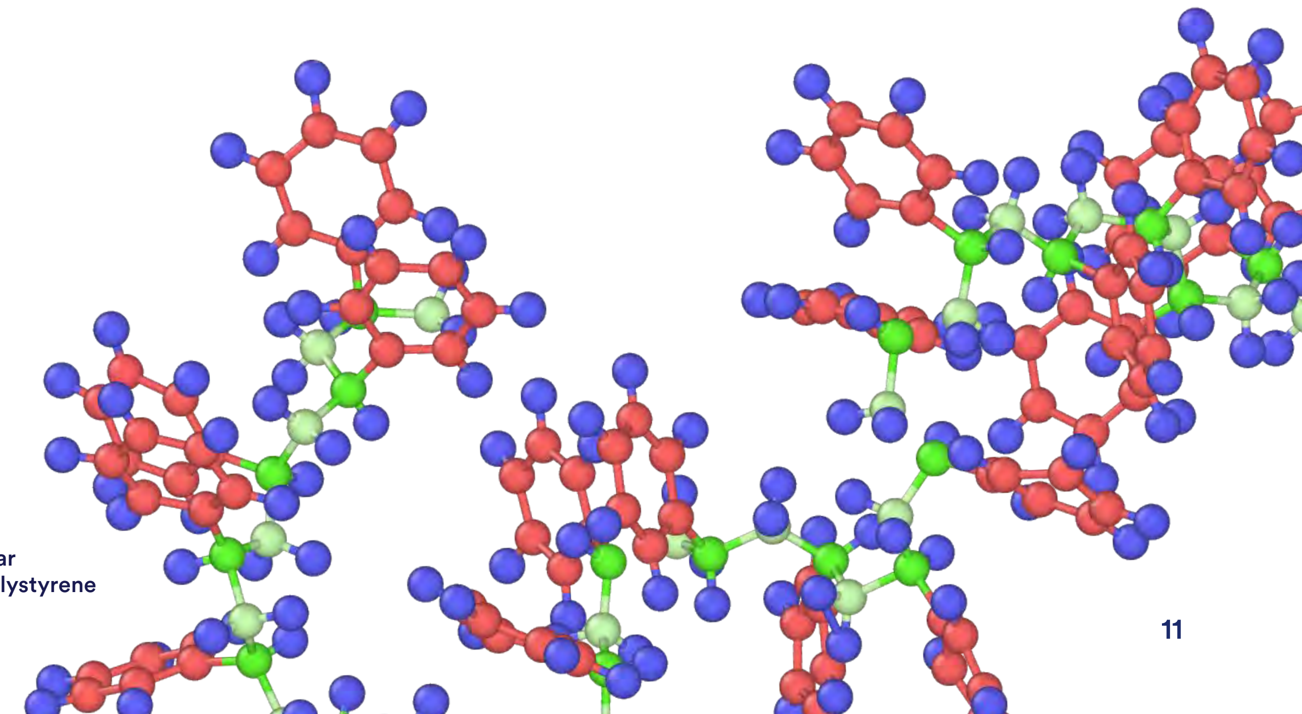


Image: Molecular simulation of polystyrene

Ongoing MetalJet projects

In-flight cooling modelling

Experiments undertaken within RC1 have succeeded in providing data for our model of in-flight cooling of metal droplets produced by the MetalJet printing device. This has distinguished between solidification in flight and after landing through the analysis of the microstructure of the solidified droplets. For comparison to these experiments, the model was extended to much larger working distances than it was designed for, where the effects of drag and a nonlinear ambient temperature dependence along the flight path had to be taken into account. While there are uncertainties in both the experiments and the model, experimental results are consistent with the calculations. A joint publication between modellers and experimentalists is now in preparation.

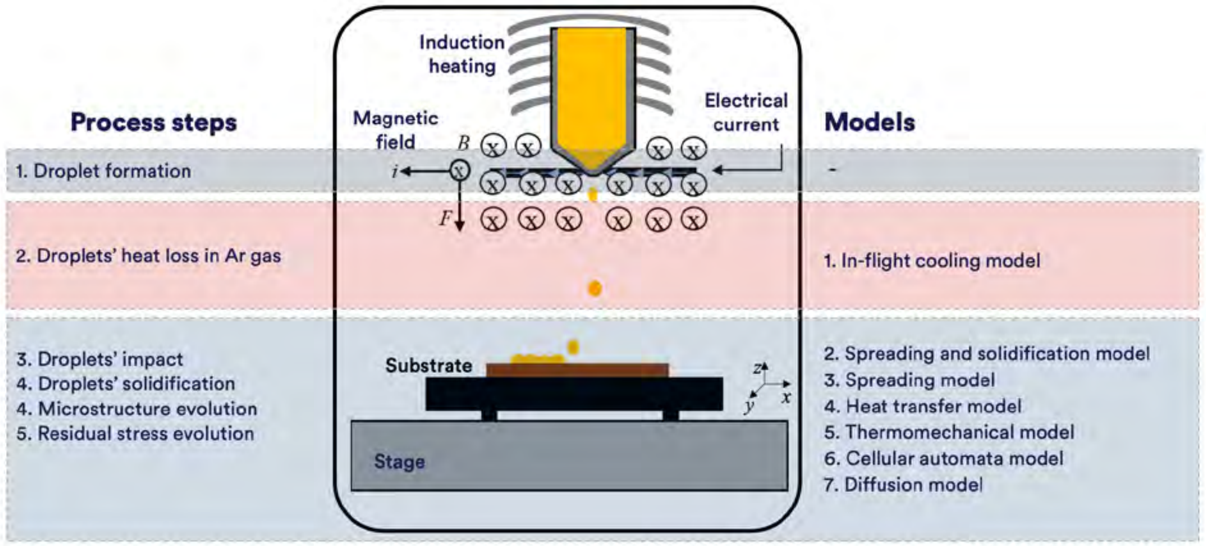
Dynamic wetting with heat transfer and phase transitions for drop-on-demand additive manufacturing

In drop-on-demand additive manufacturing, the outcome of the process is largely determined by small-scale effects at the level of individual printing droplets, such as dynamic wetting, heat transfer and solidification. Consequently, models that can effectively inform innovation must integrate all these effects.

The interface formation model for capillary flows is the natural foundation for such a modelling framework. At this stage, technically the most challenging part of this model, describing the wetting phenomena, has been implemented in a finite element framework. Detailed study of the effect of the flow configuration on the wetting process has been carried out. The initial geometry of the drop has been shown to largely determine the short-term spreading dynamics, in particular resulting in highly nontrivial patterns in the contact angle-versus-contact line speed diagram.

Ongoing work includes integrating the thermal phenomena and analysing the interaction between the hydrodynamic and thermal fields aimed at determining optimal regime of the droplet deposition depending on the external conditions.

Figure: MetalJet – a multiphysics process.



Computational modelling of heat transfer and residual stress evolution during the droplet deposition in MetalJet

The physical factors that govern the quality and properties of the net-shapes produced by the MetalJet include the temperature at the interfaces, the cooling rates, and the residual stresses. These factors define the level of bonding, the microstructural development, and the distortion and/or de-bonding possibility, respectively. In order to provide insights into these elements, a computational 3D thermo-mechanical finite element model was established, and experimentations through the MetalJet platform were performed to verify these models.

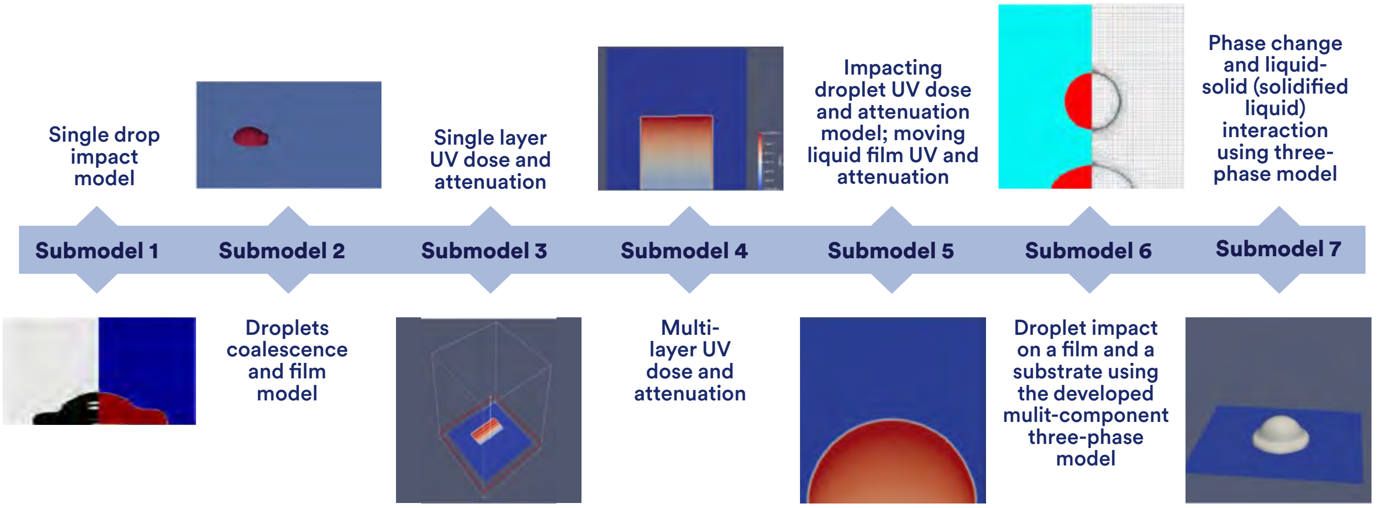
Through these numerical results, experimentally-observed features such as various droplets' morphologies, lack of bonding at the interfaces for high-temperature material, and delamination at the interfaces were understood. Moreover, low-cost virtual experiments were performed, which provided solutions to rectify the observed challenges.

The outputs from these models have been published in two articles in the *Additive Manufacturing* journal, and the third article is currently in preparation.

Image: SEM image of a tin [Sn] structure printed using the MetalJet platform, showcasing the capacity of the system to achieve high-density layouts.

Ongoing inkjet projects

Computational fluid dynamics (CFD) modelling framework to predict and optimise the inkjet-based 3D printing



To date, modelling of the 3D ink jet processes has ignored dynamic, wetting, and coalescence and UV curing effects, and accepts as an input perfectly formed layers of material. This proposed approach is being extended with a CFD based modelling framework, with a specific target to be able to capture 'sagging' and other non-desirable fluid effects that disrupt the precision of inkjet printing. As part of this project, we propose a framework comprised of seven submodels (figure).

To date, we have developed and validated four sub-models of fluid dynamics of droplet impact, droplets coalescence and film formation, single/multi-layer UV dose and attenuation. Three other developed sub-models that are currently being validated include: a moving liquid film UV dose and UV attenuation model; a droplet impact on a partially cured film and substrate using the three-phase model; and phase change and liquid-solid (solidified liquid) interaction using the three-phase model.

Once all sub models have been validated, the overall model will instigate an inverse approach, providing a design tool to those seeking to perfect the inkjet process.

Inkjet printing of conducting polymers modelling: the coffee ring effect

The coffee ring effect occurs when solute particles are carried by an evaporation-induced capillary flow towards the contact line of a droplet, thereby giving a more pronounced particle deposit at that location. While this effect has been studied extensively and is well understood, it is undesirable in most industrial settings.

As observed experimentally by Li et al. (2016), increasing the rate of evaporation (by increasing the ambient temperature or otherwise) can lead to particles being captured by the receding liquid-gas interface, ultimately giving less contact line accumulation and an attenuated coffee ring. This phenomenon, which we refer to as surface capture, has been recognised in a theoretical study by Kang et al. (2016), but lacks a description that also accounts for particle aggregation affects ("jamming").

In our model, we are attempting to interpolate between the coffee ring and surface capture regimes using an evaporation strength-dependent parameter. The assumptions made in this model will be reinforced by full simulations over the droplet domain. A primary aim of our modelling is to predict, as a function of the ambient conditions, an onset of surface capture and use this to devise theory-driven experiments that will be conducted at Nottingham.

Figure: Full 2D simulation: advection-diffusion in an evaporating drop

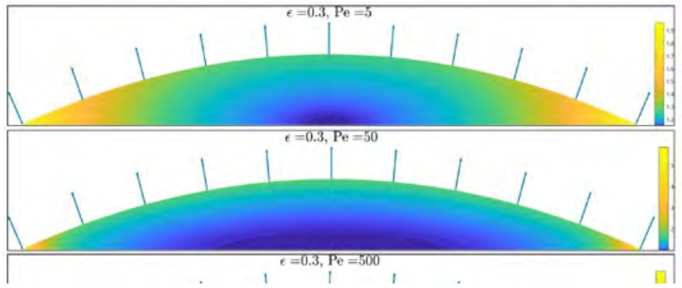


Figure: 1D interpolation model: the transition to interface capture

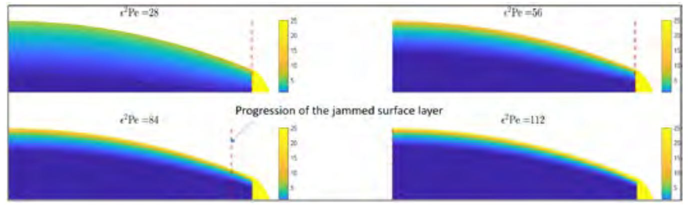


Image: Internal view of the Toucan six printheads inkjet system

Research Challenge 03

Image: Maria Ines Evangelista Barreiros (final year PhD student) working with the Cellink+ system in the clean room

This Research Challenge 3 aims to control the connectivity of additively manufactured layers in order to enable the material full functionalisation. In the first part of the Programme, there was a focus on processes and material library development for two-photon polymerisation (2PP), as well as advancements in both the 3D inkjetting and MetalJet processes. During the second part of the Programme, we have focused on the manufacturing process itself, providing inputs for RC2's interface study and set the foundations for RC4's device manufacturing.

During 2022, we had significant progress in the development of our bespoke multi-material MetalJet process, with completion of the software control of the new system and initial experiments. Furthermore, we saw significant progress in the development of materials and processes for multifunctional inkjet printing.

We have also had a further increase in our research capabilities, with the development of a multi-material projection micro stereolithography (SLA) system, alongside the commissioning of a laser powder bed fusion Aconity system. The latter, includes a multimaterial capability, thereby enabling further research into functional metallic materials such as hard and soft magnetic materials

Some additional achievements for 2022 include:

- reformulating functional inks to improve compatibility with new inkjet equipment, substrate adhesion in water, and multi-material inkjet printing of PolyPills with geometry
- re-commissioning the PixDRO six-material inkjet printer for multi-material functional devices
- demonstrating the influence that plasticisers can have on the printability and stability of formulations containing poorly soluble drugs and their influence on the release of these drugs
- demonstrating the use of a low-cost SLA printing approach with hydrolytically labile macromers, helping to address fundamental factors, allowing and influencing model protein release
- developing the world's first and only multi-metal drop-on-demand printer – MetalJet 3.0 – and completion of the software control for the MetalJet 3.0, including a series of experiments to verify the accuracy and stability of the system
- developing towards functionality with metaljetting: printing 2D and 3D electronics with high electrical performances
- investigating the formation of high-temperature metallic microdroplets through a magnetohydrodynamic actuator (droplet formation)

3D-printed pills will allow digital design of medication release. In this image, the insoluble core and barriers used to control the drug release of a 3D-printed pill.

Ongoing projects

Six printhead inkjet system for medical device production delivery and printed electronics

As a drop-on-demand manufacturing process, multi-material inkjet 3D printing offers the ultimate flexibility to manufacture complex bespoke devices with tailored hybrid functionalities. This capability is of particular interest for medical devices and printed electronics, the central application focus of this Programme's research.

Our recently enhanced multi-printhead inkjet 3D print system (Toucan) enables us to integrate up to six different functionalities into one single device. Combined with the new functional formulations developed within the team, we have been able to reliably process materials during the past year without any printhead failure.

For example, batches of printed pills with hybrid delivery behaviours and biofilm resistant implants that can self-assemble after application have been successfully manufactured using this system: the implant has been published, and the release-programmable pill publication is in preparation. Our next step is to introduce design tools to guide the distribution of multiple functional materials alongside utilising metallic nanoparticle and dielectric inks for metamaterial antenna application.

Development of photo-cleavable ligand functionalised nanoparticles processed by UV light to sinter

We have developed photocleavable ligand-functionalised gold nanoparticles for facile UV-assisted sintering, eliminating the need for high temperature sintering that can be deleterious for flexible polymer substrates. This breakthrough approach enables in-situ printing and UV-sintering for a continuous manufacturing process and multi-material printing of complex electronic devices. This core technology has potential impact for AM of highly conductive and functional inks for printed electronics. Currently, we are optimising the ink formulation for material jetting and demonstrating multifunctional structures through multimaterial co-deposition.

Image: Researcher using the 2PP Nanoscribe.

Self-cyclising diacrylates: inkjet materials with programmable crosslink degradation

To enable recyclability of crosslinked polymers, there is a need to enable a simple means of degrading them in a controlled manner at temperatures below 140°C. This project is developing an acrylate crosslinker, which undergoes thermal degradation at a tuned temperature range, for formulation of polymeric inks that can be printed with a high crosslink density (a rigid structure). These structures can be degraded to soft or dissolvable materials with low crosslink density. Proof of concept studies show that self-cyclising effect in an acrylate blend has been achieved, with work now underway to amplify and tune the effect, and implement in 3D printing.

Image: Bottom left – 3D-printed pill containing dozens of cube-shaped drug-carriers that are released as the pill dissolves.
Top right – cube-shaped components, after dissolution is complete.

Processes in development and new capabilities

Development of multi-material projection micro stereolithography 3D printing systems

The projection micro stereolithography (PμSLA) approach gives a manufacturing precision of up to 100 times higher than an inkjet system and is potentially a powerful technique for applications that require high resolution manufacturing (<10μm). However, due to the single material nature of the process, PμSLA has a reduced capability for the production of hybrid functional composites. To increase its versatility and subsequently the range of applications, we are developing two multi-material projection micro stereolithography systems: a top-down fluid chamber design and a bottom-up multi-vat system.

The top-down fluid system includes an airtight chamber created in collaboration with Boston Micro Fabrication Limited coupled with a Wintech projector (PRO 4710). Additional electronics were implemented to regulate the ink flow through the chamber. A new control system has been implemented to allow the user to control image projection, printing bed motion and adjustment and ink swap, as individual steps or as part of a complex printing routine. Next development steps for this system include the optical alignment and optimisation.

For the bottom-up multi-vats system, the full 3D model design was completed and all necessary parts were outsourced, dry fitted and modified as needed. The next step includes assembling the system in its final form. A controlling software was developed for both top-down and bottom-up fluid systems.

The Aconity system

The Aconity system is funded through an EPSRC Strategic Equipment Grant and forms the kernel of a facility to unlock the ability to understand, control and manipulate metallic materials and components that are manufactured by a method called metal laser powder bed fusion (L-PBF), a type of additive manufacturing technique. The instruments provides unrivalled flexibility in process and material deposition that is not available in commercially available equipment.

The AconityMIDI+ is an open multi-laser mLPBF system for the production of metal parts. This custom made state of the art system benefits from three lasers ranging from 400w to 1Kw with the addition of an Aerosint dual material recoater, InfraTec VarioCAM thermal imaging camera, dual Kleiber pyrometers, 500°c heated substrate and an exchangeable process chambers including additional axis.

The open multi laser configuration enables total control of each laser individually, including multiple speeds and powers within a single vector. This total control, coupled with weld pool monitoring via the thermal imaging camera and pyrometers, gives the ability to manipulate and vary the microstructure within a part. This manipulation can be applied to 2 materials within the same part when using the Aerosint dual material recoater.

With the additional process chamber, a parallel setup can be prepared to minimise downtime between builds. This additional chamber also benefits from an extra axis which opens up the opportunities for future binder jetting and mLPBF research.

The flexibility offered provides scientists and engineers the ability to change parameters to modify how the metal powders within the machine heat up and solidify. Controlling this heat treatment within the machine provides further control on how the metal performs later in service, through controlling the grain size, shape and direction. Coupling this capability of modifying the heating and cooling of components with the ability to add in other materials through inkjet printing we can also control the components composition. Again, this provides more control to the engineer, giving the ability to change the materials crystal structure, it's constituents and even to produce nano-composites within a metal framework.

The third and final element of this facility is that of monitoring the build during manufacture using Spatially Resolved Acoustic Spectroscopy, 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 in specification.

Image: Alasdair Bulloch (PhD student) working on the new Aconity system

Research Challenge 04

This Research Challenge aims to investigate strategies for the macroscale co-deposition of functional and structural materials via piezo-driven inkjetting, high temperature metaljetting and functionalised multiphoton techniques, with a focus on producing electronic devices and healthcare demonstrators.

Image: Dr Feiran Wang (post-doctoral researcher) printing a graphene structure

As the Programme moves towards completion, there has been a strong focus on understanding the processes and materials integration of printing strategies to develop multimaterial devices and heterostructure with tailored functionalities. Significant advancements have been made in the past year, including internal and external project collaborations that allow us to demonstrate these developed capabilities. Some recently completed projects include the inkjet-printed electroadhesive grippers for crawling robots and batch production of customised pills.

Further highlights on electronic materials and devices:

- Improved performance for the fully inkjet-printed graphene-based multifunction sensor for temperature, humidity and pressure sensing, alongside additional functions including drug delivery sensing.
- Development of inkjet printing strategy for perovskite nanocrystals as well as the fabrication of several types of photodetectors, including graphene-perovskite hybrid structures and heterostructures, with optimised device performance for high tunable photoresponse in UV and vis range.
- Development of scalable AM for millimetre-size glass vapour cell as a core component for quantum technology sensors, such as optically pumped magnetometers for magnetoencephalography.
- Monte Carlo methods were successfully expanded to graphene superlattices, consisting of twisted graphene and hBN layers, demonstrating experimentally observed superlattice features even under diffusive electron transport.
- Development of quantum tunnelling and thermally assisted hopping calculations to explain the temperature and gate voltage dependences of graphene networks in inkjet printed devices.
- Development of new technique for high-resolution inkjet pattern design, enabling precise control of droplet positions for printing patterns with high fidelity, precise gap control, thin lines and continuous curves.
- Identification and elimination of substrate contamination by standard laboratory equipment, which had been disrupting inkjet deposition of functional inks.
- Development of two strategic methodologies that enable the incorporation of plasmonic metal nanoparticles in 3D microstructures via optimised intermolecular interaction between nanomaterials and the polymer matrix for two-photon polymerisation process.
- Development of new conductive ink formulation including photocleavable ligand-functionalised metal nanoparticles for in-situ printing and UV sintering.

Highlights of biomedical materials and applications:

- Developed high resolution microcapillary scaffolds using multi-material inkjet 3D printing.
- Exploration of bioprinting of biocompatible ink formulation and 3t3 cells with the DLP 3D printer to form vascularised scaffolds.
- Set up a new collaboration with the School of Pharmacy focussing on the interface between quantum mechanics and biology for exploitation in healthcare devices.
- Development of a stereolithography (SLA) ink that can bind proteins for application in soft tissue engineering, in collaboration with PG dial-up.
- Investigation of methods for the multimaterial printing of hydrogel-based SLA ink for the purpose of its use in the creation of customised intestinal patches.

Ongoing projects

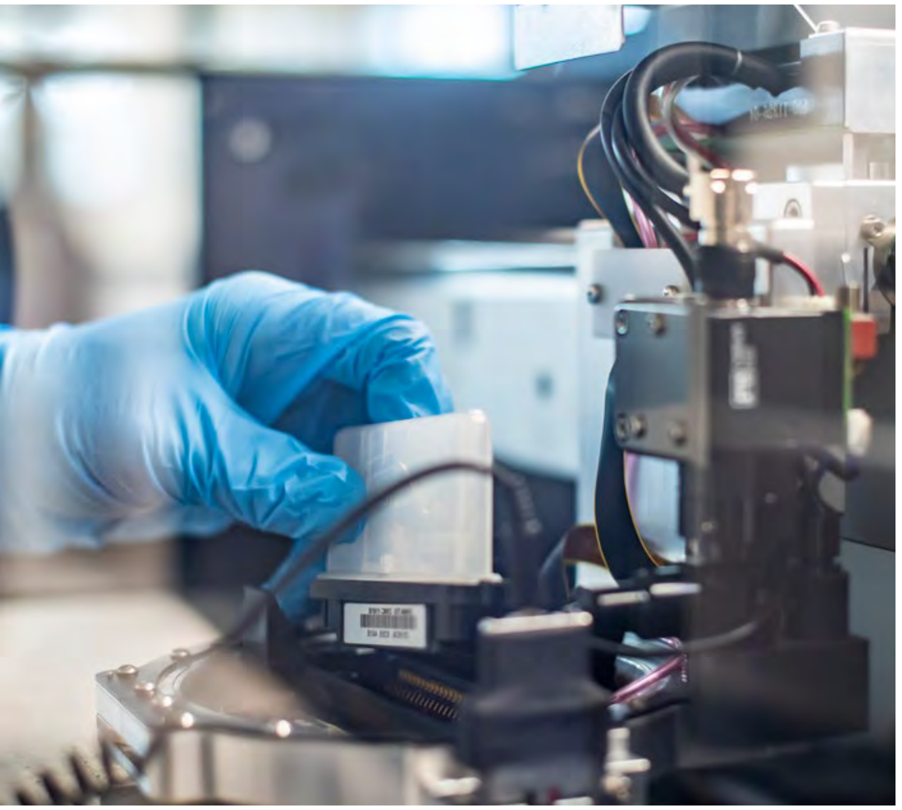


Image: Researcher loading a SAMBA cartridge in a Dimatix inkjet printer

Temperature-dependent electron transport

The mechanisms governing thermally activated charge transport can vary, particularly between individual graphene sheets in the networks formed in printed graphene layers. In single layer graphene, the dominant effect of increased temperature is an increased electron and hole concentration around the Dirac point, most noticeable in highly pure samples, resulting in an increased conductivity, while the electron-phonon scattering resulting in a decreased conductivity away from the Dirac point.

In inkjet-printed graphene, electron transport at the interface between flakes is most important, and thermally assisted hopping and phonon-induced tunnelling enhance such transport at elevated temperatures. We developed a universal model that can be used in the analysis of monolayer graphene devices under varying temperatures, connecting key transport parameters, and performed detailed modelling of the effect of temperature on the electrical properties.

Inkjet printing of perovskite nanocrystals towards flexible display devices

Ceaseum lead halide perovskite nanocrystals (PeNCs) are promising materials for application in optoelectronics owing to their tunable optical properties, narrow emission bandwidth, and high photoluminescence quantum yield. By formulating inks containing PeNCs and developing the inkjet printing protocol, photodetectors have been fabricated on graphene layers and achieved a high photoresponsivity of 1000A/W. We have identified the route to a fully inkjet-printed LED for flexible display devices and have formulated and tested the required materials for functional layers, including injection layers and transport layers. Currently, charge optimisation of layer deposition is underway to achieve required interface properties for enhanced performance.

Inkjet-printed stretchable electrodes for wearable devices

Wearable devices require their components to be stretchable and conductive. Moreover, the stiffness of most highly conductive materials used in electrodes results in cracking when stretched, negatively impacting conductivity. To combat this, a fully inkjet-printed composite electrode is under development; incorporating silver nanoparticle ink with a novel stretchable PEDOT:PSS ink to act as an inter-crack conductor, printed onto a newly developed inkjet-printed elastomer. Preliminary results have identified an additive, developed by collaborators in the School of Chemistry at the University of Nottingham, which enables self-healing properties in the PEDOT:PSS, leading to long-term stability under stretching.

Charge transport in graphene superlattices

When two or more hexagonal lattice structures overlap with lattice mismatch or an angular rotation, they form patterns known as Moiré interference patterns. In adjacent graphene layers, these patterns cause a Moiré interference potential, distorting the low-energy electron bandstructure. Using model Hamiltonians and Monte Carlo methods, we showed that flattening of the energy bands causes an increase in the energy density of states and, therefore, an increased charged carrier density. However, the band gaps opened by the overlapping 2D bands results in an increased effective mass and Bloch oscillations of electrons, resulting in a suppression of charge transport. We further find a striking negative differential conductance, the effect of which increases with decreasing electron scattering.

Towards functionality with MetalJet: flexible electronics circuits

Drop-on-demand MetalJetting (DoD-MJ) is an emerging additive manufacturing technology that has the potential to fabricate flexible electronics whilst overcoming the challenges associated with nanoparticle-based inkjet printing, including nozzle clogging, ink formulation, nanoparticle synthesis, drying, and sintering of the nanoparticles. Furthermore, direct molten metal printing opens new avenues to overcome the common quality-related challenges observed in inkjet printing, such as higher electrical resistivity than the corresponding bulk metal, poor adhesion of printed traces to the substrate, and the coffee ring effect.

In this study, MetalJet is used to print electronic traces in tin (Sn) onto polymer substrates (PEEK and Kapton films). The work presented here reports that interface formation at the droplet-substrate level during the deposition of molten droplets embeds them into the substrate to obtain an acceptable level of adhesion. Moreover, strong metallurgical droplet-droplet bonding was obtained through re-melting the interfaces.

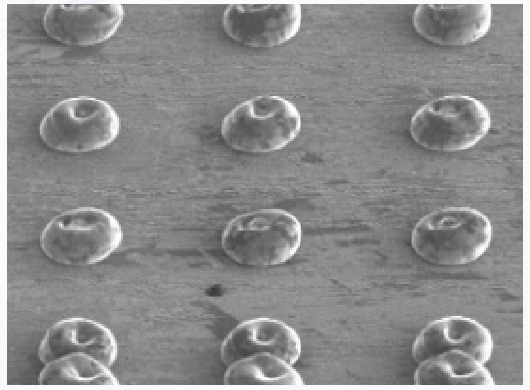
Consequently, the electrical resistivity of printed structures was comparable to that of the corresponding bulk metal. Overall, the work paves the way for the fabrication of next-generation 3D electronics.

Batteries: demonstrator project

Energy storage is a critical research focus area, with industry and society at large standing to benefit dramatically from improvements in reliability, weight reduction, storage capacity, and renewability. Modern battery technology tends to be dominated by i) rare metals such as lithium, and ii) flat-laminated battery geometries that rely on nano-scale morphology. To overcome the rare-material limitation, CfAM looks to develop AM-compatible materials based on common metals, and use disordered carbon for the anodes: both renewable and plentiful, though challenging to process in an AM environment. To seek improvements of operation, CfAM seeks to implement multi-scale internal complexity of the battery layers that are only accessible with AM. Collaboration with battery material groups is underway to support this project, seeking to adapt their renewable materials to CfAM's extensive repertoire of AM techniques.

Projects completed in 2022

For a full list of completed and published projects, please refer to the publications section.



Droplet dynamics on deposition and interface formation for high-temperature metal

Silver (Ag) is the most conductive metal and has the potential to be used in the electronic industry for radio frequency identification antennas, touch screens, printed circuit boards, and flexible/ wearable electronics. Consequently, Ag is one of the most interesting metals in drop-on-demand (DoD) deposition processes, but its high melting temperature (962 °C) has restricted the research to the nanoparticle inkjetting technologies.

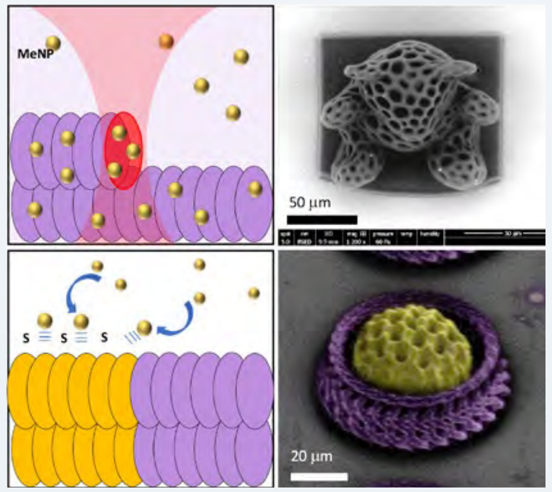
MetalJet enables direct printing of silver microdroplets, however, our previous printed structures in silver suffered from a lack of consolidation between droplets, which was detrimental to the electrical conductivity and the structural integrity of parts. To overcome these challenges, the underlying physics of droplet dynamics and solidification, which set the final morphology, and interface formation, which defines the droplet-droplet and droplet-substrate bonding, were investigated.

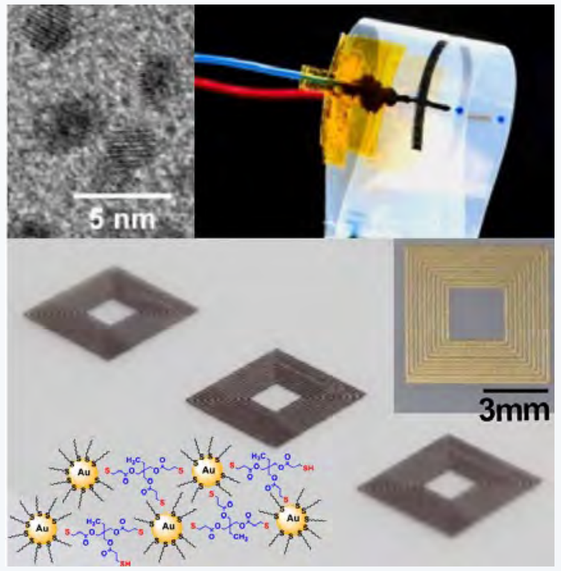
These studies were carried out using an integrated computational, analytical, and experimental approach. The output of this project led to new deposition strategies to improve the shape of droplets during solidification and enhance the bonding level, both of which are essential for printing functional electronics.

Low dimensional nanomaterials for the two-photon polymerisation process

This project involved the fabrication of complex 3D metal nanoparticulate demonstators – polymer nanocomposites, using two-photon polymerisation (2PP). Three complementary strategies were used: (a) in-situ formation of metal nanoparticles (MeNPs) through a single step photoreduction process, (b) integration of pre-formed MeNPs into 2PP resin and (c) site-selective MeNPs decoration of 3D 2PP structures.

In the *in-situ* formation strategy, a phase-transfer method was applied to transfer silver and copper ions from an aqueous phase into a toluene solvent to disperse them in photoreactive monomers. As a result, it was found that the addition of a photosensitive dye facilitated the reduction of silver ions and improved the distribution of silver nanoparticles (AgNPs). This strategy was successfully used to produce other MeNPs, such as Cu and Au. The integration of pre-formed MeNPs enabled highly controlled NP size distribution within the 2PP structures. The size of the nanoparticle was selected to eliminate laser absorption and scattering and to produce high fidelity 3D structures containing embedded nanoparticles. Finally, to enable selective decoration of 2PP surfaces with MeNPs, a multimaterial strategy was developed, with one of the resins designed for thiol-ene reaction. Following the formation of 3D structures, the thiol-functionalised parts of the 3D structures demonstrated high level selective binding to AuNPs.





Functionalised gold nanoparticles (AuNPs) with a cohesion enhancer for robust flexible electrodes

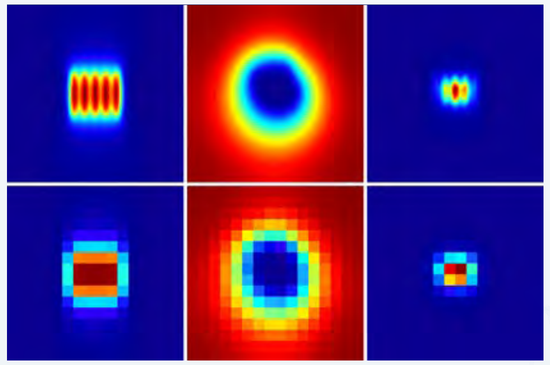
The development of conductive inks is required to enable additive manufacturing of electronic components and devices. A gold nanoparticle (AuNP) ink is of particular interest due to its high electrical conductivity, chemical stability and biocompatibility. However, a printed AuNP film suffers from thermally induced microcracks and pores that lead to the poor integrity of a printed electronic component and electrical failure under external mechanical deformation, hence limiting its application for flexible electronics.

In this project, we employed a multifunctional thiol as a cohesion enhancer in the AuNP ink to prevent the formation of microcracks and pores by mediating the cohesion of AuNPs via strong interaction between the thiol groups and the gold surface. The inkjet-printed AuNP electrode presented an electrical conductivity of 3.0 × 10_6 S/m and stable electrical properties under repeated cycles (>1000) of mechanical deformation even for a single printed layer and in a salt-rich phosphate-buffered saline solution, offering exciting potential for applications in flexible and 3D electronics as well as in bioelectronics and healthcare devices.

2PP: towards full-structure simulations

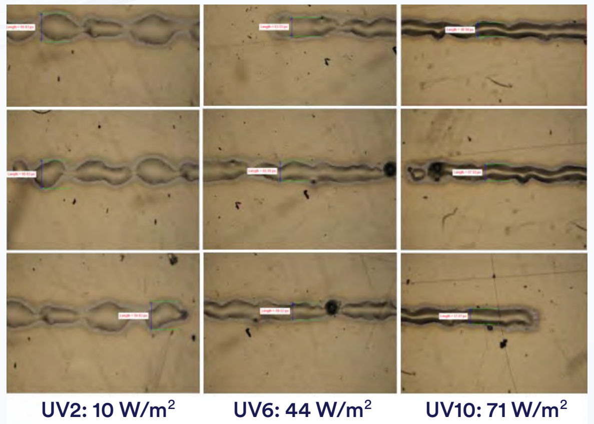
The previously developed extension of a single-voxel model of two-photon polymerisation (2PP) allows to easily simulate a few dozen or hundred voxels, hence it cannot model real 2PP structures, which can consist of millions and even billions of voxels. Due to the long-range nature of heat and mass transfer during the 2PP process, full-structure simulations are required.

Through this project, we have confirmed the validity of significant coarse-graining of our model, which enables simulations of much larger structures. Such simulations reproduce non-uniform polymerisation, also observed experimentally, and have attracted some interest from industry. Currently, we are working on publishing these results and planning follow-up projects in collaboration with experimentalists.



Projects completed in 2022

For a full list of completed and published projects, please refer to the publications section.



Characterisation and modelling of UV curing rheological properties for optimisation of inkjet based 3D printing

As part of the CFD modelling framework, seven submodels are required, which have been developed and are currently being validated. The lack of understanding of the UV ink rheological properties and quantitative photopolymerisation stages could lead to localised performance deviation and affect product quality of 3D printing.

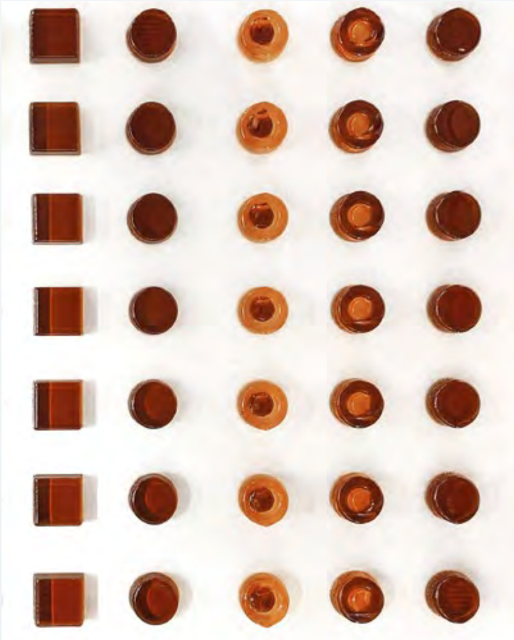
For this purpose, we have designed a UV system to study the influence of light intensity, initiator concentration and resin thickness on the induction period, autoacceleration period and transient curing viscosity. A theoretical descriptive and predictive model is developed to evaluate the localised UV curing viscosity by considering the photopolymerisation stages and UV curing rheological properties. Based on the proposed model and experimental study, we developed a design framework to help the user optimise their printing strategy and find the best manufacturing strategy with minimum experimental trials.

The UV curing model has been developed and tested by using an assumed correlation between viscosity and the accumulated UV dose. The bottleneck of the developing modelling framework was the lack of UV curing viscosity validation data for the UV curing model, therefore, in the past year, a characterisation of UV curing rheological properties was carried out. A characterisation methodology has been developed to study the UV curing rheological properties for validating the developed UV curing model.

Batch production of customised pills through multi-material inkjet-based 3D printing

3D printing of pills allows patients to receive more targeted therapeutics and improved treatments. However, achieving this goal requires a suitable 3D print technique that is able to handle multiple drug-loaded excipients for the pill to deliver a choice of drug 'loads' in a designed and controlled way. In addition, the technique needs to be feasible for batch production to offer pills at affordable prices.

We have successfully demonstrated the use of 3D inkjet printing for customized pill production that has enabled us to produce batches of pills (50-100), each with individualized customized design, drug loading and distribution. Also by co-printing different excipients, we are able to programme the release of the loaded drug as needed. We continue to work on expanding the database of IJ3DP compatible excipient formulations and implementing a releasing model to assist in the design of more controlled drug release, more complex drugs loading, for more rapid turnaround.

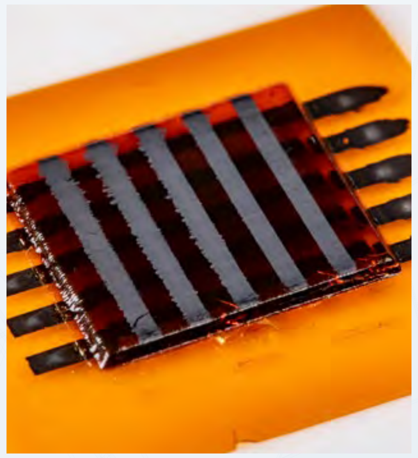


Inkjet-printed electroadhesive grippers for a crawling robot

With the ongoing rise of soft robots, there emerges a need for new technologies that can cope with lightweight and flexible electroadhesive grippers with flexibility. In collaboration with the soft robotics group, we fabricated electroadhesive grippers by inkjet printing conductive tracks with resolutions of ~100 microns on flexible films and characterised their performance.

Our results suggest that the normal adhesive force has significantly increased and allowed the grippers to attach to smooth surfaces such as glass and acrylic sheets, which is challenging for conventionally fabricated grippers. Our work paves the way for low cost, lightweight electroadhesive grippers for soft robots.

Inkjet-printed graphene sensor



Our previous work has shown that inkjet-printed graphene has unique properties, owing to the percolating networks of electron tunnel junctions between the constituent graphene flakes. On this project, we exploit these properties, developing a multifunctional sensor, consisting of graphene layers and a TPGDA dielectric medium, capable of sensing changes in response to different environment conditions: humidity, temperature and pressure.

Electrical conductivity and capacitance measured across the sensor, in response to external stimuli, have an effect on changes due to percolating network and flake-to-flake interactions, or through bulk changes to the TPGDA dielectric thickness.

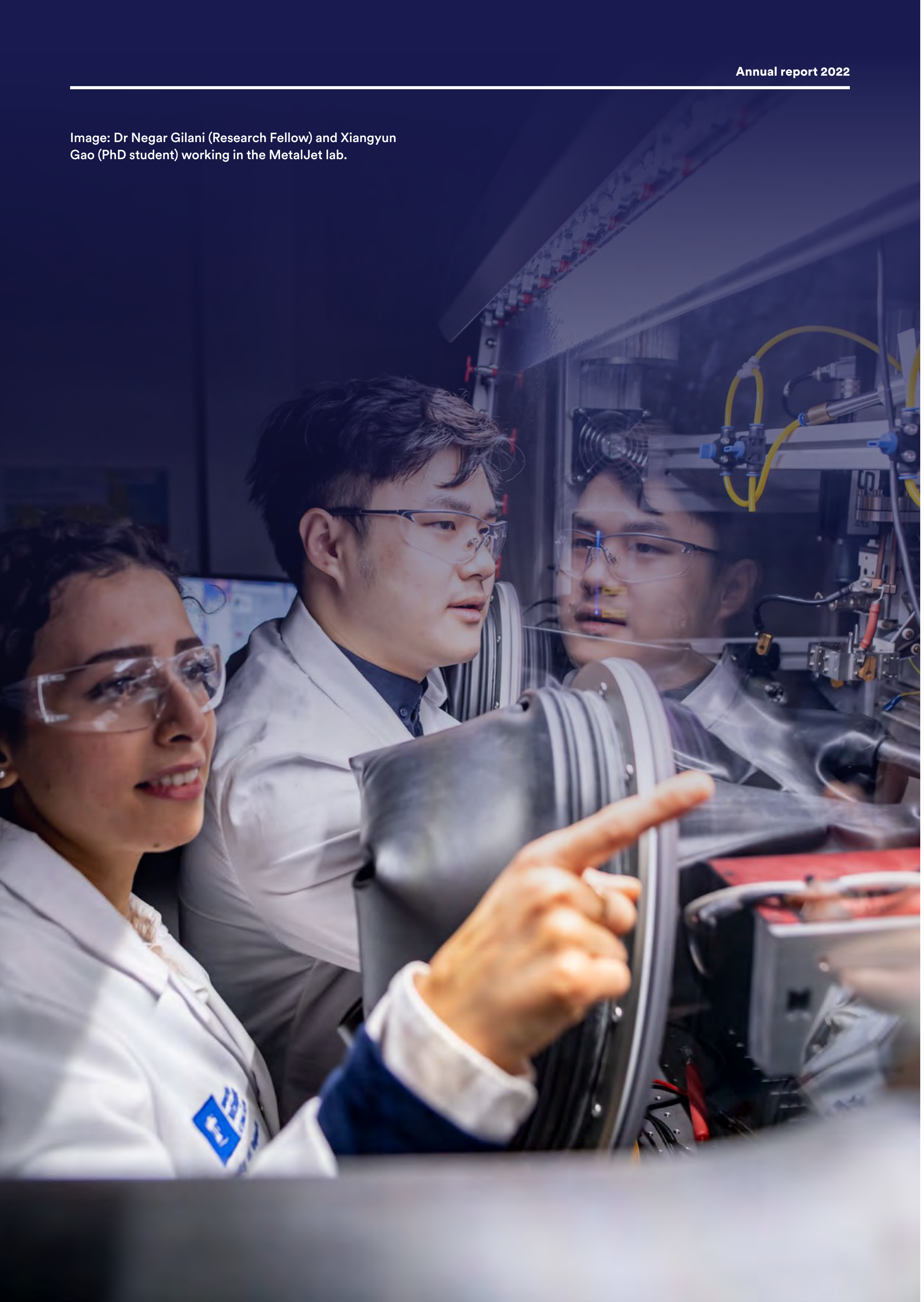
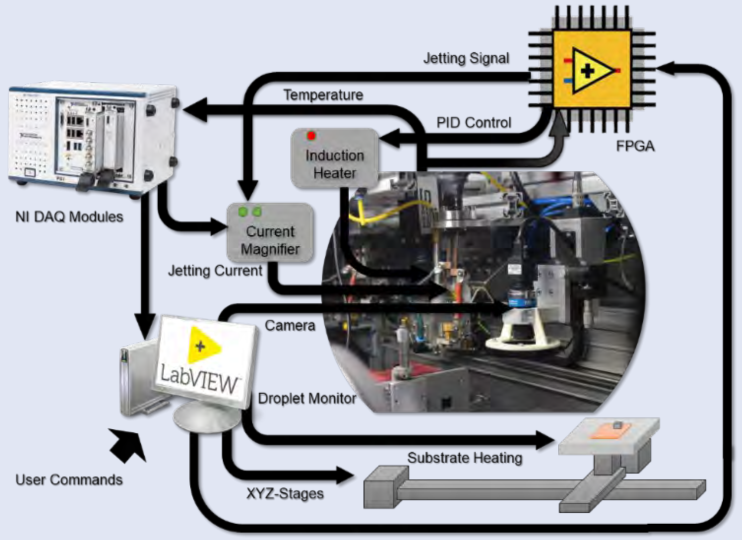


Image: Dr Negar Gilani (Research Fellow) and Xiangyun Gao (PhD student) working in the MetalJet lab.

Case study Metaljet 3.0

Our in-house Multi-MetalJet platform is the first drop-on-demand multi-metaljetting technique that enables printing functional components from at least two (can be extended to several) different metals in one printing operation.



This is accomplished by coordinating the deposition of dissimilar metallic materials on a substrate such that components with spatially varied compositions can be directly created within the build process. This provides the unique opportunity to 3D print components with various properties throughout while eliminating the need for welding or other joining procedures. The voxel-by-voxel deposition of various metallic microdroplets offers unmatched control for tuning the local properties of 3D parts and sets this technology apart from the existing metal additive manufacturing techniques.

Progress to date

The hardware and software development of the in-house Multi-MetalJet was accomplished in 2022. The system consists of two high-temperature printing heads and a building platform with a spatial resolution of 200 nm, which are kept inside a glove box to maintain the oxygen content below one ppm. The control software is developed in LabVIEW, which sends commands to various devices and integrates their functions, such as stage movement, jetting control, temperature control, camera monitoring, and toolpath planning. The implemented programmable chip (FPGA) allows working at high frequencies while ensuring the accuracy required due to fast response speeds.

The system is currently fully operational, and several experiments have been conducted to evaluate jetting on both printheads, stage control and accuracy. Moreover, the jetting waveforms have been optimised for low-temperature materials. To showcase the performance of the system, a demonstrator was successfully printed (see figure above).

Next steps

- Selecting the ideal material combinations based on their mutual interaction and compatibility to design components with extended functionality.
- Optimising the waveforms and jetting voltages for selected materials.
- Printing bimetal patterns to investigate the voxel-by-voxel definition capacity of the system.
- Studying the interface between the droplets of dissimilar materials.
- Printing functionally graded bimetallic structures.
- Studying the effects of material composition ratios and printing strategies on the interface formation.

Aligned doctoral research

This Programme has provided an important contribution to developing the next generation of researchers in additive manufacturing for the UK and beyond. We have been supporting their development through the progression of PhD students working on PG-aligned projects, providing academic guidance from PG academic and researcher supervisors, alongside access to the state-of-the-art research equipment. As result, these PhD students have been producing valuable inputs to the Programme progress.

Congratulations to...

Dr Eric Lehder
Attended PhD viva in September 2022
—

Optimising the geometry of a fracture healing assembly that includes a cell seeded scaffold and a stiffness graded auxetic fixation plate

Additively manufactured scaffolds with biocompatible, biodegradable and bone matched mechanical properties could improve the outcomes of bone healing and regeneration. To keep the bone-scaffold assembly stable while osteo-blast cells develop into mature bone, a fracture fixation plate is necessary. Therefore, to allow a bone fracture to heal as quickly as possible, it is important to optimize both the scaffold as well as the fracture fixation plate. Triply Perdiodic Minimal Surface (TPMS) scaffolds offer a large surface-to-volume ratio as well as ideal curvature profiles for cell growth. Two promising solutions for the problem of stress shielding with stiff plates are stiffness grading and auxetic structures.

During his research, Eric worked on the development of a computational method to address this problem by using a curvature dependent model to optimise a triply periodic minimal surface (TPMS) geometry bone regeneration scaffold, maximising the regenerative capacity; and a mechanical performance finite element model to optimise the plate geometry, minimising the stress shielding. Lately, he has worked on cell culture experiments and compared the results with the cell growth model and carried out a compression strain test to verify the plate optimisation. The computational method has been developed in such a way that it can be easily adopted by medical designers to optimise bone healing implants.

Dr Jonathan Gosling
Attended PhD viva in November 2022
—

Electronic properties of graphene-based electronics

Inkjet printing of 2D materials involves depositing individual flakes into a matrix form. Many features of printed heterostructures influence the performance of conductive components, from the disorder of flakes to the properties of surrounding dissimilar materials.

In this project, the electrical properties of dissimilar materials were predicted by quantum transport simulations under multiple sources of electronic scattering. Jonathan also developed a model that explains charge transport in graphene-based heterostructures, including percolation and disorder effects. The model accurately reproduces the observed properties of inkjet-printed graphene. The size and density of flakes, and amount of disorder were found to have significant effects. Latest developments include modelling of the effects of temperature and interlayer twisting on the transport properties of graphene based heterostructures. The models developed aim to inform the next stages of 2D material printing with a deeper understanding of the mechanics that govern transport between 2D films and within constituent flakes.

Jonathan has also received the prestigious EPSRC Doctoral Prize, which aims to develop independent researchers by encouraging PhD graduates to move into new areas of research and demonstrate the ability to work independently from their former PhD supervisor.

Good luck in your new ventures, Jonathan!

Dr Negar Gilani
Attended PhD viva in December 2022
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Control of high temperature drop-on-demand metaljetting through numerical modelling and experiments.

Drop-on-demand metaljetting (DoD-MJ) is a new exciting fabrication technique for single and multi-metal components at high resolutions that avoids the use of powders or complicated post-processing. MetalJet, a bespoke DoD-MJ platform, can produce molten microdroplets (<70 μm) at high temperatures (up to 2000 °C) to form single and multi-material objects.

Negar's PhD project focussed on understanding the deposition of metallic microdroplets produced by MetalJet through an integrated computational and experimental approach. To achieve this, a thermomechanical finite element model was developed to predict the temperature and residual stress evolution during the solidification and cooling of single and multiple droplets. In parallel, printing experiments were performed, and characteristics of micro-droplets were investigated using various characterisation techniques such as FIB-SEM, EBSD, and TEM. The research provided insight into the underlying physics of metaljet droplets' morphology after deposition and solidification, the interface formed by such droplets, microstructure formation, and residual stress evolution, all of which define the consistency and quality of printed parts. The knowledge obtained through this research permitted the optimisation of the jetting and deposition parameters involved in producing consolidated 3D prints.

The research represented a step forward in the direct metal printing of high resolution functional multi-material components and set the foundations for Negar's current post as a Research Fellow, where she continues to investigate the fundamentals behind DoD MJ.

Formulation strategies for the 3D extrusion printing of tablets containing a poorly soluble drug

Maria Ines Evangelista Barreiros
Final year CDT student, *University of Nottingham
—
Started February 2019

Whilst there are several different 3DP methods and many of these have been used to produce oral solid dosage forms, Ines's project focusses on exploring different formulations for the material extrusion of tablets containing poorly soluble drugs. Using one single drug as a model drug and the same printer, the release profile of the drug in different formulations can be established.

During this project, Ines has been working on three different types of formulations: a paste-based with commonly used excipients, a polymer based for direct powder printing (hot melt) and a eutectic mixture, whilst comparing the processes and produced tablets. To date, Ines has completed the paste-based and direct powder printing and she is currently assessing the stability of the direct powder printing tablets under accelerated conditions. Concomitantly, Ines is working on optimising the printing and characterisation of the eutectic mixture.

*EPSRC Centre for Doctoral Training in Additive Manufacturing

Production and use of oligomers in additive manufacturing

Joseph Sefton
Final year PhD student, University of Nottingham
—
Started October 2019

Within the group, we have identified isobornyl acrylate (IBA) as a photopolymerisable linear acrylate suitable for stereolithography (SLA) printing. Due to the theoretically linear nature of the polymer compared to typical insoluble crosslinked systems, this provides an opportunity to study the resultant polymer properties via standard polymer analyses. By utilising SLA as a photopolymerisation method, IBA has been homopolymerized and copolymerised with methacrylate monomers and reactive methacrylic oligomers.

This investigation has allowed Joe to begin detangling the complex interplay between resin formulation and print parameters, and the fundamental properties of the resultant polymer. This work has highlighted a dependence on the molecular weight of IBA with varying concentrations and types of methacrylic material, and has allowed us to extract distinct information regarding the molecular weight, resin composition and print parameters which result in build failure.

Novel approaches to the long-term release of biomacromolecules

Kristian Plender
Final year PhD student, University of Nottingham
—
Started October 2019

Long-term delivery of therapeutic biomacromolecules has seen increasing interest for the provision of chronic disease treatment. However, retaining therapeutic function until final elution from a delivery device is a multi-factorial challenge. Additive manufacturing techniques present a high degree of flexibility regarding delivery device geometry and control over spatial location of bioactives to achieve and optimise release for intended patient groups.

Kristian's project focusses on encapsulation of model proteins within formulations that are printable using UV stereolithography (SLA). He has fabricated implant structures to understand the biomacromolecule release over sustained periods, 1-3+ months, via the tailoring of formulations and design changes. The proof-of-concept preparation of different hydrolytically labile macromers has helped establish the fundamental factors to consider, with the findings potentially transferrable for delivery of higher cost therapeutics biomacromolecules.

Additive manufacture of vascularised bioactive scaffolds for bone tissue engineering

Nur Rofiqoh Eviana Putri
Final year PhD student, University of Nottingham
—
Started December 2019

In tissue engineering, the lack of vasculature invasion into scaffolds leads to cell death due to nutrient and oxygen shortages. It is still challenging to replicate the complex vasculature using conventional methods. To solve these problems, additive manufacturing offers high resolution with the potential to mimic the capillaries. Nur is working on the development of bone tissue analogues with integrated vasculature using multi-material inkjet 3D printing to achieve microcapillaries and using DLP 3D printing for bioprinting.

To date, she has developed a small vasculature that mimics the bridging of arteries/veins and capillaries. She set up the bioreactor for the perfusion analysis of the vascularized scaffold and analyzed the seeded hiMSC (human immortalized mesenchymal stem cells) inside the vasculature which showed good cell attachment. She is now working on using a DLP 3D printer for bioprinting the ink formulation with 3t3 cells to show the benefits of vasculature on cell growth.

Novel micro/nano scale characterisation of interfaces in multi-material additive manufacturing

Tien Quach
Final year PhD student, University of Nottingham
—
Started December 2019

Additive manufacturing has many different applications, yet it is still challenging to enable the next generation of 3D printing technology due to the physiochemical incompatibility properties among materials. Tien's study aimed to investigate the interactions of formulations-formulations and formulations-substrates by designing, co-printing and analysing a range of patterns of water-soluble inks (WI) and structured inks (SI).

An enhanced framework has been built and developed to understand and monitor the interfaces-interphases by: identifying original inks via Microelemental analysis and Inductively Coupled Plasma (ICP) techniques; selecting suitable substrates via pre-testing with Contact Angle Measurement (CAM), in-situ imaging with a high-speed camera; confirming layer thickness-roughness layer via Profilometry-Interferometry and Atomic Force Microscopy (AFM); understanding chemical changes via Fourier-Transform Infrared (FT-IR) Spectroscopy, and Nuclear Magnetic Resonance (NMR) Spectroscopy; and monitoring effects of printing strategies via Focused-Ion-Beam Scanning Electron Microscopy (FIB-SEM) with Energy Dispersive X-Ray Analysis (EDX) and Time-Of-Flight Secondary Ion Mass Spectrometer (Tof-SIMS) with Hybrid Orbitrap (OrbiSIMS).

Additive manufacturing based on hybrid low dimensional 0D/2D heterostructures

Jonathan Austin
PhD student, University of Nottingham
—
Started October 2020

Jonathan's project aims to develop low-dimensional optoelectronic devices such as photodetectors, solar cells, and LEDs using inkjet printing. Inkjet printing enables efficient and upscaled production of electronic components, however, there are still major challenges in printing the multi-layered and multi-material heterostructures that are required for optoelectronic devices.

To date, he has developed inkjet printing of perovskite nanocryatals which were used to photosensitise Chemical Vapour Deposited (CVD) graphene and fabricate fully printed photodetectors on flexible substrates. He is now currently developing a fully inkjet printed perovskite LED and has formulated inks and optimised the printing of the final layer require for this device: the charge transport materials poly-TPD and TPBi. Current work also includes developing the printing of other optically active materials such as graphene quantum dots and using ToF-SIMs and cross-sectional SEM to understand the interfaces and thus performances of inkjet devices.

Oliver Nelson-Dummett PhD student, University of Nottingham

—

Started October 2020

3D multimaterial inkjet printing of electrically active materials

3D inkjet printing is well suited to printing functional devices but is limited in its 3D nature and multimaterial prints are usually just simple heterostructures. Oliver's project is working towards complex 3D structures made from silver embedded in a dielectric matrix to make metamaterials in the microwave/THz frequency range. Early results include printing high-aspect-ratio, freestanding silver pillars, which can form the basis of metamaterial waveguides or photonic crystals. The next steps involve characterising the interface between the silver and dielectric matrix, as well as improving the resolution of material placement within each layer. The latter has become a separate, concurrent project in collaboration with Geoffrey Rivers to investigate improvements in pattern design and printing control, with applications that go beyond metamaterials to any high-fidelity devices, such as auxetic conductive patterns and miniaturised antennas.

Xiangyun Gao
PhD student, University of Nottingham

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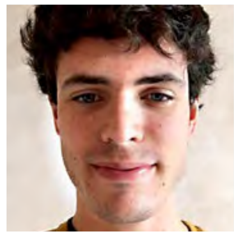
Started April 2021

Multi-material metaljetting: developing a colour metal printer

The metaljetting platform is being investigated within the Programme in collaboration with industrial partner Canon and has demonstrated great potential for the deposition high temperature metals. This ability to deposit "real" metals, as opposed to the usual nano-particulate materials found in drop-on-demand systems, enables additional functionality (e.g. conductivity) to be gained in parts produced using this approach.

Xiangyun's project focusses on the investigation of multi-metaljet printing. As no system currently exists for such research, the first step was the development of a MetalJet platform capable of depositing two materials with melt points more than 1000°C. In his first and second years, Xiangyun has developed, with technical support from CfAM, all the control software of the system. A series of experiments have been conducted to verify that the system has a good performance. Later, he will move on to the experimental stage, to investigate the challenges of multi-metal deposition and develop multi-metal applications using the system.



Nathan Coombs
PhD student, University of Warwick

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Started October 2021

Computational modelling of 3D inkjet printing: PEDOT residue patterns

PEDOT is a conductive polymer commonly used for printed electronics. In practice, nanoparticles of the PEDOT:PSS complex are first dissolved in a printing medium which, after jetting onto a substrate, subsequently evaporates to leave a residue. The caveat of this method is that PSS has relatively poor conductivity: if the residual profile contains PSS-rich regions with very little PEDOT, this will significantly reduce overall conductivity.

Nathan's research project aims to capture the entire PEDOT printing process in a mathematical model by considering how the PEDOT:PSS nanoparticles are transported during solvent evaporation and how they will interact with the solvent in the later stages of drying. Focusing initially on the former of these, he is investigating how evaporation-driven capillary flow can influence the morphology of the residue. To date, Nathan has been developing a 1D model describing capture of solute particles by a receding interface, a phenomenon which has been observed in evaporative flows but has had little attention theoretically.

Ana Valeria Gonzalez Abrego
PhD student, University of Nottingham

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Started November 2021

3D printing of multi-functional scaffold and tissue models through multimaterial pμSLA

Bioprinting has been widely used and shown great promise for creating models and implantable artificial organ development, but the technology to incorporate various materials into the final printed articles still needs considerable investigation. Valeria's project is focussed on using a projection micro-SLA printer that uses different bioinks during the same printing process to create tissue models. Having this technique in place will allow the incorporation of natural microarchitecture into study models of different tissue types such as hepatic and intestinal being able to replicate their micro and macro environment using different biomaterials within the same structure.

In the past year, Valeria has been working on the development of materials aiming that they complement each other when printed together providing structure as well as cell attachment. She has also been able to print complex microarchitectural structures in one of the materials developed. Future research will include co-printing the developed materials and the incorporation of living tissue into the structures printed.

James Caruana
FROG* PhD student, University of Nottingham

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Started October 2022

Synthesis of Novel High Performing Polymers for the Additive Manufacture of Bacterial Biofilm Resistant Surfaces

This project serves as an amelioration of the traditional manufacturing process of medical devices by utilizing novel high performing polymers for the production of bacterial biofilm resistant surfaces. The pathogenicbacteria which undergo a biofilm lifecycle on the surface of medical devices pose an extreme risk to patients.

Bacteria living in their biofilm mode of growth immensely contrib ute to chronic infection and the emergence of drug-resistance with biofilms forming on both biotic and abiotic surfaces. Thus, the project aims to fabricate bespoke devices through additive manufacturing techniques by utilising bacterial biofilm inhibiting materials without the need of external coatings or antibiotics.

*Faculty Research Operation Group

Charles Heaton
PhD student, University of Nottingham

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Started October 2022

Inkjet deposition of low dimensional materials for flexible healthcare devices

Microelectronics have been increasingly used within healthcare technology, with the primary focus of providing analytical feedback on the patient's condition. One particular application of this, is in terms of wound dressings, where biomarkers can be detected giving clear indication of the wound's healing status.

Charlie's work will focus on developing inkjet printed graphene-based sensors for such dressings, with the ability to provide real-time feedback of the wound's status. There is further potential in this project for the incorporation of a drug delivery mode into the wound dressing. This could allow treatment of infection or other wound requirements to be performed without having to remove the dressing.

Knowledge exchange, career development and impact activities

During 2022 we developed a plan to quantify, extend reach and increase the impact of the outcomes delivered by the Programme Grant. This delivery plan has our stakeholders key at its centre and focusses in five main areas (pillars) for implementation: internal, academic, business/industrial, policy and general public.

Among our internal impact activities, our focus falls on knowledge management and team development activities. As a multidisciplinary group, we place strong focus on building upon our internal breakthroughs and passing the knowledge ahead to future generations. Likewise, the continuous development of our resources is crucial to CfAM's long-term research vision.

In relation to our academic activities, after two years of restrictions related to Covid-19, in 2022 we have resumed external activities, with a strong focus on attending high-impact conferences and developing partnerships. We have also progressed with our pipeline of publications in high-quality journals.

Our business and industrial activities focus on knowledge exchange and partnership with a range of organisations for co-developments, projects collaborations and sponsorships. We have also restarted our industrial visits programme.

Finally, this year we have placed strong focus on exploring policy and public engagement, with an internal review of the individual's contributions to committees, leadership activities and other ways of voicing the importance of our research. As part of our policy engagement efforts, we are developing a cohesive plan for dissemination, including discussions with the Royal Academy of Engineering (RAEng), presence in research strategic advisory boards of renowned institutions and meetings with government authorities. As part of our public engagement plan, we are currently working with STEM organisations to develop a toolkit for primary school aged kids and will be resuming our participation in local science events.

In the following pages, we have presented the activities delivered in 2022. For ongoing activities as well as planned activities for 2023, please check: nottingham.ac.uk/research/groups/cfam/major-epsrc-funding/enabling-next-generation-additive-manufacturing/outputs-and-impacts/outputs-and-impact.aspx

Image: Annual meeting, April 2022

Launch event

For the new Additive Biofabrication Facility located in the Nottingham Biodiscovery Institute – 5 May 2022.

Sponsored by the University of Nottingham Interdisciplinary Research Cluster (IRC) in additive biofabrication.

In May 2022, we celebrated the opening of our new Additive Biofabrication Laboratory at the University of Nottingham. The day included a series of presentations from our early career researchers to highlight the growing research activity in this area and included laboratory tours for our guests to learn more about the equipment and capability of the facility. Our keynote speaker, Professor Rachel Williams from the University of Liverpool, described her work in materials development and printing for corneal regeneration purposes. The day was concluded with the official opening of the laboratory by our Associate Vice-Chancellors for Research and Knowledge Exchange, Professor Christopher Tuck (Engineering) and Professor Philip Williams (Science).

The Additive Biofabrication Laboratory will allow us to expand our expertise in additive manufacturing for biological applications and will strengthen our interdisciplinary collaborations between the Centre for Additive Manufacturing and the School of Pharmacy with a focus on healthcare.

Image from left to right: Professor Philip Williams, APVC Research and Knowledge Exchange, Faculty of Science; Professor Rachel Williams, Professor of Ophthalmic Bioengineering, University of Liverpool (keynote speaker); Professor Ricky Wildman, Principal Investigator of the *Dialling up performance for on demand manufacturing* Programme Grant; Professor Felicity Rose, Director of Research and Knowledge Exchange, Faculty of Science; Professor Christopher Tuck, APVC Research and Knowledge Exchange, Faculty of Engineering.

Aligned to Nottingham's Research Publication Framework and CfAM's publication strategy, the PG has strived to produce high quality publications which translate the depth of research undertaken within the Programme.

In 2022, there were 13 new manuscripts aligned with the theme of the Programme accepted and published. Currently, there are further seven manuscripts under review and 15 manuscripts in preparation, which will consolidate the knowledge and research developed within the Programme Grant.

Publications

Ink-jet 3D printing as a strategy for developing bespoke non-eluting biofilm resistant medical devices. *Biomaterials, Volume 281, 2022, 121350, ISSN 0142-9612.*	Yinfeng He, Jeni Luckett, Belen Begines, Jean-Frédéric Dubern, Andrew L. Hook, Elisabetta Prina, Felicity R.A.J. Rose, Christopher J. Tuck, Richard J.M. Hague, Derek J. Irvine, Paul Williams, Morgan R. Alexander, Ricky D Wildman. doi.org/10.1016/j.biomaterials.2021.121350
Computational modelling of Leidenfrost drops. *Journal of Fluid Mechanics, 936, A12.*	Chakraborty I, Chubynsky M, Sprittles J. doi.org/10.1017/jfm.2022.66
Developing echogenic materials as catheters for use with ultrasound. *ACS Biomater. Sci. Eng. 2022, 8, 3, pp.1312–1319.*	Contreras J, Stimpson A, Ahmed I, Irvine DJ, Whittington AR. doi.org/10.1021/acsbiomaterials.1c01323
Bespoke 3D-printed polydrug implants created via microstructural control of oligomers. *ACS Applied Materials and Interfaces 2022, 14 (6), pp.8654-8654.*	Laura Ruiz-Cantu, Gustavo F. Trindade, Vincenzo Taresco, Zuoxin Zhou, Yinfeng He, Laurence Burroughs, Elizabeth A. Clark, Felicity R. A. J. Rose, Christopher Tuck, Richard Hague, Clive J. Roberts, Morgan Alexander, Derek J. Irvine, and Ricky D. Wildman. doi.org/10.1021/acsami.2c00035
Molecular Formula Prediction for Chemical Filtering of 3D OrbiSIMS Datasets. *Analytical Chemistry 2022 94 (11), pp.4703-4711.*	Max K. Edney, Anna M. Kotowska, Matteo Spanu, Gustavo F. Trindade, Edward Wilmot, Jacqueline Reid, Jim Barker, Jonathan W. Aylott, Alexander G. Shard, Morgan R. Alexander, Colin E. Snape, and David J. Scurr. doi.org/10.1021/acs.analchem.1c04898
The influence of printing parameters on multi-material two-photon polymerisation based micro additive manufacturing. *Additive Manufacturing, Volume 51, 2022, 102575, ISSN 2214-8604.*	Qin Hu, Graham A. Rance, Gustavo F. Trindade, David Pervan, Long Jiang, Aleksandra Foerster, Lyudmila Turyanska, Christopher Tuck, Derek J. Irvine, Richard Hague, Ricky D. Wildman. doi.org/10.1016/j.addma.2021.102575
Functionalized gold nanoparticles with a cohesion enhancer for robust flexible electrodes. *ACS Applied Nano Materials 2022 5 (5), pp.6708-6716.*	Jisun Im, Gustavo F. Trindade, Tien Thuy Quach, Ali Sohaib, Feiran Wang, Jonathan Austin, Lyudmila Turyanska, Clive J. Roberts, Ricky Wildman, Richard Hague, and Christopher Tuck. doi.org/10.1021/acsanm.2c00742

In total, 44 manuscripts aligned with the theme of the Programme have been published in high leading journals since 2018. For full list of publications, please check: nottingham.ac.uk/research/groups/cfam/major-epsrc-funding/programme-grant-next-gen-am/outputs-and-impacts/publications-and-conferences.aspx

Publications

The onset of solidification: From interface formation to the Stefan regime. *J. Chem. Phys. 156, 194701 (2022).*	Alexander A. Belozerov and Yulii D. Shikhmurzaev. doi.org/10.1063/5.0084044
Stability and bifurcation of dynamic contact lines in two dimensions. *Journal of Fluid Mechanics, 945, A34 (2022).*	Keeler J, Lockerby D, Kumar S, Sprittles J. doi.org/10.1017/jfm.2022.526
From impact to solidification in drop-on-demand metal additive manufacturing using MetalJet. *Additive Manufacturing, Volume 55, 2022, 102827, ISSN 2214-8604.*	Negar Gilani, Nesma T. Aboulkhair, Marco Simonelli, Mark East, Ian A. Ashcroft, Richard J.M. Hague. doi.org/10.1016/j.addma.2022.102827
Impact of dielectric substrates on chipless RFID tag performance. *International Journal of Microwave and Wireless Technologies, 1-11 (2022).*	Ali, A., Smartt, C., Im, J., Williams, O., Lester, E., and Greedy, S. doi.org/10.1017/S1759078722001039
Magnetic and electric field dependent charge transfer in perovskite/graphene field effect transistors. *Advanced Electronic Materials (2022).*	N. D. Cottam, J. S. Austin, C. Zhang, A. Patanè, W. Escoffier, M. Goiran, M. Pierre, C. Coletti, V. Mišeikis, L. Turyanska, O. Makarovsky. doi.org/10.1002/aelm.202200995
A spacer cation assisted nucleation and growth strategy enables efficient and high-luminance quasi-2D perovskite LEDs. *Advanced Functional Materials 2209186 (2022).*	L.i Kong, Y. Luo, L. Turyanska*, T. Zhang, Z. Zhang, G. Xing, Y. Yang, C. Zhang, X. Yang. doi.org/10.1002/adfm.202209186
Graphene FETs with high and low mobilities have universal temperature-dependent properties. *Nanotechnology (2022).*	J. H. Gosling, S. V. Morozov, E. E. Vdovin, M. T. Greenaway, Y. N. Khanin, Z. Kudrynskyi, A. Patanè, L. Eaves, L. Turyanska, T. M. Fromhold, O. Makarovsky. doi.org/10.1088/1361-6528/aca981
Strategies for integrating metal nanoparticles with two-photon polymerisation process: toward high resolution functional additive manufacturing. *Advanced Functional Materials (2022).*	Jisun Im, Yaan Liu, Qin Hu, Gustavo F. Trindade, Christopher Parmenter, Michael Fay, Yinfeng He, Derek J. Irvine, Christopher Tuck, Ricky D. Wildman, Richard Hague and Lyudmila Turyanska. doi.org/10.1002/adfm.202211920

Conferences, committees and other academic contributions

Conference presentations and posters

January 2022			
Additive manufacture of vascularized biocompatible scaffold for bone tissue engineering	Nur Rofiqoh Eviana Putri	16th Annual Meeting RSC Biomaterials Chemistry Group	Online
March 2022			
Interface analysis of the new gold conductive ink formulation	Tien Thuy Quach	The Forge, Particle Characterization in Formulation 2022	Belfast, Northern Ireland
The importance of exploring the rheological propertiesof formulation inks for 3D printing dosage form manufacture (poster)	Maria Ines Evangelista Barreiros	13th World Meeting on Pharmaceutics, Biopharmaceutics and Pharmaceutical Technology (PBP)	Rotterdam, Netherlands
3D Printed fenofibrate tablets using direct powder printing (oral presentation)	Maria Ines Evangelista Barreiros	13th World Meeting on Pharmaceutics, Biopharmaceutics and Pharmaceutical Technology (PBP)	Rotterdam, Netherlands
June 2022			
Implementing SLA Printing to Understand Matrix Mesh Size Influence on Biomacromolecule Release (poster)	Kristian Plender	United Kingdom and Ireland Controlled Release Society (UKICRS) Symposium 2022	Manchester, UK
Additive manufacture of vascularised bioactive scaffold for bone tissue engineering (poster)	Nur Rofiqoh Eviana Putri	Engineering and Regenerative Medicine Society (TERMIS)-EU Chapter Conference 2022	Krakow, Poland Tissue
July 2022			
The effect of a plasticiser on the printability and solubility of a poorly soluble drug in a 3D printed tablet (oral presentation)	Maria Ines Evangelista Barreiros	Controlled Release Society (CRS) Annual Meeting 2022	Montreal, Canada
September 2022			
Two photon polymerization for manufacturing three-dimensional metamaterials (oral presentation)	Dr Jisun Im	Bulk and Surface Metamaterials Showcase 2022	Online
November 2022			
Surface and Interface Controlled Zero-Dimensional Nanomaterials for Advanced Printed Electronics (oral presentation)	Dr Jisun Im	2022 Materials Research Society Fall Meeting and Exhibit	Boston, USA

Delegations

Advanced Electronic and Photonic Materials 2022
7-8 September 2022, Manchester, UK

This event focused on the enabling role of materials for future photonic electronic and quantum technologies, an area of great interest and aligned with the Programme Grant.

Programme committee and invited speaker: Professor Lyudmila Turyanska – *Perovskite-graphene heterostructures: exploring charge transport in inkjet-printed devices*

Papers accepted for poster presentation:

- *Inkjet-printed graphene photodetectors decorated with all-inorganic perovskite nanocrystals*, Jonathan Austin
- *Scalable and multifunctional sensors by inkjet-printed graphene network*, Dr Feiran Wang
- *Additive manufacturing processable functional nanomaterials for advanced printed electronics*, Dr Jisun Im
- *Development of PEDOT:PSS for low-loss and flexible electronics*, Dr Geoffrey Rivers

The 33rd Annual International Solid Freeform Formulation Symposium 2022
25-27 July, Austin, Texas, US

Symposium committee: Professor Richard Hague

Papers accepted for poster presentation:

- Insights into the droplets' behaviour to control the quality of 3D parts: MetalJet, Negar Gilani
- *Reliable PEDOT:PSS inks using bio-renewable green co-solvents for inkjet 3D-printed electronic*, Dr Geoffrey Rivers
- *Volumetric sintering of polymers via radio frequency additive manufacturing*, Professor Richard Hague and Professor Chris Tuck
- *Functional polyurethane composites via reactive binder jetting (RBJ) of a dual-ink binding system*, Professor Richard Hague and Professor Chris Tuck

Additive International
13-14 July 2022, Nottingham, UK

This conference brings together academic and industry experts to share their knowledge and experience and provides the essential forum to fully understand the technical and commercial opportunities.

During the event, we had the opportunity to promote some of the outcomes of the Programme's grant, including the annual report and the virtual tours to the CfAM and Biofabrication labs.

Co-chairs: Professor Richard Hague and Professor Chris Tuck.

Presentation: Delivered during the Next Generation Additive Manufacturing session entitled: *Probing the response of cells on architectured surfaces*, by Professor Ricky Wildman.

Attended by: Feiran Wang, Flavia Villarroel, Jisun Im, Negar Gilani, Jonathan Austin, Xiangyun GAO, Professor Richard Hague, Professor Chris Tuck, Professor Ricky Wildman, Dr Lyudmila Turyanska, Dr Nesma Aboulkhair, Dr Marco Simonelli.

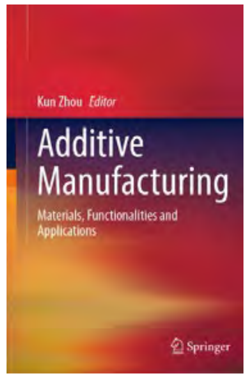
Strategic attendance and guest speakers

May 2022			
UK Metamaterials Network	Dr Jisun Im	The aim of this event was to enhance scientific understanding and relationships across the breadth of the UK metamaterials research landscape.	Dorking, UK
July 2022			
XXII School on Experimental Nuclear Physics – Gas Electron Multipliers: Fundamentals and Applications	Dr Feiran Wang	Guest lecture: Microfabrication by additive manufacturing. The lecture mainly focused on projection micro-lithography and inkjet printing materials and techniques developed within the programme grant.	Sao Paulo, Brazil
September 2022			
Swiss ePrint 2022: The Swiss Conference on Printed Electronics and Functional Materials	Professor Richard Hague	Keynote speaker: Beyond structure – enabling 21st century products through the 3D deposition of functional materials.	Buchs, Switzerland
October 2022			
Materials Research Exchange	Flavia Villarroel	The event is designed to enable closer collaboration between industry and the materials research and innovation community.	London, UK
Ada Lovelace Day	Dr Negar Gilani	Guest speaker: My journey from the Middle East to Occident: How Computational Mechanics empowers surfing the 'wind of change'. This event, sponsored by the Royal Academy of Engineering, aims to increase the profile of women working in STEM (Science, Technology, Engineering and Maths).	Nottingham, UK
November 2022			
Formnext 2022 – International exhibition and conference of the next generation of manufacturing technologies	Professor Richard Hague, Mark East	This event is the leading industry platform for additive manufacturing and industrial 3D printing.	Frankfurt, Germany

Book chapter

Yinfeng He and Maria Ines Evangelista Barreiros have been invited to share their expertise by contributing to a chapter of *Additive manufacturing: materials, functionalities and applications*, by Kun Zhou.

They have co-authored the chapter *Personalised medicine: manufacturing oral solid dosage forms through additive manufacturing*, which speaks about how medicine is moving towards personalised treatments, with the ultimate goal of customisation of drug delivery devices and loaded pharmaceutical tablets to meet the specific needs of individuals.



They also cover the evolution of additive manufacturing and its importance in accelerating progress to meet this target; the recent multi-material additive manufacturing techniques which allow a new manufacturing strategy to customise complex therapeutics; and, the choices of materials and active pharmaceutical ingredients available for additive manufacturing of personalised medicine. Finally, they compare and explain the key advantages and limitations of the available techniques for small-scale and large-scale production, providing the reader with an in-depth view of this emerging field.

The book is published by Springer Nature: link.springer.com/book/10.1007/978-3-031-04721-3

Image: 3D printed stent composed of soft bio-compatible polymers. New materials are currently under development for 3D-printing of stents with advanced functionalities, including antimicrobial surfaces and programmable shape-memory.

Awards

EPSRC Doctoral Prize (Jonathan Gosling), August 2022

The EPSRC Doctoral Prize aims to develop independent researchers by encouraging PhD graduates to move into new areas of research and demonstrate the ability to work independently from their former PhD supervisor.

Project **Quantum mechanical approaches in the development of healthcare devices**

Description This project aims to develop models of quantum transport/electron transfer mechanisms applicable to two types of healthcare devices: metal nanoparticle-based devices and chemical sensors. From this project, we expect to gain a more fundamental understanding of the electrical processes in nanoparticle-biological hybrid systems and to inform the development of healthcare devices, which may lead to the development of a new therapeutic class defined as quantum medicines.

C-DICE Energy Storage Sandpit Proposal (Feiran Wang)

A C-DICE sandpit is a unique opportunity for teams of exclusively postdoctoral researchers to develop a collaborative research idea to win up to £30k in seed-corn funding. The C-DICE sandpit also provides a unique opportunity for postdoctoral researchers to acquire multidisciplinary and cross-sector skills and expertise; learn how to shape a tractable, fundable research project; work collaboratively and write and develop a funding proposal.

Project **Project: Metal hydride nanoparticles for thermal energy storage by additive manufacturing**

Description This project, developed in collaboration with the materials group at the University of Nottingham and University of Bristol, aims to develop a 3D printed hydride-based thermal energy storage. Firstly, candidate materials for hydrogen storage via hydride-based thermal energy stores will be identified. Following that, metal oxide nanoparticles and supporting polymers for lattice structures of high surface to volume ratio will be inkjet-printed using the new LP50/Xaar system.

Broadening Horizons in the Chemical Sciences Programme, issued by the Royal Society of Chemistry

Tien Thuy Quach was shortlisted for participating in the first cohort (2022-2023) of the Broadening Horizons in the Chemical Sciences Programme. The programme is a new three-year pilot to support chemistry students and graduates from black and minority ethnic backgrounds to pursue careers in chemistry. This new programme has a variety of practical resources, mentoring, networking, and industry internship/placement from different partners such as AM Technologies, AstraZeneca, BASF, GSK, Johnson Matthey, Nanomerics, Oxford Nanopore, RSSL, Syngenta, Unilever, etc.

University of Nottingham recognition

Research academy conference, travel, and training fund (CTTF), The University of Nottingham (Nur Putri) – June 2022

Research academy from the University of Nottingham offers a funding for student and researcher to present their research at academic conferences, and to visit overseas institute doing the collaboration with another researcher.

This award gave me the opportunity to attend the scientific conference which I was interested to join since the beginning of my project about additive manufacturing and regenerative medicine. I was able to learn new things and got insight from the leading expert in this field that I cited most for my project, especially in bioprinting and vascular tissue. Besides, I was so grateful to present my research and discuss the progress with another researcher which beneficial to improve my research. I was also able to gain connections with another young scientist in their platform during the conference called Student and Young Investigators Society (SYIS).

Engineering Research Showcase (Xiangyun Gao / Jonathan Austin) – April 2022

The annual Engineering Research Showcase was held on 28 April 2022. There were 68 presentations and 31 posters from PGRs and the day was followed by the Postgraduate Engineering Society (PGES) Gala at the Crowne Plaza. Two PGRs, linked to the Programme Grant, won the awards in the Pitch Perfect and Best Poster-Research Quality categories. Congratulations to Xiangyun and Jonathan!

Category winner

Pitch perfect Ph D Xiangyun Gao (CfAM)

Best poster Research Quality Jonathan Austin (CfAM)

UNICAS-Researcher Academy (RA) Grant 2022, The University of Nottingham (Tien Quach) – March 2022

Tien attended the UNICAS sandpits to connect with potential researchers and prepare the proposal to achieve the UNICAS-RA Grant 2022 (£3124). The project (A7I241) titled "Investigation of the potential cross-contamination in multi-functional additive manufacturing" started from April to July 2022. Other collaborators worked at the Faculty of Engineering (Dr. Yinfeng He, Dr. Jisun Im, Dr. Geoffrey Rivers, Dr. Feiran Wang, and Dr. Peng Zhao), National Physical Laboratory (Dr. Gustavo Ferraz Trindade), and the Faculty of Medicines and Health Sciences (Prof. Clive Roberts).

*The University of Nottingham Interdisciplinary Centre for Analytical Science (UNICAS) brings together cross-discipline groups and provides internal funding to exciting, novel research projects involving analytical science. To lead on an application you must have attended the appropriate sandpit event. UNICAS sandpits take place yearly to facilitate face-to-face networking and fund the novel and scientifically excellent research projects that arise from these events

Opportunities for career development

Being involved in academic activities and supervision is an important role for researchers' experience and career development. During summer 2022, the researchers of the programme supervised eight master student projects and one NSERP summer intern.

Student projects (Summer 2022)

Project title	Student	Supervisor(s)
(NSERP intern) Rheometry of Polymeric Materials in 3D Printing	Joseph Green	Dr Peng Zhao
Design and manufacture of novel prosthetics, orthotics or other biomedical devices	Ming-Han Lin	Academic: Professor Ian Ashcroft Researcher: Dr Peng Zhao
Melt pool dynamics induced by continuous and pulsed laser irradiation: a study informed by fidelity simulations	Arvind Chandramowliswaran	Academic: Dr Marco Simonelli Researcher: Dr Peng Zhao
Multifunction healthcare patch by inkjet-printed graphene network	Samantha Baker-Jones	Academic: Dr Lyudmila Turyanska Researcher: Dr Feiran Wang
Responsive dyes in flexible electronics	Shuyi Zhao	Academic: Dr Lyudmila Turyans Researcher: Dr Geoffrey Rivers
Responsive dyes in flexible electronics	Moises Clemente Guzman	Academic: Dr Lyudmila Turyans Researcher: Dr Jisun Im
The design and performance of hierarchical cellular structures	Reuben Inganni	Academic: Dr Ian Maskery Researcher: Dr Anna Lion
Design and manufacture of novel prosthetics, orthotics or other biomedical devices	Ming-Han Lin	Academic: Professor Ian Ashcroft Researcher: Dr Negar Gilani
Investigation of additively manufactured electrical motors	Magnus Kristensen	Academic: Professor Richard Hague Researcher: Dr Negar Gilani

Other ongoing students projects include: Two MEng Hons Mechanical Engineering, one MEng Hons Aerospace Engineering and three MEng Chemical Engineering

Public speaking workshop

As part of the skills development plan, the PG hosted a public speaking workshop with Martin Berry, Director of Participation at Nottingham Playhouse. The workshop focussed on techniques to improve and utilise vocal delivery in presentations, allowing members to expand their knowledge on vocal techniques to become a more confident presenter. Maria Ines Evangelista Barreiros, Jonathan Austin, Keyvan Jodeiri Iran, Flavia Villarroel, Tien Quach, Xiangyun Gao and Marco Simonelli attended the event.

Image: Group visit to AstraZeneca facilities

Industrial partners engagement activities

In 2022, the Centre for Additive Manufacturing (CfAM) organised a series of industrial activities, giving the opportunity to all researchers and students to visit some of our industrial partner's facilities.

Visit to the Manufacturing Technology Centre (MTC), Coventry
October 2022

Maria Ines Evangelista Barreiros and Tien Quach attended. During the visit, they could understand the updated operation and resources via a range of collaborative projects in additive manufacturing.

Workshop in 3D bioprinting for healthcare applications, by Cellink, hosted in partnership with the Henry Royce Institute, Manchester
October 2022

The course explored the use of 3D bioprinting techniques in the development and manufacture of bioengineered systems/devices for application in Tissue Engineering, Regenerative Medicine, Drug Development and other more traditional areas of healthcare, covering both the use of extrusion- and light-based printing approaches. Training attended by Maria Ines Evangelista Barreiros.

Visit to AstraZeneca, Macclesfield
November 2022

Dr Jonathan Booth (member of the PG's advisory board), with the support of his colleagues, enabled this visit, which covered Chemical Engineering, product development, Biopharmaceutical, 3D-printing and formulation facilities. Maria Ines Evangelista Barreiros, Kristian Plender, Nur Putri, Keyvan Jodeiri Iran and Tien Thuy Quach attended this activity.

Outreach events

FOSAC February 2022

On February 10 2022, the Nottingham Festival of Science and Curiosity hosted the Real Science in Schools Symposium and PhD students from CfAM and the School of Pharmacy showcased advances in science and technology to primary school pupils.

CfAM's stall was split into three stations; 1) What is 3D printing, 2) Can you design the object? and 3) How does 3D printing work? Around 50 children attended the demonstrations.

At the How does 3D printing work? station, children were able to see a 3D printer in action, printing a small object that they took away to keep in their classroom. At this station, they were also able to have a look at some pre-printed objects while they guessed what the material was. At the end of the session, each child went home with a 3D-printed dolphin keychain as a token to remember their experience.

Young researchers meeting July 2022

This event was hosted at the University of Nottingham on behalf of the MacroGroupUK, an interest group of the Royal Society of Chemistry, on 18-19 July 2022. Every year, this meeting brings together current PhD students and early-stage postdoctoral researchers working in the broad and fascinating field of Polymer Chemistry from all around the UK and Ireland. In 2022, this event was organised by PhD students and postdoctoral researchers from the School of Chemistry, the School of Pharmacy and the Department of Engineering and it took place in the Monica Partridge building, on the main University Park campus.

The event spanned two days and offered 24 talks, 14 flash presentations, and 81 posters and was attended by 200 delegates. Professor Ricky Wildman was invited as one of the guest speakers.

The event was kindly sponsored by Unilever, Lubrizol, Synthomer, Asynt, Merk and Royal Society (Polymer Chemistry).

The Roaring 20's Girl Guiding Nottingham Event October 2022

Tien Thuy Quach, representing the Institute of Physics – East Midland Branch, volunteered to demonstrate making and using a pinhole camera with simple materials (e.g. papers) for 60 to 80 girls at Elton Campsite.

STEM in schools Ongoing in 2023

As part of the Programme Grant's delivery plan and our drive to promote STEM disciplines, we are currently working on developing targeted materials to school aged kids as well as engaging with the Public Engagement team at the University of Nottingham to attend further events in 2023. For 2023 planned activities and latest updates, check our page: nottingham.ac.uk/research/groups/cfam/work-with-us/work-with-us.aspx

Committees and leadership activities

UK Metamaterials Network

Professor Chris Tuck and Dr Jisun Im, leadership team members

3DMM20

Professor Richard Hague, member of the Scientific Advisory Board

The FWO (The Research Foundation Flanders)

Professor Richard Hague, research policy inputs

2023 TERMIS (Tissue Engineering and Regenerative Medicine International Society)

Professor Felicity Rose, member of the International Scientific Advisory Board

EPSRC CDT in Advanced Biomedical Materials

Professor Felicity Rose, Chair of the External Advisory Board

The year ahead

The Programme continues to run well and to schedule, where much progress within the exciting field of multi-material Additive Manufacturing (AM) and the understanding of how to interface dissimilar materials has been made, placing the UK at the forefront of this next generation AM research domain.

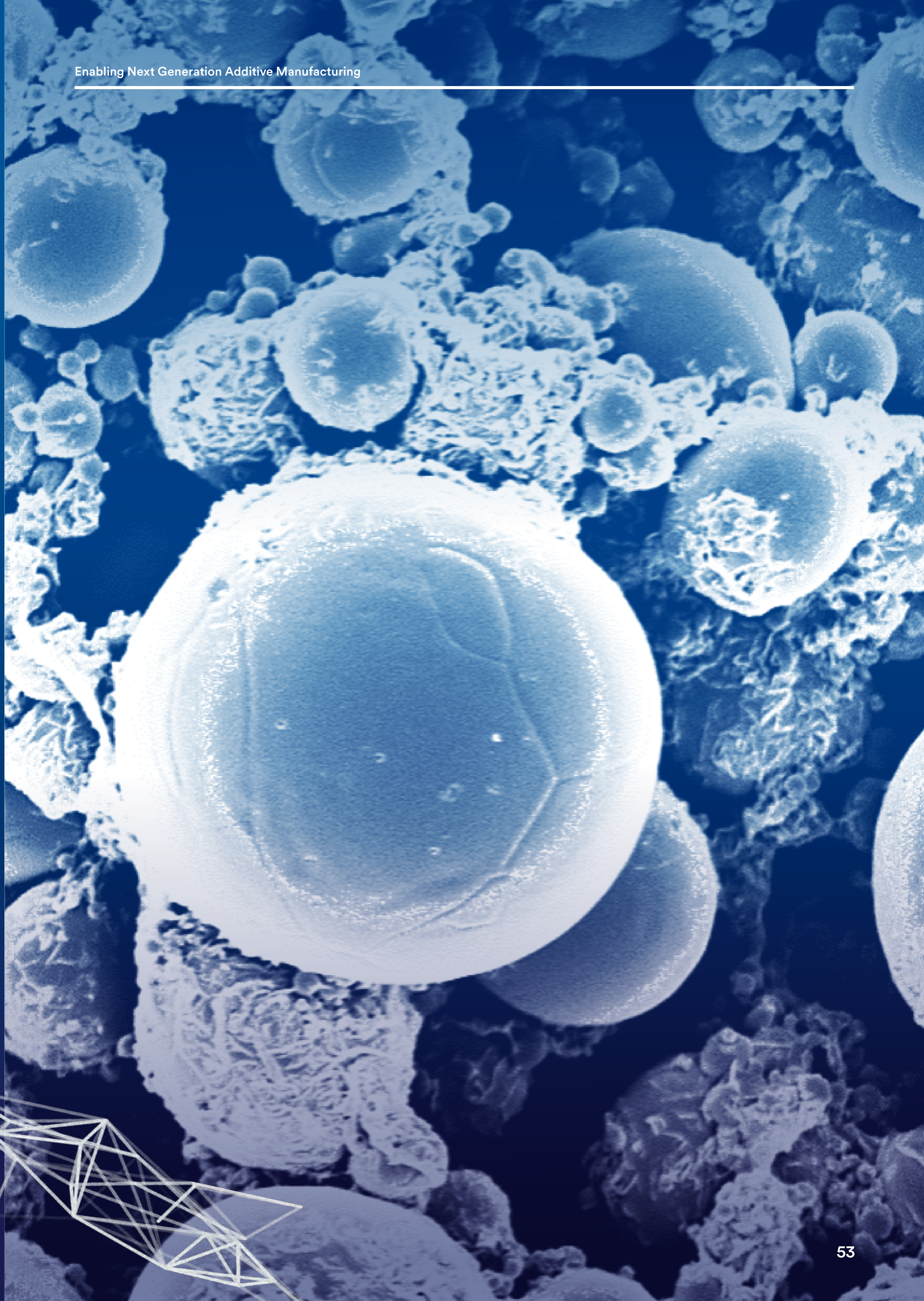
As the Programme moves into its final year, the development of our PhD students and post-doctoral researchers into future leaders and leading scientists and engineers in industry and academia remains one of our key priorities, side-to-side with impact to our stakeholders. We will continue to use the device-led approach to drive the direction of the research of both researchers and aligned cohorts of PhD students; whilst being aligned to the PG's vision, this focus also allows the individuals to have a strong impact within additive manufacture for important areas of research, as applications span across pharmaceutical, regenerative medicine and electronic devices.

Some projects, such as the modelling frameworks and modelling tools of the project, are coming to an end, with relevant advances in the processes understanding. We are currently focussing on documenting and publishing the findings of these activities. Likewise, healthcare activities will mainly progress via the new Programme Grant, Dialling up performance for on demand manufacturing (EP/W017032/1), which started in October 2022. In 2023, we will continue the characterisation activities, especially those in collaboration with NPL and we are planning to deliver on the next generation of MetalJet, after hardware and software completion in 2022. We will also continue to evolve our inkjet processes, and will work towards a demonstration project, by combining materials and AM processes towards a demonstrator device. The recent advances, as seen in the ongoing projects, are a positive indication that we have in-house capabilities to work out most of the upcoming challenges. Yet, we will further explore collaborations outside this grant to expand our possibilities.

In order to retain our talented researchers and maintain our position as leaders in this field, we will continue to pursue related funding applications with EPSRC and other strategic partners, and build on the strong relationships with our high-profile collaborators. At the moment, we are investing our resources in the development of new collaborations to further advance our research, whilst exploring new frontiers and incorporating knowledge from across a range of disciplines to help us solve integrated challenges.

In terms of expected impact, we will continue to consistently communicate our work by publishing in high-impact journals as seen in the recent years, as well as taking part in international conferences, workshops and technical committees. Furthermore, we have been strengthening our collaborations with the National Physics Laboratory in the UK and Lawrence Livermore National Laboratories in the US, with further projects and workshops scheduled for 2023.

Beyond our academic impact, we are working on further outreach and engagement activities. The level of internal and external activities observed in 2022, in relation to the past years, demonstrates our strong aim to cover all relevant stakeholders. As seen in the impact section, we will be delivering further activities covering knowledge exchange and will be pursuing opportunities for IP protection and commercialisation; and public and policy engagement, by promoting the importance of AM research to the different audiences.



Management structure

Executive team

Professor Richard Hague
University of Nottingham
Principal Investigator

Professor Ricky Wildman
University of Nottingham
Co-Investigator

Professor Yulii Shikhmurzaev
University of Birmingham
Co-Investigator

Professor Clive Roberts
University of Nottingham
Co-Investigator

Professor Derek Irvine
University of Nottingham
Co-Investigator

Dr Lyudmila Turyanska
University of Nottingham
Co-Investigator

Professor Ian Ashcroft
University of Nottingham
Co-Investigator

Professor Chris Tuck
University of Nottingham
Co-Investigator

Professor Felicity Rose
University of Nottingham
Co-Investigator

Dr James Sprittles
University of Warwick
Co-Investigator

Professor Mark Fromhold
University of Nottingham
Co-Investigator

Flavia Guzman Villarroel
University of Nottingham
Programme Manager

Advisory board

Dr Will Barton
Chair, WillB Consulting

Mark Tarplee
EPSRC

Professor David Rosen
Georgia Tech and SUTD

Rebecca Mangham
Defence Science and Technology Laboratory (dstl)

Mark Swan
Atomic Weapons Establishment (AWE)

Dr Jonathan Booth
AstraZeneca

Professor Ian Gilmore
National Physical Laboratory (NPL)

Dr Christopher Spadaccini
Lawrence Livermore National Laboratory (LLNL)

René Waarsing
Canon Production Printing

Our partners and collaborators

We thank all our partners who have supported the delivery of the Enabling Next Generation Additive Manufacturing Programme, including our industrial collaborators, allied research institutions and technology organisations and our funder, EPSRC.

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Printed March 2023.