EPSRC Centre for
Innovative Manufacturing in
Additive Manufacturing

Annual Report
2014–2015

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

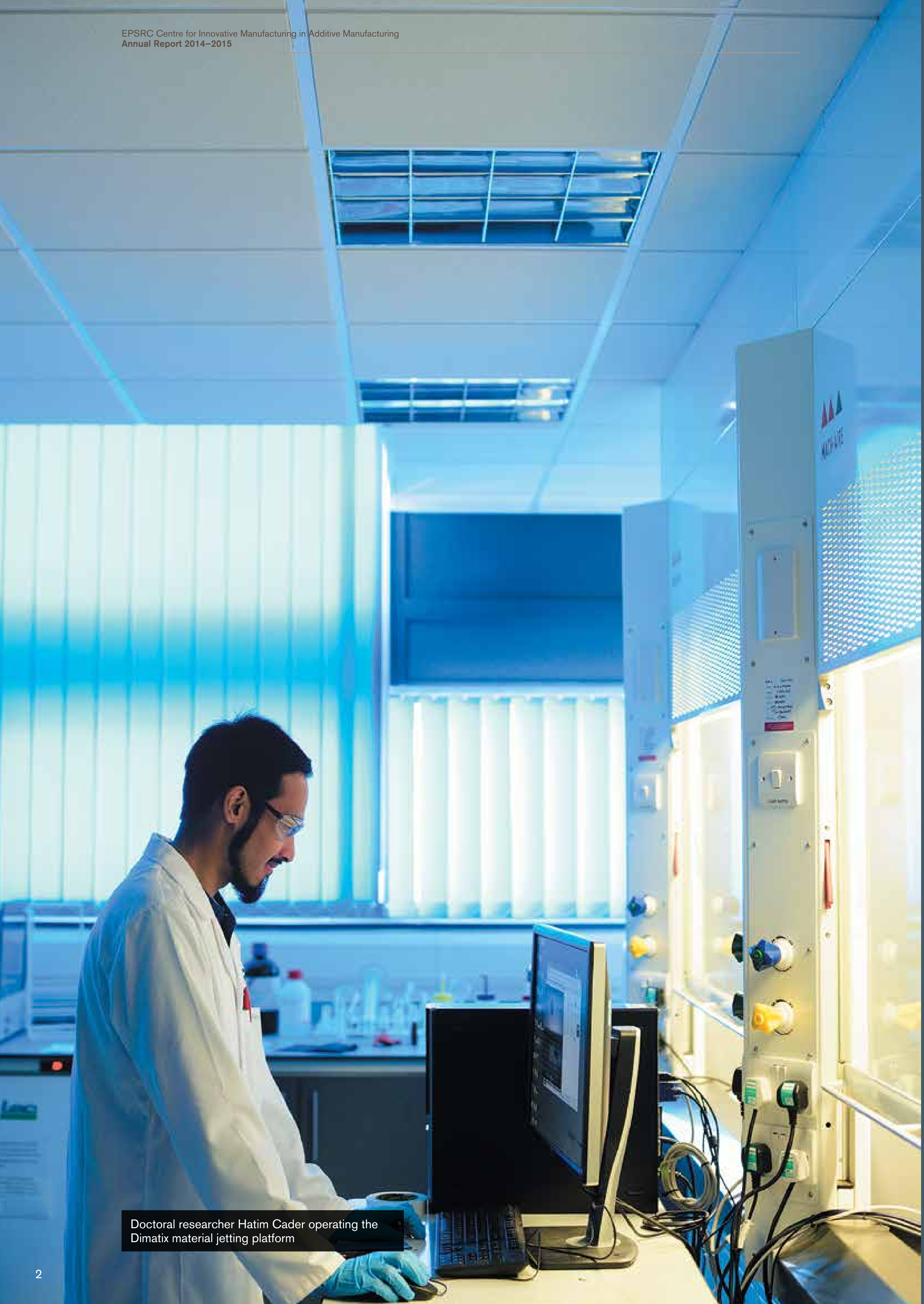
Faculty of Engineering
The University of Nottingham
NG7 2RD
United Kingdom

t: +44 (0)115 846 6374
e: 3dprg@nottingham.ac.uk
w: **3DP-research.com**

EPSRC
Engineering and Physical Sciences Research Council

In partnership with
Loughborough University

Powered by
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA



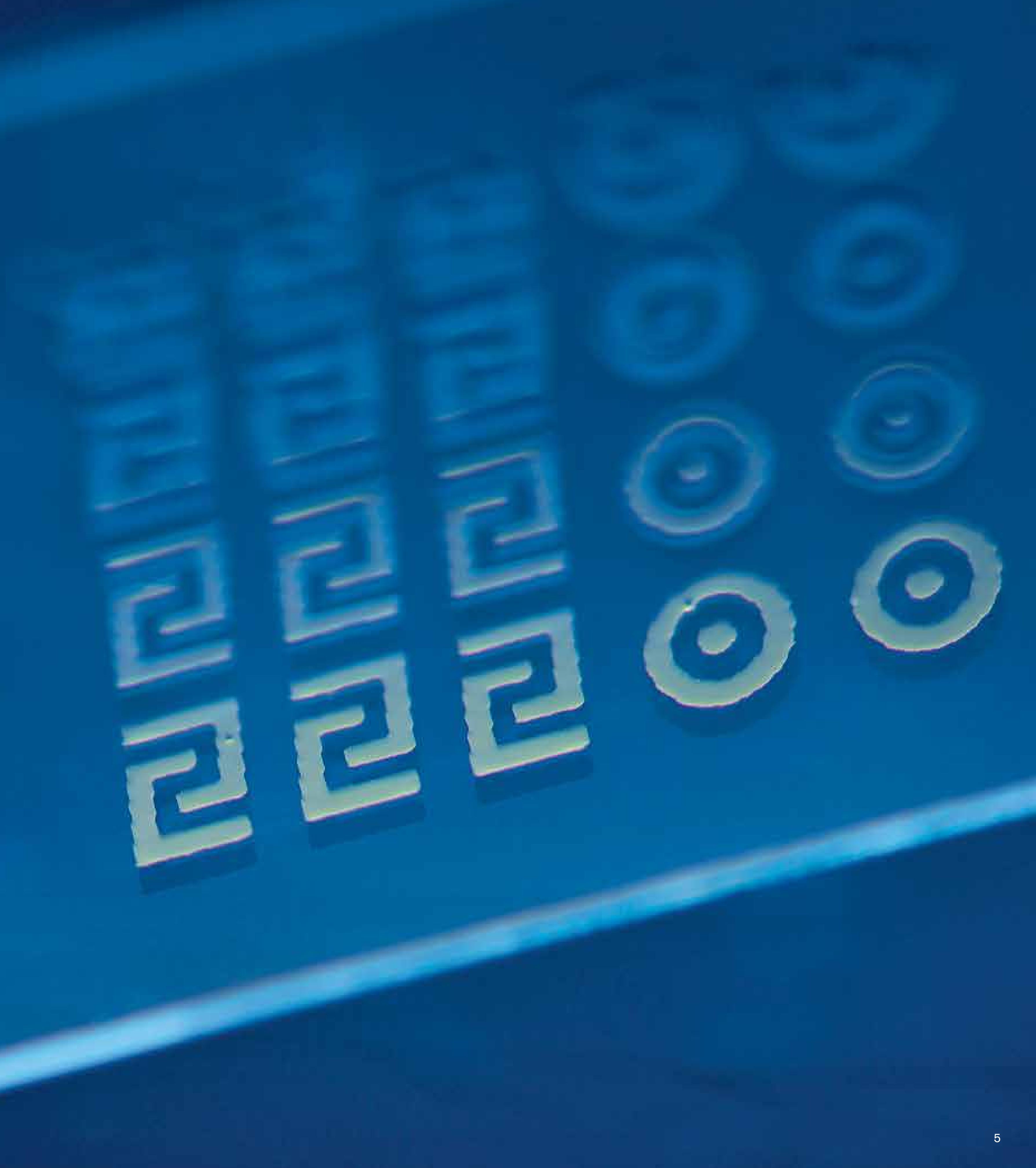
Doctoral researcher Hatim Cader operating the Dimatix material jetting platform

Contents

Our vision realised

At the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing we have formed the nexus of research activity on multifunctional Additive Manufacturing (AM) in the UK. The fundamental and translational research carried out within this world-class hub is influential in shaping the national and international AM research agenda toward the next generation of AM technology.

Through our extensive technological expertise and inherent research professionalism, our activities are enabling the UK to achieve and maintain leadership in the commercial realisation of this next generation of AM technology.



Conductive silver structures deposited onto a glass substrate

Defining multifunctional Additive Manufacturing

Existing 3D Printing technology operates on the principle of adding material in a sequential process, therefore it is also referred to as 'Additive Manufacturing'. It affords an ability to manufacture parts and products directly from raw material in powder, liquid, sheet or filament form using digital 3D design data. A central characteristic of Additive Manufacturing is that the process operates by depositing material, usually layer-by-layer, without the need for moulds, tools or dies of any kind.

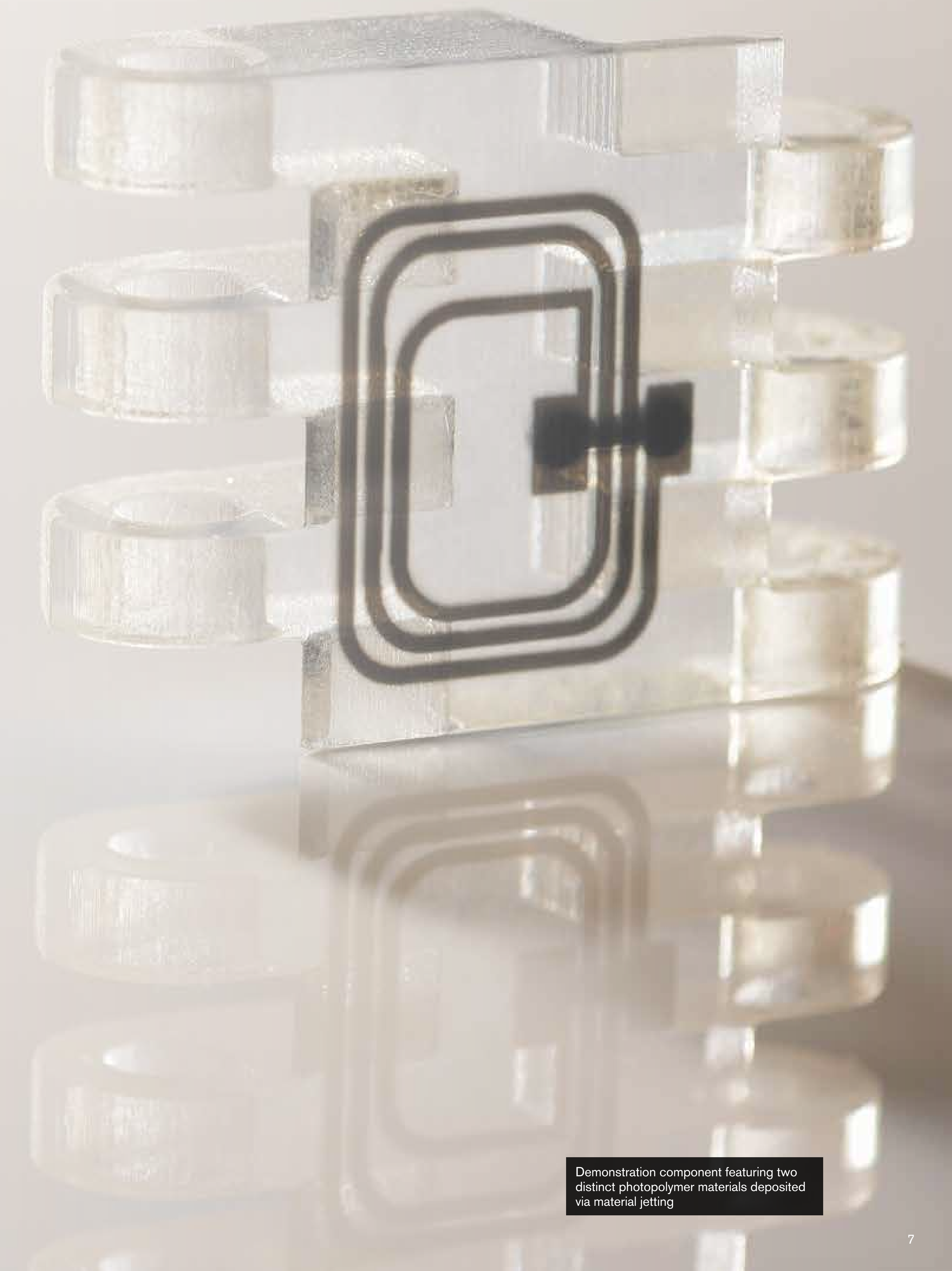
Additive Manufacturing is generally associated with two key advantages over conventional manufacturing techniques. Firstly, Additive Manufacturing enables the creation of products without many of the limitations that normally constrain the designs realisable with conventional methods. Secondly, it enables the production of bespoke and low to medium volume products with high degrees of efficiency. This advantage can be used to realise geometrically complex and highly tailored products for particular functions or individual users.

Within the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, hosted by The University of Nottingham in partnership with Loughborough University since 2012, researchers are investigating ways of evolving Additive Manufacturing to the next technological level. By depositing multiple dissimilar materials within a single build procedure, it is possible to go beyond the deposition of individual passive components to print entire working systems. These could, for example, incorporate embedded electronics, chemicals, pharmaceutical agents or even biological structures. Thus, multifunctional Additive Manufacturing technology can be characterised as a digital manufacturing technology capable of joining dissimilar materials to build objects composed of distinct functional structures.

"Our objective is to go beyond geometry. We are moving from passive AM to multifunctionality where there's nothing to stop you from building electronic, optical, pharmaceutical or even biological functionality within parts."

Prof Richard Hague
EPSRC Centre Director

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015



Demonstration component featuring two distinct photopolymer materials deposited via material jetting

Executive summary 2014–2015

Completing the fourth year of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, this review proudly outlines our achievements and activities throughout the last year. Hosted by the Additive Manufacturing and 3D Printing Research Group (3DPRG) at the University of Nottingham, with Loughborough University as a partner institution, our EPSRC Centre forms the core of UK research activities toward next generation Additive Manufacturing technology.

After the fourth year of our operation, concluding in October 2015, we are pleased to present to you our Annual Report for the period 2014-2015. The EPSRC Centre for Innovative Manufacturing in Additive Manufacturing was launched in October 2011, made possible by an initial sponsorship of £5.9M from EPSRC. From the start, our focus has been on developing the next generation of Additive Manufacturing through the implementation of a strategic fundamental and translational research agenda. We see our contribution as helping shape the future UK Additive Manufacturing research strategy, acting on behalf of the UK academic science and engineering communities and actively engaging with other EPSRC Centres and leading research groups across the UK and globally.

Richard Hague (Centre Director) and Chris Tuck (Centre Deputy Director)

As one of 16 Centres for Innovative Manufacturing funded by the EPSRC via the 'Manufacturing the Future' programme, the mission of our Centre is to maximise the impact of innovative research carried out within the UK, support existing industries nationally, and use our resources to enable the formation of new industries and growth markets. Over the course of our EPSRC Centre, we have pursued this goal through a portfolio of over 40 interconnected research projects which have together leveraged an additional £25M of funding from both governmental agencies and industry; we believe that this level of engagement demonstrates the very real industrial and societal interest in multifunctional Additive Manufacturing and places the UK in a commanding position in this developing field.

As outlined in this annual report, the first wave of flagship AM research projects have reached completion or are about to do so. They have created significant avenues for novel intellectual property strands, led to our EPSRC Centre being awarded multiple new research contracts, and have further enhanced the spectrum of our research activities within this EPSRC Centre. Some examples of additional programmes that our research Centre is now engaged in include:

- Jetting of pharmaceuticals (EPSRC & industry)
- Drop on demand jetting of high temperature metallics (EPSRC & industry)
- Jetting of syntactic foams and silicones (industry)
- Next generation biomaterials (EPSRC)

Corresponding to our pursuit of key elements of intellectual property underpinning the realisation of industrially deployable multifunctional Additive Manufacturing, the last year has seen significant expansions to our laboratory at the University of Nottingham. Over this period we have assembled a truly unique set of one-of-a-kind Additive Manufacturing platforms in support of our efforts to prove technological feasibility and increasingly demonstrate the industrial potential of such systems. This portfolio includes a large scale custom built PiXDRO Toucan multimaterial jetting platform, incorporating a total of six print heads, and a bespoke MetalJet platform capable of the drop on demand depositing of molten metal droplets at very high temperatures. For our research on the deposition of components and functionality at the nano / micro-scale we have upgraded our experimental two-photon polymerisation and optical trapping system to multimaterial capability and have also acquired a Nanoscribe system, which is a commercially available two-photon lithography platform. To support our increased emphasis on materials discovery and characterisation, we have also expanded our laboratory at the Faculty of Engineering by more than 160m², giving our researchers sufficient space to synthesise new materials and analyse their performance on a suite of tailored analytical equipment.

The outreach activities performed in the context of the EPSRC Centre over the last year have concentrated on strengthening our national and international portfolio. As in the previous three years of operation, the Centre has again organised the highly influential International Conference on Additive Manufacturing, which attracted over 290 delegates from 18 countries.
To support the profile of research activity complementary to the work within our EPSRC Centre, the National Centre has hosted a special one-day conference on underpinning scientific activities in conjunction with the International Conference, impressively demonstrating the scientific impact of the 10 complementary research projects funded by our EPSRC Centre through the 'jump-start' framework in the previous year. To initiate engagement with the UK Additive Manufacturing community, our EPSRC Centre hosted two events shaping a national strategy for additive manufacturing. Facilitated by Phill Dickens from the University of Nottingham and Tim Minshall from Cambridge University, strategy development is now progressing with contributions from key industrial players including Airbus, GKN, GSK, Renishaw, Dyson and Rolls Royce.

We are also happy to report that the initial cohort of students in the Centre for Doctoral Training in Additive Manufacturing have completed their first year of studies. Forming a collaboration between the universities of Nottingham, Liverpool, Loughborough and Newcastle, the Centre for Doctoral Training will recruit an additional cohort averaging 14 students each year. We are confident that the UK manufacturing sector will benefit from the high quality of these graduates for decades to come.

Looking ahead to our next year of operation, which will see the conclusion of this EPSRC Centre's current phase, our activities will be focussed on building a future core research agenda for the successor entity.
The cluster of complementary research studies undertaken in the context of the jump start programme, together with the outputs of our completed flagship research projects, will form the foundation for this.
As evidenced by the novel and bespoke equipment now in operation at our laboratory, the realisation of multifunctional Additive Manufacturing is fully underway. The efforts of the successor entity to our Centre must lie on guiding the process of increasing technology readiness and moving ever closer to implementation. Having identified and helped establish the conceptual bedrock of multifunctional Additive Manufacturing over the recent years, we are now keen to understand the challenges of operationalising this radically different approach to manufacturing.

We understand that the success of this EPSRC Centre rests on the shoulders of all those engaged in it, in particular our researchers, industrial partners, academic collaborators, technical and support staff, all of whom we wish to cordially thank. Of course, we also wish to express gratitude to the members of our Advisory Board for their guidance in our journey and to EPSRC for their continuing support of our research activity.

Prof Richard Hague

Highlights at a glance

- In the period 2014-2015 our EPSRC Centre has secured additional funding of over £2.9M, raising the overall amount of funding received over the course of this EPSRC Centre to over £25M.
- First cohort of doctoral students for the EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing, operated in partnership between the universities Nottingham, Liverpool, Loughborough and Newcastle, has successfully completed their first year.
- Continued recruitment effort for talented new staff: 5 new researchers and 8 new standard PhD students over the course of the last year.
- Expanded the laboratory by an additional 163m², hosting analytical equipment, giving our researchers sufficient space to synthesise new materials and analyse their performance on a suite of tailored analytical equipment.
- Installed two unique Additive Manufacturing platforms: a six-head PiXDRO Toucan multimaterial jetting platform and a MetalJet platform capable of depositing high temperature molten metal via a jetting head.
- Underpinned the research on novel micro-additive processes by acquiring a Nanoscribe microstereolithography system.
- Successfully organised the International Conference on Additive Manufacturing and 3D Printing in July 2015, attended by over 290 delegates from 18 countries.
- Successful completion of the third cohort of summer interns from mixed disciplines.

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015

Photopolymer test specimen created via the PiXDRO Toucan multimaterial jetting platform

An outlook on UK Additive Manufacturing strategy

by Professor Phill Dickens

Many stakeholders involved in Additive Manufacturing research, innovation and early stage industrial implementation efforts recognise the urgent need to develop a UK Strategy for Additive Manufacturing. Industry sees numerous opportunities that Additive Manufacturing can offer for new products, business models and distribution chains. The UK has a variety of organisations involved in this technology such as machine, material and software suppliers, end users in OEMs and bureaus, consultants, research and technology organisations, universities, colleges, hospitals, banks etc. However, there is no joined up national strategy to ensure that Additive Manufacturing is effectively exploited. There is an opportunity for the UK to take a lead and develop a clear strategy and implementation framework to ensure that maximum economic value and exploitation of Additive Manufacturing technology occurs within our businesses.

The idea for this strategy came out of an Evidence Paper produced by Prof Phill Dickens of the University of Nottingham as part of the government's Foresight process. There have been two workshops which have detailed the need for a strategy and implementation plan by the beginning of 2016. Additionally, the workshops have formulated the objective to maximise UK business growth and long term economic value through the successful industrial implementation of Additive Manufacturing. It was emphasised that the developing strategy process must be industrially led and involve all sectors and material groups and be integrated with UK Government Industrial Strategy.

Workshops have recently been held at the MTC, Coventry, and the University of Nottingham to launch the activity of producing a UK National Strategy for Additive Manufacturing. The objectives of these events included raising of awareness of the UK strategy development activity, discussion of the structure of the activities, initiation of evidence collection, and the identification of members for working groups. A broad range of organisations and individuals was represented at the meetings, with delegates being predominantly from small, medium and large industrial stakeholders. These stakeholders included:

- Material suppliers
- Software companies
- Additive Manufacturing machinery manufacturers
- Ancillary equipment and processing
- Additive Manufacturing parts manufacturers
- End-users from wide range of sectors

These events were also attended by academics from leading universities engaged in Additive Manufacturing research as well as representatives from research and technology organisations, High Value Manufacturing Catapult, EPSRC, Department for Business Innovation and Skills, Knowledge Transfer Networks, Innovate UK and several trade bodies.

Prof Phill Dickens from the University of Nottingham and Dr Tim Minshall from the University of Cambridge are coordinating the ongoing evidence gathering process. For further information or to provide input into the process we invite you to visit this initiative's website at www.amnationalstrategy.uk.

Research Fellow Dr Ehab Saleh supervising the build process on the Toucan material jetting system

EPSRC Centre management

Starting in October 2011, the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing assembles significant expertise in scientific and engineering research with a strong linkage to industrial reality. Hosting the EPSRC Centre at The University of Nottingham, along with colleagues at Loughborough University, we have a long-established background in Additive Manufacturing research and are recognised as internationally leading in this ground breaking field of engineering research.

The operation of this EPSRC Centre has shown that bringing the disruptive technology of multifunctional Additive Manufacturing to wide scale adoption in industry will necessitate both substantial fundamental research efforts and also a refined approach.

Dr Will Barton
Chair, Advisory Board

Will is a Fellow of the Royal Society of Chemistry, a Member of the Institute of Directors, a Member of the Council of the Chemical Industries Association, and has a Certificate in International Business General Management from INSEAD. After gaining a B.A. in Physics and a D.Phil. in Theoretical Physics from the University of Oxford, Will gathered 40 years of experience in manufacturing, technology and business leadership, mainly in the Chemical Industry. He has held leadership roles at multinational organisations ICI, FMC and Flexsys, a joint venture of Akzo Nobel and Monsanto, and Oxford Catalysts (now called Velocys), a spin out from the University of Oxford. From 2009, Will was responsible for establishing the UK's first Catapult centre in High Value Manufacturing at the Technology Strategy Board (now Innovate UK), but now spends most of his time with early stage technology companies, including Oxford Biotrans, Amalyst and Added Scientific where he chairs the boards. Will has joined the EPSRC Centre as the Chair of the Advisory Board in May 2014.

Prof Richard Hague
Director

Richard is a Professor of Innovative Manufacturing in the Department of Mechanical, Materials and Manufacturing Engineering at the University of Nottingham, Head of the Additive Manufacturing and 3D-Printing Research Group (3DPRG) and Director of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing. He has been working in the Additive Manufacturing field for 20 years and has a background of leading and managing large multi-disciplinary, multi-partner research projects. Richard's research interests are focused on Additive Manufacturing processes, materials and design systems across a wide spectrum of industrial sectors with a particular interest in design and design systems; current research programmes are focused on the design and production of multifunctional additively manufactured devices. Richard is also Chair of the International Conference on Additive Manufacturing & 3D Printing and active within the ASTM F42 Additive Manufacturing Standards initiative.

Dr Chris Tuck
Deputy Director

Chris is an Associate Professor in the University of Nottingham's Faculty of Engineering. At the EPSRC Centre of Innovative Manufacturing in Additive Manufacturing, Chris is Director of the newly awarded EPSRC Centre for Doctoral Training in Additive Manufacturing and also runs a number of projects based around the manufacture of multi-material and multifunctional inkjet printing, nano-scale Additive Manufacturing systems, and the development of metallic Additive Manufacturing systems for use in industry. Chris has worked in the field of Additive Manufacturing research from 2003, investigating the supply and business effects of Additive Manufacturing on a number of DTI, European and EPSRC funded projects. Chris is also an Executive Member of the ASTM F42 Additive Manufacturing standards committee and a participant in the BSi initiative of Additive Manufacturing standards development. Chris is a regular presenter at numerous international conferences, a panel member for EPSRC and a reviewer for international funding agencies.

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015

Prof Ian Ashcroft
The University of Nottingham

Ian is a Professor of Mechanics and Solids at The University of Nottingham, and Training Programme Director for the newly awarded EPSRC CDT in Additive Manufacturing and 3D Printing. After being awarded D.Phil from Oxford University in 1991, Ian held various postdoctoral positions in UK and Australia and worked at DERA Farnborough until 2000. His research interests and activities include: design and analysis of composite joints for aerospace applications, modelling environmental degradation in bonded joints, lifetime prediction for joints subjected to variable amplitude fatigue, in-service monitoring of bonded joints, indentation of viscoelastic materials, and hybrid joining techniques

Prof Paul Conway
Loughborough University

Paul is a Professor of Manufacturing Processes at Loughborough University. Educated at the University of Ulster, Jordanstown and Loughborough University. He is interested in joining and assembly processes in micro-scale systems, packaging of intelligent sensor and electronics data processing into new environments, materials processing for electronics and photonics intensive products, micro materials analysis and modelling, Design for manufacture of electronics systems, and Healthcare production engineering

Prof Phill Dickens
The University of Nottingham

Phill is a Professor of Manufacturing Technology at the University of Nottingham. Phill founded the Rapid Manufacturing Research Group in the early 1990's leading various research projects, supervising many successful PhD students. Phill has led international government missions, published widely, given a number of international keynote speeches and acts as a consultant to this industry. His research work has evolved through Rapid Prototyping and Rapid Tooling and is now concentrating on Additive Manufacturing processes.

Dr Ruth Goodridge
The University of Nottingham

Ruth is an Assistant Professor in Additive Manufacturing & 3D Printing at the University of Nottingham. Upon completion of her PhD in 2004, Ruth was awarded a JSPS Fellowship to investigate new materials for laser sintering at NAIST, Japan. She joined the Additive Manufacturing Research Group at Loughborough University in 2006, where she continued her research into new materials for Additive Manufacturing/3D-Printing. In April 2012, she moved to the University of Nottingham as part of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing.

Prof Russ Harris
Loughborough University

Russ is a Professor of Medical Engineering and Advanced Manufacturing at Loughborough University. He specialises in materials and manufacturing process research, conducted through research council and industrially sponsored projects. His research achievements have been recognised by a multitude of prize awards, peer reviewed publications, press features, and invited presentations. He has received grant funding awards as Principal Investigator from EPSRC, EC Framework Programme, and Department of Health. He has presented his research, by invitation, at the Royal Society and provided keynotes at many International conferences.

Prof Ricky Wildman
The University of Nottingham

Ricky is a Professor of Multiphase Flow and Mechanics at the Faculty of Engineering, University of Nottingham. He has a background in Physics and Chemical Engineering, and is contributing his expertise in the areas of multiphase flow and mechanical modelling, stress analysis, transport phenomena and biomedical engineering. His main areas of interest are in the rheological characterisation and modelling of ink jetting materials and in the development of reactive jetting processes for 3D printing. Currently he is leading the connections to biological applications, working with colleagues in Pharmacy and Biology on the development of 3D printing for pharmaceutical delivery and the manufacture of drug delivery devices

Key individuals

Meisam Abdi
Research Associate
The University of Nottingham

Dr Adedeji Aremu
Research Fellow
The University of Nottingham

Mirela Axinte
EPSRC Centre Research Coordinator
The University of Nottingham

Dr Martin Baumers
Research Fellow / Projects Coordinator
The University of Nottingham

Dr Belen Begines
Research Fellow
The University of Nottingham

Dr David Brackett
Research Assistant
The University of Nottingham

Dr Xuesheng Chen
Research Fellow
The University of Nottingham

Dr Elizabeth Clark
Research Fellow
The University of Nottingham

Mark East
Head Technician
The University of Nottingham

Dr Ross Friel
Wolfson School
Loughborough University

Hagit Gilon
Research Assistant
The University of Nottingham

Dr Guangying Guan
Research Fellow
The University of Nottingham

Mark Hardy
Additive Manufacturing Technician
The University of Nottingham

Yinfeng He
Research Fellow
The University of Nottingham

Dr Qin Hu
Research Fellow
The University of Nottingham

A broad range of interlinking disciplines flows into the EPSRC Centre's flagship research in the areas of multifunctional additive processes, materials and design systems, and the scaling down of these processes to the nano scale. These research activities and the EPSRC Centre's day-to-day operation are conducted in collaboration between the two partner institutions, The University of Nottingham and Loughborough University.

Dr Ji Li
Research Fellow
Loughborough University

Dr Iria Louzao
Research Fellow
The University of Nottingham

Dr Ian Maskery
Research Fellow
The University of Nottingham

Dr Tho Nguyen
Research Fellow
The University of Nottingham

Dr Ajit Panesar
Research Fellow
The University of Nottingham

Dr Phil Reeves
National Centre
Outreach Coordinator

Dr Ehab Saleh
Research Fellow
The University of Nottingham

Dr Marco Simonelli
Research Fellow
The University of Nottingham

Dr Jill Thurman
CDT Manager
The University of Nottingham

Dr Jayasheelan Vaithilingam
Research Fellow
The University of Nottingham

Dr Marcin Wegrzyn
Research Fellow
The University of Nottingham

Joe White
Additive Manufacturing Technician
The University of Nottingham

Dr Fan Zhang
Research Fellow
The University of Nottingham

Projects in core theme 1:

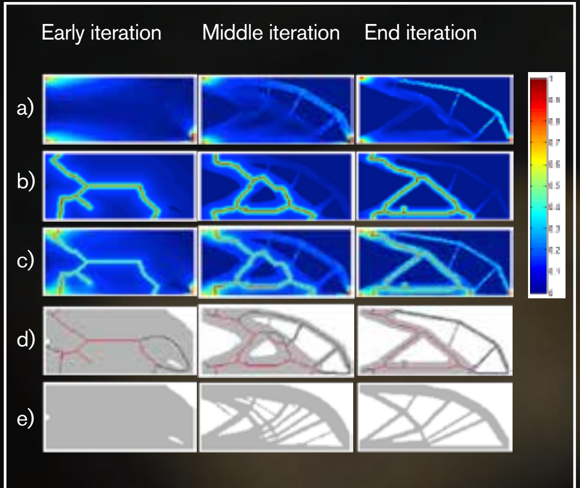
Multifunctional additive processes, materials and design systems

To investigate delivery platforms and design systems for multifunctional Additive Manufacturing

Design Systems Development for Multifunctional Additive Manufacturing

The key to unlocking the benefits of multifunctional Additive Manufacturing lies in the design freedoms that the additive approach engenders. A major challenge is to produce a methodology that enables the design of multifunctional Additive Manufacturing parts that are optimised. This optimisation problem must consider: efficient topology generation with integrated lattices and opto-electrical pathways (for embedded functionality). The multifunctional Additive Manufacturing design paradigm presents a radical advance in product design where weight, performance, functionality and aesthetics are combined in one part and manufactured as a single item.

Currently, work is concentrating on a two stranded multi-scale approach with system optimisation being tackled first to determine where to place components within a structure and how to route between them. The individual components can also be redesigned to exploit the design freedom of multifunctional Additive Manufacturing. Work is currently ongoing in collaboration with other researchers and across departments to progress this.

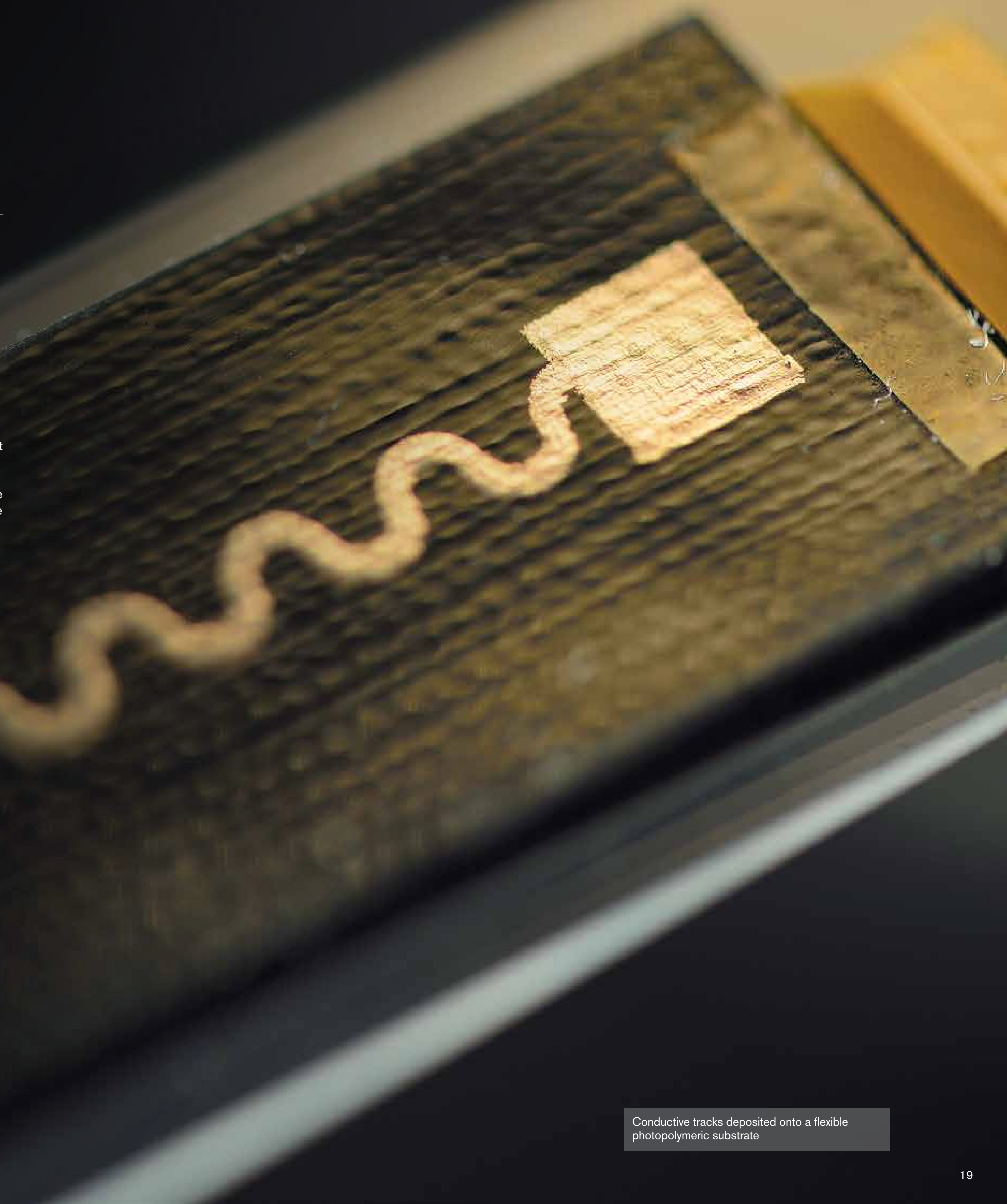


a) Sensitivities for structure, b) sensitivities for internal system, c) combined sensitivities, d) resulting coupled solution, and e) topology optimisation using just structural sensitivities for comparison.

This project has completed its third year and progress has been made in several areas of the planned work, particularly in the coupling method to allow combined optimisation of the structure and of the internal system. This works by defining design variable sensitivities for the routing which are then combined with the sensitivities from the structural analysis in a weighted sum approach. This approach is summarised in the figure below for a simple cantilever plate example. Additional work is under way to extend this approach to include internal component placement. Regarding the placement and routing capability, efforts have been focussed on defining a clustering method to group components together for more efficient routing and on implementing a prototype software system to allow evaluation of the capability.

Regarding lattice structure design, an emphasis has been placed on expanding the functional grading capability to include both cell size and material variation which will provide greater scope for optimisation. In addition, finite element analysis of unit cell performance has been carried out and validated with mechanical testing of laser melted aluminium samples.

Project Team: Prof Ian Ashcroft, Prof Ricky Wildman, Prof Richard Hague, Dr David Brackett, Dr Ajit Panesar, Dr Adedeji Aremu



Conductive tracks deposited onto a flexible photopolymeric substrate

Photopolymer part
deposited via material jetting

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015

Reactive Jetting of Engineering Materials

One of the biggest challenges facing the development of 3D Printing as a manufacturing process is the limited set of materials available. This project focuses on the discovery and synthesis of 3D printable materials and the functionalisation of already established materials. The ink jetting process operates by ejecting a drop of the required material, selectively and sequentially delivered to build up a 3D volume. The key challenges are to create printable inks, whilst at the same time ensuring that the process is triggerable to create a solid, and ensuring that the final products possess the correct properties.

Reactive jetting is a method that allows a liquid, printable ink to be converted into a useful solid through the initiation of a chemical reaction. A large number of applications of this method are investigated in this project, ranging from flexible electronics to biomaterials printing. The project team has demonstrated effective printing of materials such as Polymethyl methacrylates, Polyimides, Polysiloxanes and Polyurethanes as well as novel biomaterials, which can, for example, resist the attachment of bacteria. These materials are all created in situ during the manufacturing process, using photochemistry driven by UV absorption, reactive chemistry on the substrate or through thermal initiation.

This approach promises to open up 3D printing to an ever widening set of applications, driven by the synthesis of relevant materials, tailored specifically to the needs of the product. The project has already attracted interest and collaboration with companies in the fields of pharmaceuticals, agro-chemicals, electronics, quantum technologies and the healthcare industry.

Project Team: Prof Ricky Wildman, Prof Phill Dickens, Prof Ian Ashcroft, Dr Chris Tuck, Dr Belen Begines, Yinfeng He, Hagit Gilon, Dr Fan Zhang

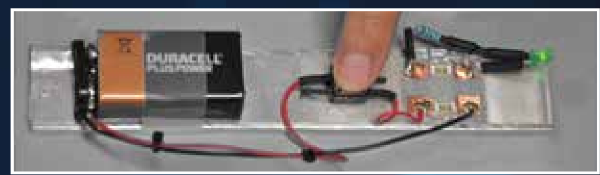
Additive Manufacture of Novel Multifunctional Metal Matrix Composites by Ultrasonic Consolidation

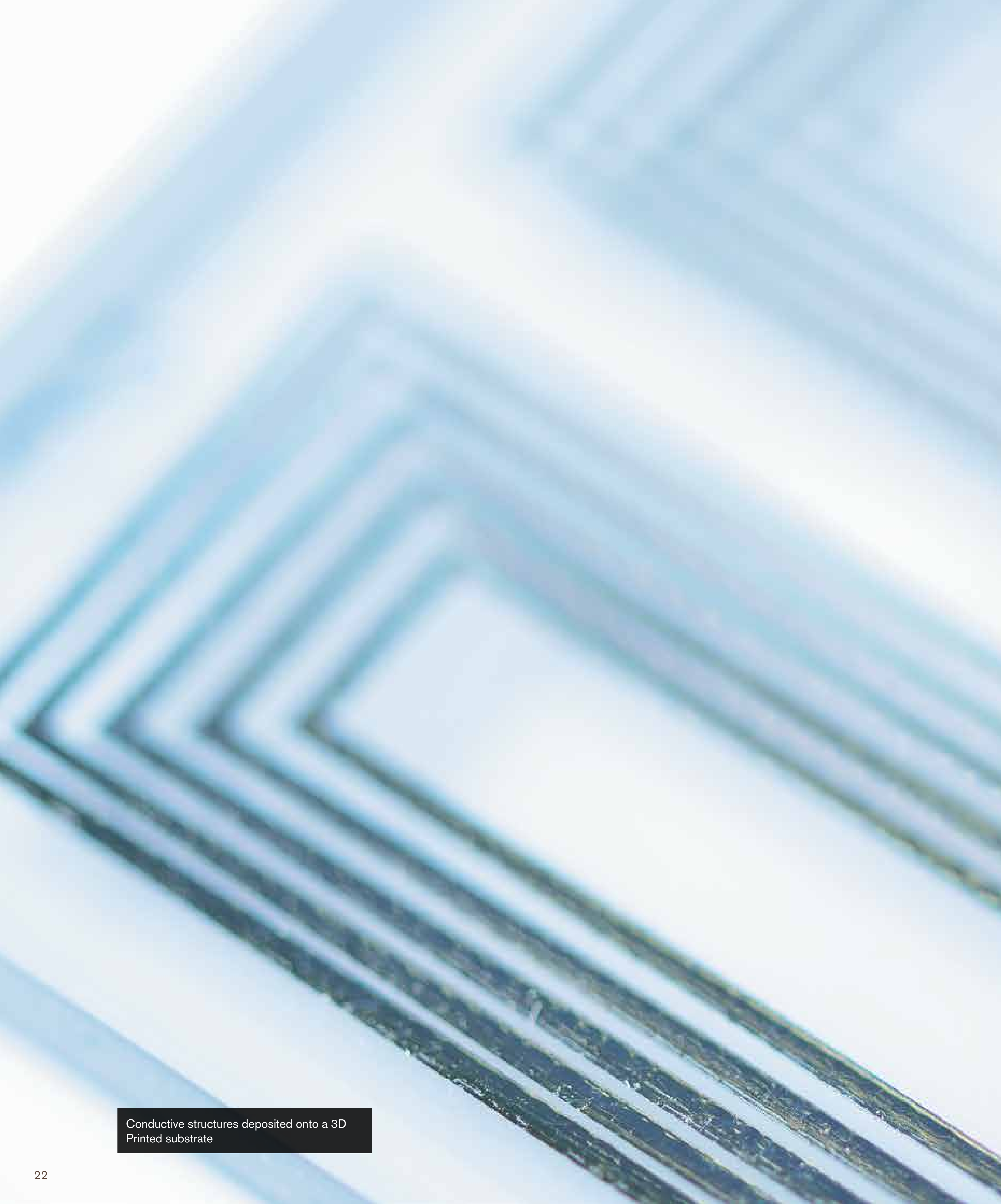
The aim of this project is to realise new multifunctional components by the freeform integration of electrical circuitry within dense metal components processed in the solid-state. This will allow the fabrication of novel engineered components that have been previously unobtainable as a result of the solid state nature of the Ultrasonic Consolidation (UC) process that will allow the integration of a wide variety of components due to the absence of elevated bulk temperatures. The printing of dielectric and conductive mediums, singularly and in unison, onto inter-laminar UC foil surfaces and their related surface geometry, and the effect on these by UC processing, is being investigated.

Since the last reporting period there has been extensive experimental work to explore and resolve issues regarding some failure modes that were observed. These included fracture of the electrically insulating dielectric component leading to shorting, and some interlaminar bond deficiencies and cracking in the metal matrix which would affect the overall mechanical integrity of the bulk device. This research has concluded this to be due to the effect of the hardness of the underlying dielectric material. Specific levels of dielectric hardness have been shown to be necessary to balance the requirements between resisting UC forces to prevent cracking of the insulator while also allowing appropriate impedance at the matrix/insulator interface to prevent cracking and bond issues. The success of this has been captured in a demonstrator which illustrates the ability to print functional embedded circuitry within metal devices (see accompanying figure). The project is now attempting to realise circuit arrangements that run in the z-axis of a device.

A journal paper has now been published in Materials Science and Engineering: A, entitled 'Exploring the mechanical strength of additively manufactured metal structures with embedded electrical materials'. The research has also recently won an IEEE prize for the research concerning the Effect of Ultrasonic Excitation on the Electrical Properties and Microstructure of Printed Electronic Conductive Inks.

Project Team: Prof Russ Harris, Prof Phill Dickens, Prof Ian Ashcroft, Dr Ross Friel, Dr Chris Tuck, Dr Ji Li





Conductive structures deposited onto a 3D Printed substrate

Jetting of Conductive and Dielectric Elements Additive Systems

The move to multifunctionality is littered with technical challenges, from the accurate and reliable deposition of different materials together and their interaction, to the design of these components and how best to integrate different materials for a given function. Current Additive Manufacturing technologies, whilst having some advantages, have some clear drawbacks for the production of multi-material parts. Among these are accuracy, resolution and the processing environment required during manufacture.

In the first year of this project a strategic review of the available manufacturing routes open to multi-functional Additive Manufacturing has been carried out, with significant promise being shown by drop-on-demand inkjet techniques for processing conductive, dielectric and other materials. On this basis, new experimental material deposition test beds have been procured and adapted along with the necessary characterisation equipment to ensure material applicability to the jetting processes. In total, three jetting systems have been commissioned, one based on the FujiFilm Dimatix DMP2831, two based on the PixDro LP50 architecture and a 6-head bespoke jetting system, commercially known as Toucan, also based on the PixDro architecture. All these systems are capable of depositing particulate based inks (such as those filled with silver nanoparticles) and a host of other materials with various viscosities and surface tensions. In particular, the PixDro systems have five different configurations to enable contemporaneous multi-material printing, particulate printing and elevated temperature printing of hot melt polymers.

The project is now concentrated on multi-material printing in 3D (especially in the vertical direction), as well as the printing onto existing additively manufactured substrates, such as those produced by ultrasonic consolidation, or materials developed in the sister project, Reactive Jetting of Engineering Materials. Various inks were specially formulated to enable printing conductive routes in the Z direction as well as real-time UV and heat curing sources to establish printing functional multi-material structures in a single process.

The project has achieved a breakthrough in sintering conductive silver nanoparticle-based inks. Where traditionally it takes a few minutes to transfer these inks into conductive tracks, the sintering time achieved in this project exhibited a duration of only a few seconds. Additional exciting achievements were made particularly in terms of graphene-based applications including all-printed graphene supercapacitors and graphene based transistors, which were fabricated using a novel graphene oxide rapid reduction method developed by the project team. Behaviour of printed conductive elements on different dielectric elements, especially printed dielectric elements was investigated to enable reliable 3D multi-material printing. Benchmarking of the printing systems, printing process and materials is a key milestone in the development of the project and a clear Design of Experiments has been formulated to ascertain best practice and the gap between capability and key performance indicators in industry.

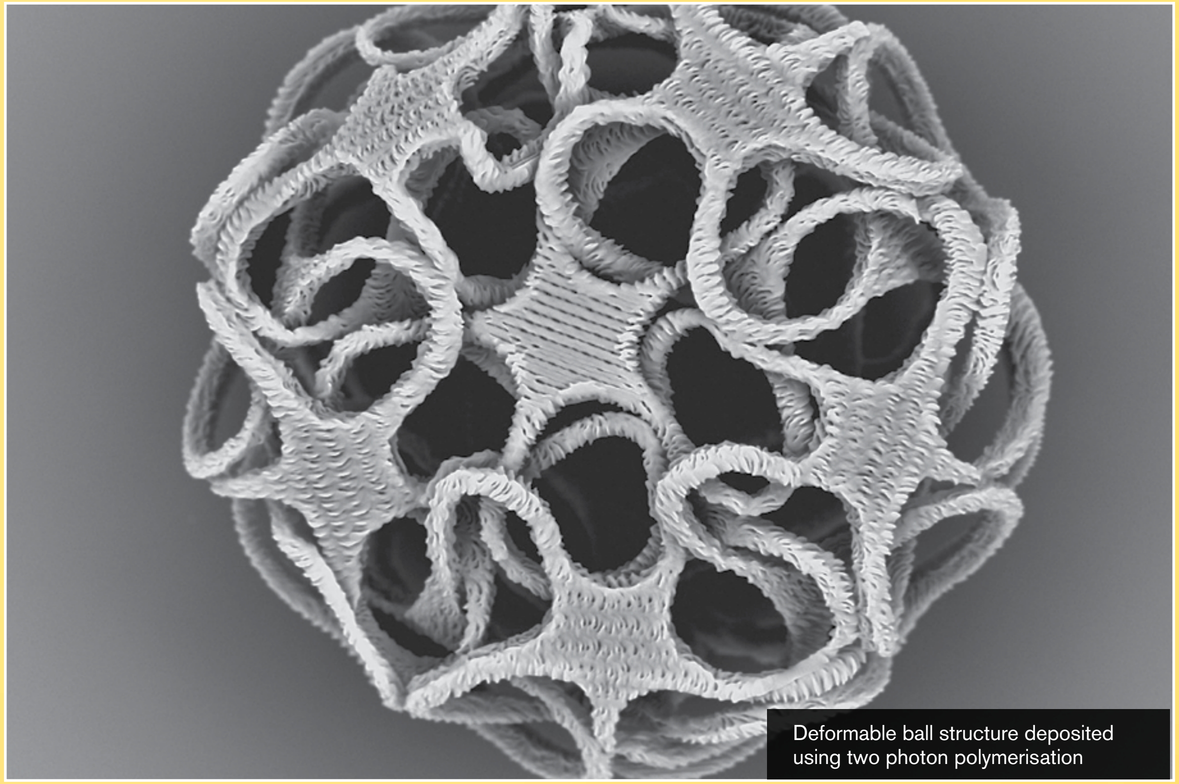
Project Team: Dr Chris Tuck, Prof Ricky Wildman, Prof Ian Ashcroft, Prof Phill Dickens, Prof Richard Hague, Dr Ehab Saleh, Dr Jayasheelan Vaithilingam

Project in core theme 2:

Scaling down of additive processes

To investigate the methodologies for micro/nano scale multifunctional Additive Manufacturing

PhD student Yaan Liu operating the Nanoscribe microstereolithography system



Deformable ball structure deposited using two photon polymerisation

Nano-functionalised Optical Sensors (NANOS)

The requirements for future Additive Manufacturing systems to produce complex multi-material and multifunctional components are reliant on two aspects; increased material capability and increased resolution. NANOS specifically targets these two aspects through the research and development of nano-resolution manufacturing systems, principally multi-photon lithography, that are capable of producing 3D structures of the order of 100 nm in materials that have relevance to sensing applications and beyond. In addition, NANOS intends to utilise developments in optical tweezer technology to functionalise the structures made using multi-photon lithography. NANOS is enabling the deposition of nanoscale structures in new materials that promote the development of novel sensory systems.

A multi-photon lithography system has been developed that is capable of fabricating three dimensional structures in the micro to nanometer size range. Currently the system is undergoing further testing and optimisation for its capability to process different materials, including polymers and metals, and to increase resolution and component complexity. The next step is to manufacture metal-polymer hybrid nano-composites in a single system with feature resolutions of less than 0.5 µm.

Since the project's inception, additional funding has been awarded from EPSRC and the United States Air Force's European Office of Aerospace Research & Development to extend the system's capabilities. Three PhD students are working on spin-off projects that involve collaborations with Nottingham's Electrical Engineering, Biomedical Sciences and Physics Departments demonstrating the wide relevance of the technology across the engineering and science fields.

Project Team: Dr Chris Tuck, Prof Ricky Wildman, Dr Qin Hu

External academic research funded by the EPSRC Centre

Investigating electrochemical deposition from a light assisted system

The aim of the project was to explore the electrodeposition of a metallic structure in a jet configuration using energy input to accelerate the deposition process. Two different approaches designed to control and understand the deposition of metals for a 3D printing application have been developed initially. The first system employed an IR laser coupled to an electrode through a fibre-optic cable. This study has shown that reductions in the uncompensated resistance of an electrode was possible through laser excitation of the system. In addition, this local heating effect was shown to enhance the rate of mass transfer of material to an electrode surface. These effects were beneficial to the development of a fibre coupled electrodeposition system. Deployment of the system within a flowing jet system was also investigated. Under the conditions employed, heating effects were minimal, suggesting that further refinement of the system is necessary. The second system constituted a ‘hot jet’ plating system. This was found to improve plating rates and hence the potential speed at which a deposit could be generated. This technique in tandem with a thorough understanding of the electrochemical cell within this environment shows promise as a versatile and cheap technology for the electrodeposition of 3D structures on a suitable substrate. It was thus able to produce rapid growth of an electrodeposit on the surface of an electrode.

The work has shown that electrodeposition under appropriate control and with careful experimental design is a versatile technology for the deposition of many different materials. This is not limited to materials with the ability to directly absorb laser light (e.g. 514 nm as described in the literature), but other highly reflecting materials. This is as a result of the novel approaches adopted where either the solvent is locally heated through the careful choice of laser wavelength and fibre optic technology or a hot jet approach where the liquid in the jet is rapidly heated and then ejected onto the electrode surface. Both approaches show significant promise and require further investigation. In addition, structures have been deposited at rates approaching those reported in the literature. However, the added versatility and simplicity of the new techniques suggest that these approaches show significant promise.

Project Team: Prof Phill Dickens, Prof Ricky Wildman, Dr Adam Clare, Dr Peter Birkin (University of Southampton)

In collaboration with:

Self-assembling hybrid jetting inks for regenerative medicine

This feasibility project sought to explore and expand the capability of current 3D inkjet printing technologies, particularly in the field of regenerative medicine. New ink formulations were targeted that possess desirable physical characteristics for jetting and that can produce the next generation of temporary templates (scaffolds) for tissue regeneration. Current jetting inks are not suitable for tissue scaffolds and adapting current biomaterials for jetting is not sufficient. The key objective of this feasibility study was to synthesise a new hybrid ink that can be jetted. Another objective of this project was to generate sufficient preliminary data to enable a larger proposal to be written that will explore candidate hybrid inks for optimal scaffold production for different tissues.

The long term aim of this collaborative study is to develop new jetting inks that will allow the manufacture of the next generation of scaffolds for bone and cartilage regeneration. The primary objective of this feasibility study was to assess the feasibility of jetting new hybrid inks containing supramolecular polymer networks and functionalised nanoparticles. The thermoreversible characteristics of supramolecular polymer networks featuring functionalised nanoparticles will also offer the capability to realise the first ink-jetted healable 3D structure.

A programme grant proposal entitled ‘Advanced synthetic hybrid materials for regenerative medicine’ has been submitted to EPSRC in January 2015, led by Prof Julian Jones, with Prof Wayne Hayes as a Co-Investigator. This project will further develop the technologies outlined in this report, building upon the use of supramolecular chemistries to create self-assembling structures for regenerative medicine. The EPSRC Centre is a project partner in this application and the consortium will seek technical input from staff at Nottingham in the 3D printing and scale-up aspects of this project.

Project Team: Prof Wayne Hayes (Reading University), Dr Julian Jones (Imperial College). The project is overseen by Prof Ricky Wildman and Dr Ruth Goodridge

This project is funded through the EPSRC Centre’s Jump Start programme.

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015

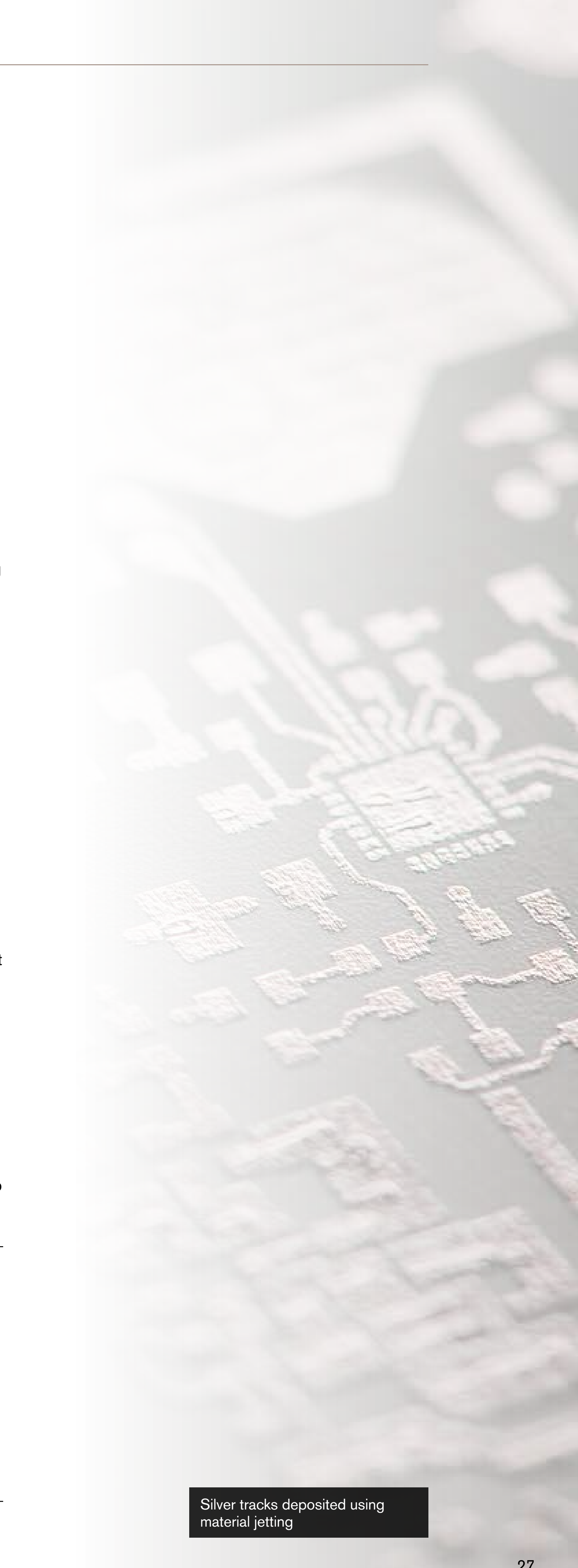
Smart Photoreactive Materials for Additive Manufacturing (University of Sheffield, University of Nottingham, Imperial College, University of Warwick)

A critical challenge faced in Additive Manufacturing is to increase the repertoire of materials that can be assembled, as well as to open up new possibilities in multimaterial systems. This project investigates the design of new ink formulations for Additive Manufacturing based on surface functionalisation with photo-responsive surfactants. By creating particles that are dispersed in the dark but agglomerate upon UV irradiation, it would be possible to control this aggregation process and tune it for two solid free form fabrication techniques, continuous extrusion and stereolithography.

This approach is simple (based on a single additive), flexible (allows for the use of different Additive Manufacturing techniques) and versatile (different ceramic materials could be printed following this approach). Thus, the overall aim of this project is to explore a novel production route for ceramic-based 3D architectures. These architectures will be built from a smart photoreactive nanoparticulate material. These particulate materials will be formulated so that they exist as a stable dispersion (surfactant initially repulsive), but aggregate upon irradiation via electrostatically driven self-assembly (surfactant reveals an attractive component upon radiation). This project has received an extension, it will be completed in early 2016.

Project Team: Dr Frederik Claeyssens (University of Sheffield), Dr James Dowden, Dr Frankie James Rawson (University of Nottingham), Dr Esther Garcia-Tunon Blanca (Imperial College), Dr Simon Leigh (University of Warwick). The project is overseen by Dr Ruth Goodridge and Prof Phill Dickens.

This project is funded through the EPSRC Centre’s Jump Start programme.



Silver tracks deposited using material jetting

In-Situ Imaging of Particle-Beam Interactions in SLM and Modelling of Powder Spreading (Heriott-Watt University, STFC, University of Leeds, University of Manchester)

The elimination of the detrimental effect of pores on the fatigue life of titanium components, without resorting to using additional costly process steps, such as hot isostatic pressing, is desirable for the industrial adoption of AM in aerospace manufacturing. With all AM platforms there is, therefore, a requirement to develop a better systematic understanding of the relationships between the process parameters, and the size, density, and 3D spatial distribution of pores within a final component.

This feasibility study evaluated complementary experimental and modelling techniques with the potential to step change understanding in this area. The specific objectives of this project were to:

- Determine if in-situ flash x-ray imaging can be used to monitor powder bed melting and the generation of gas bubbles and pores within the melt pool
- Investigate discrete element method modelling to simulate the powder spreading in the SLM process and the effect of powder morphology on packing density variability
- Use ex-situ high resolution x-ray tomography to characterise the powder packing in the bed and the retained defects in melted layers, to support the experiments and modelling

Project Team: Prof Andrew Moore (Heriott-Watt University), Dr Joe Kelleher (STFC), Prof Andrew Bayly (University of Leeds), Prof Phil Prangnell (University of Manchester). The project is overseen by Dr Chris Tuck and Dr Adam Clare

This project is funded through the EPSRC Centre's Jump Start programme.

Science & Technology Facilities Council
MANCHESTER 1824 The University of Manchester
HERIOT WATT UNIVERSITY
UNIVERSITY OF LEEDS

Optimising Impact Protection through Additive Manufacturing (University of Bath, University of Cambridge, Cardiff University)

This project aims to develop a method for establishing the topologically optimised microstructure of cellular materials, for use within high strain-rate (i.e. impact) scenarios. The project brings together expertise of topology optimisation, impact materials and modelling and experimental characterisation of impact performance. This project has identified the key challenges in the topology optimisation formulation that need to be addressed to optimise materials for impact. The results of the project form the basis for substantial future research, by clarifying the key challenges in the formulation parameters for optimisation for impact material. A conference paper that rigorously identified the research challenges provides the basis and track record for a collaborative proposal.

The results of the work have been accepted for oral presentation: Kim HA, Duro J, McShane GJ, Theobald PS (2015) "Topology optimisation of additively manufactured impact resistant structures," Proceedings of the 23rd UK Conference of the Association for Computational Mechanics in Engineering, Swansea University, Swansea. This research also provided opportunities to widen industrial contacts and to discuss future research with companies.

The jumpstart funding has been useful in bringing together the research fields of injury metrics, mechanics of cellular materials and topology optimisation and enabled the rigorous identification of a new exciting research area utilising the complimentary skill set. The project provided the insights and challenges in topology optimisation of impact material, new industrial contacts and the necessary collaborative track record to build future proposals.

Project Team: Dr Alicia Kim (University of Bath), Dr Graham McShane (University of Cambridge), Dr Peter Theobald (Cardiff University). The project is overseen by Prof Ian Ashcroft and Prof Ricky Wildman

This project is funded through the EPSRC Centre's Jump Start programme.

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
UNIVERSITY OF CAMBRIDGE
UNIVERSITY OF BATH

High Resolution Jet Printing for Additive Manufacturing (Queen Mary University of London, University of Cambridge)

In inkjet based Additive Manufacturing processes, one of the major limiting influences on resolution and quality is the size of the ink drops used. Conventional inkjet systems are typically operated in the drop volume range 1 pl to 500 pl yielding surface features typically greater than~20 μm. Electrostatic inkjet printing has the potential to deposit significantly smaller volumes of material, using fluids having a viscosity range several orders of magnitude broader than from conventional inkjet and hence potentially obtain improved surface feature definition and reduce surface roughness in Additive Manufacturing. The aim of the project was to use the high speed imaging capability at Cambridge Inkjet Research Centre to gain better understanding of the process of small droplet generation and deposition obtained via electrostatic printing, based on an approach developed at QMUL. The ability to use the technique to build a micron scale structure was also to be attempted.

The project confirmed that electrostatic inkjet can generate drop-on-demand volumes of fluid typically two orders of magnitude smaller than conventional inkjet technologies currently used in Additive Manufacturing applications. These deposition volumes are however generated in a fine jet (in the fluids used typically one micron in diameter), rather than in a single drop.

The jet/droplet velocity is high and hence high spatial accuracy in an Additive Manufacturing deposited volume may be anticipated. The observation and measurement in this project of where the jet breaks into droplets which eventually diverge, clearly has implications on the print distance in such an Additive Manufacturing system, and this requires further investigation to understand the full governing features of these processes in order that they may be controlled. Techniques to investigate and print with small high velocity jets and drops have been refined and can be applied to this and other processes in the future.

Project Team: Prof John Stark (Queen Mary University of London), Dr Graham Martin (University of Cambridge). The project is overseen by Prof Richard Hague and Dr Chris Tuck

This project is funded through the EPSRC Centre's Jump Start programme.

UNIVERSITY OF CAMBRIDGE
Queen Mary University of London

Biomorphic polymer structure created with Laser Sintering

Complementary research at the 3DPRG

ALSAM – Aluminium Lattice Structures via Additive Manufacturing

The ALSAM project came to a successful end in May 2015, having run since February 2013. Its main purpose was to realise lightweight components made from aluminium alloys suitable for the automotive, motorsport and aerospace sectors. This was achieved by embedding lattice structures in components selected by our industrial partners. This significantly reduced their weight and provided the advantage of multifunctional capabilities, such as heat dissipation and enhanced metal-composite bonding.

During the ALSAM project, software tools were developed to make use of a broad range of lattices in Selective Laser Melting (SLM) components. This was incorporated into a software package, which will be released commercially by one of the project partners. Other partners were motivated by component performance improvement, which was generally achieved by reducing unnecessary weight, but also by adding new functionality only possible through the adoption of lattice structures.

Within this project, some of the most pertinent results originated from investigations into self-supporting lattice structures. The lattices were examined theoretically by computational methods and experimentally. The findings were presented at several international conferences and led to a number of journals publications. In addition, the results of the lattice characterisation work fed directly into the design of lightweight components for the project partners. More publications are planned regarding SLM aluminium material properties and lattice performance, and selected results will be presented at international conferences in 2015, including Solid Freeform Fabrication in Austin, Texas, and Rapid and SEM Experimental and Applied Mechanics, in Los Angeles, California.

Project team: Dr. Chris Tuck, Prof. Richard Hague, Prof. Ian Ashcroft, Prof. Ricky Wildman, Prof. Colin Garner (Loughborough University), Dr. Yau Yau Tse (Loughborough University), Dr. Adedeji Aremu, Dr. Ian Maskery

This project is funded by Innovate UK.

ALMER – Advanced Laser-additive layer Manufacture for Emissions Reduction

Future generations of propulsion and energy systems will need to push back the boundaries of current state of the art in order to meet future emissions and performance criteria. Additionally, components will need to fulfil multiple functions, reducing the inventory and number of discrete systems within a larger system. Additive Manufacturing is expected to provide a platform to introduce such disruptive technology into future products and services.

Additive Manufacturing has been identified as a key enabler that will allow increasingly complex components to be manufactured at a reduced cost, thereby allowing companies to meet both environmental targets as well allowing them to remain competitive in the aviation industry. The aim of ALMER is to develop the UK Additive Manufacturing capability through a consortium of both large and small companies, research organisations and academic institutions. ALMER is specifically designed to tackle the manufacturing challenges that must be overcome so that the potential design opportunities afforded by Additive Manufacturing can be exploited fully.

The objectives of the ALMER project include the generation of production standard data for a nimonic alloy (C263), optimisation of post processing techniques, development of inspection methods, process development of a high temperature alloy (CM247LC) and the generation of a design and optimisation tool that will seek to exploit the weight reduction opportunities in component design. The combination of these developments will enable the advancement towards productionisation of Additive Manufacturing components.

The work stream being carried out by The University of Nottingham builds upon research that has been conducted in the field of topological optimisation methods. It seeks to advance these methods closer to commercial realisation by exploring existing and new methods to fully exploit the design freedoms offered by Additive Manufacturing, whilst incorporating the nuances and performance limitations of this modern manufacturing method.

Project Team: The ALMER project team is composed of a number of industrial and academic partners. At The University of Nottingham, the project team includes Prof Ian Ashcroft, Prof Ricky Wildman, Dr David Brackett, and Meisam Abdi

This project is funded by Innovate UK.

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015

The research groups contributing to the EPSRC Centre at the University of Nottingham and Loughborough University are also participating in a number of projects in close collaboration with industry, other funding agencies and partner institutions.

ASID – Advanced Structural Integrated Demonstrator

Reduction in mass, improved performance, sustainable manufacturing and reduced manufacturing costs are common goals across all sectors of the aerospace industry and a number of discrete emerging technologies are well placed to offer suitable advancements. The ASID project is combining a number of these technologies, namely topologically optimised titanium Additive Manufacturing and advanced thermoplastic composites. Whilst the benefits of the individual technologies are understood, realisation of their true potential is dependent upon their successful integration. To this end, ASID aims to develop novel methods of integration to provide strong, lightweight structures that reduce the requirement for conventional mechanical fixings. In doing so, ASID will demonstrate a design and manufacturing philosophy that is applicable to both military and civil applications across a range of highly loaded metallic-composite integrated airframe structures. The project is investigating the feasibility of this approach and the demonstrator will be used to assess the expected benefit of exploiting both innovative techniques.

The focus of the ongoing work at The University of Nottingham is to carry out topology optimisation and associated analysis and design tasks for the demonstrator component for manufacture in titanium using Selective Laser Melting. In addition, novel fastening approaches that take advantage of the design freedoms of Additive Manufacturing are investigated to join the titanium hinge to thermoplastic component geometry.

Project Team: Prof Ian Ashcroft, Dr David Brackett, Dr Adedeji Aremu, and Prof Richard Hague

This project is funded by Innovate UK.

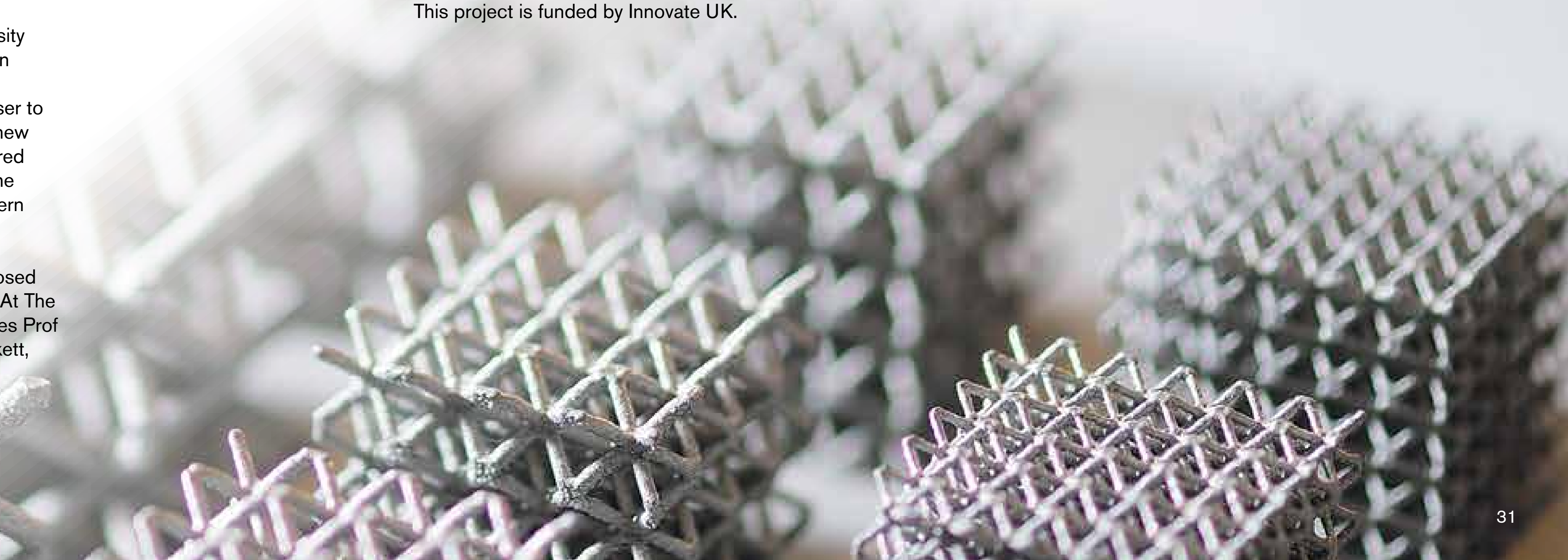
Two-photon Photoreduction and Polymerisation for Nanoscale Assembly

The aim of this project is to combine two-photon polymerisation and photoreduction to enable the manufacture of metamaterials at the nanoscale. Metamaterials are artificial multi-material constructs with sub-wavelength-sized periodic structures containing both conducting (metal) and dielectric (polymer) components. Their unique but previously unachievable properties have challenged the understanding of the interaction between light and matter, thus promoting numerous extraordinary applications. The current techniques for metamaterials manufacturing are mainly based on traditional microchip patterning techniques which are expensive and often prone to failure and material waste; to date they also exhibit insufficient control to truly form multimaterial components.

This project explores the feasibility of a new method of manufacturing metamaterials by combining two-photon polymerisation and photoreduction. By coupling multi-photon lithography with Stimulated Emission and Depletion (STED), it is possible to control the fabrication of 3D nano-composites precisely through selective polymerisation or photo-reduction on demand. A new rig has been built for this purpose and various polymer-metal nano-composites have been created.

Project team: Prof Ricky Wildman, Dr Chris Tuck, Prof Richard Hague and Dr Qin Hu

This project is funded by the United States Air Force European Office of Aerospace Research & Development.



Aluminium lattice structures created via Selective Laser Melting

Automation of 3D Cell Model Assembly by Additive Printing

Tissue engineering and regenerative medicine are key healthcare challenges for manufacturing. The EPSRC Centre's involvement in this field has been to examine the feasibility of 3D printing complex tissue structures. Potential applications for this research include the manufacture of cell based biosensors, in-vitro models of complex organs, implanted cell-factory devices, or external assist devices for organs.

This work complements a growing portfolio of biomaterial and healthcare related research emerging from the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing. In collaboration with the Centre of Biomolecular Sciences (CBS) and the School of Pharmacy at The University of Nottingham, research areas ranging from bioprinting to pharmaprinting are being explored, taking basic science to application.

Project Team: Prof Ricky Wildman, Dr Chris Tuck, Yinfeng He, Hagit Gilon
This project is funded by Innovate UK.

Auxetic nylon structure created via Laser Sintering

The enabling role of 3DP in redistributed manufacturing: A total cost model

To date costing approaches of Additive Manufacturing have largely focused on investments and consumables. Analyses of these well-structured costs have observed that fully utilizing the available machine capacity forms a prerequisite for efficient operations. However, existing analyses of Additive Manufacturing resource consumption have largely ignored hidden or so-called 'ill-structured' costs relating to build failure and ancillary manual processes, such as part finishing and support removal, and perhaps most importantly costs relating to unintended product variation.

This project aims to establish an understanding of Additive Manufacturing as a parallel digitally integrated manufacturing technology capable of operating in a redistributed setting. Improved cost models will describe configurations minimising overall monetary cost, energy consumption, and in many cases also waste caused by unintended variation. Unlike conventional manufacturing, the parallel and digital design-driven nature of 3DP also gives rise to network effects in 3DP. Such network externalities, which are also investigated by this project, can improve the value, or benefit, of an individual process as the installed base of such platforms increases.

Project Team: Dr Martin Baumers, Prof Matthias Holweg (University of Oxford), Jonathan Rowley (Digits2Widgets)
This project is funded through the Bit-by-Bit project at the University of Cambridge.

3DP-RDM: Defining the research agenda for 3D Printing enabled re-distributed manufacturing

The objective of 3DP-RDM is to convene a multi-disciplinary research and multi-industry user network that provides the required breadth and depth of research capabilities to define and disseminate the research agenda for 3DP-enabled re-distributed manufacturing. The formation of this community will provide a platform for the delivery of a portfolio of research feasibility studies to explore the following three clusters of research questions:

- Identification of features of Additive Manufacturing technologies that help enable re-distributed manufacturing;
- How re-distributed manufacturing may accelerate the diffusion of 3DP technologies, and vice-versa;
- Analysis of sector specific and generic aspects of 3DP enabled re-distributed manufacturing;

The network launched at the beginning of this year with a scoping workshop where a group of academics and industrialists explored what research topics should be addressed through feasibility studies in the first year of the network. Informed by these workshop outputs, 34 proposals were received during a feasibility study competition, four of which have been selected for funding following a rigorous review process. These four studies will be conducted during 2015, with the results shared at an event in January 2016. A second round of the feasibility study competition process will take place in 2016.

Project Team: Dr Tim Minshall (PI), Institute for Manufacturing, University of Cambridge, Professor Phill Dickens, (Co-I), University of Nottingham, Dr Simon Ford (Network Coordinator), Institute for Manufacturing, University of Cambridge.

The 3DP-RDM project is part of the Engineering and Physical Sciences Research Council's (EPSRC) "Manufacturing the Future" theme and is being funded through the joint invitation for proposals "Re-distributed Manufacturing - Call for Networks" with the Economic and Social Research Council (ESRC).

Wearable Soft Robotics for Independent Living

The aim of this project is to develop wearable soft robotic technologies which exhibit sophisticated sensing, actuation and control and which can be fabricated into complete wearable devices. This project will be the first time that emerging soft robotics technologies are employed to address multiple rehabilitation and health care needs in one single class of wearable device, enabling effective and comfortable rehabilitation, functional restoration and long term assisted living. In contrast to conventional rigid robotics, the inherent physical compatibility of soft robotics with biological tissue and human motion means that truly adaptive assistive and rehabilitative technologies (or aART) can be realised. Soft robotic aART has the potential to be the ubiquitous, low cost and highly adaptable technology that transforms independent living for the disabled and infirm.

This project forms a collaboration between the universities of Bristol, Nottingham, Loughborough, Leeds, Southampton, Strathclyde and UWE. Academics from the EPSRC Centre (Ruth Goodridge & Russ Harris) are looking to develop new fabrication methods for compliant 3D smart materials and functionalised polymers in conjunction with wearable fabrics.

Project Team: Dr Jonathan Rossiter (University of Bristol), Prof Russ Harris (Loughborough University), Dr Abbas Dehghani (University of Leeds), Dr Ruth Goodridge, Dr Rory O'Connor (University of Leeds), Dr Ailie Turton (University of West England), Dr Christopher Freeman (University of Southampton), Dr Arjan Buis (University of Strathclyde)

The project is funded by EPSRC.

In collaboration with:

Projects funded by AWE Plc

- **Jetting of Silicones**
- **Powder Bed Fusion of Syntactic Foams**
- **Metal Jetting of Functionally Graded Materials**

Reaching out: the National Centre

After the start of the EPSRC Centre in 2011, funds were awarded to act as a National Centre for Additive Manufacturing research. These funds are targeted at supporting the UK research community in project initiation and to foster joint working. Funds are available to external organisations to support travel for research set-up meetings and also to allow the use of the EPSRC Centre's facilities to UK researchers. A budget has also been allocated to support networking and focus groups.

Specialist Additive Manufacturing consultants continue to support the delivery of elements of the National Centre agenda, including the organisation of the International Conference on Additive Manufacturing and a number of associated events in addition to providing research data on the UK Additive Manufacturing research base.

Engaging with the wider Community

International Conference on Additive Manufacturing and 3D Printing 2015

In July 2015, the EPSRC Centre once again hosted the International Conference on Additive Manufacturing and 3D Printing. The three-day event was attended by over 290 delegates from 18 countries, including the United States, Taiwan, Israel and Japan along with many countries in mainland Europe. 19 speakers were invited to present at the conference by the Centre Director and National Centre Coordinator, from organisations including Laing O'Rourke, Autodesk, Arup, Hewlett Packard, Océ Technologies, Rolls Royce, The National University of Taiwan & the Lawrence Livermore National Laboratories. The event also included a technology vendors' exhibition which was attended by some 18 companies providing Additive Manufacturing hardware, materials, services and supporting scientific equipment.

Scientific Advancement in Additive Manufacturing conference

Directly preceding the International conference in July 2015, the National Centre was delighted to arrange and host a special one day conference entitled "Understanding the Science Behind Additive Manufacturing". The event included presentations outlining cutting edge research into the enabling science behind Additive Manufacturing and 3D Printing. Each of the selected speakers from universities, including Herriot Watt, Bath, Imperial College, Cambridge, Liverpool, Warwick, Southampton and Reading, presented research funded directly by the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, through the EPSRC Centre's 'jump-start' funding process.

State of the art review of research competence

A detailed review of UK Additive Manufacturing research competence and funding was completed and published by the National Centre in 2015. The review identified some 244 active Additive Manufacturing research projects taking place across the UK involving over 250 research organisations and companies. In total some £30-million per annum of research has been identified directly supporting Additive Manufacturing research within either the science base or industry. A large portion of this funding is attributable to single material homogeneous metal parts. However, a very significant proposition is to research multimaterial, multifunctional 3D Printing of which Nottingham University is the undoubted lead institution within the UK. The research highlights the changing technology readiness level of Additive Manufacturing and how the technology is starting to gain mainstream adoption into new sectors of the economy from retail and the creative industries to the medical sector and aerospace.

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
Annual Report 2014–2015

Engaging with Industry

National Strategy Events

In 2015 two events were organised by the National centre on behalf of the UK Additive Manufacturing community. The events at the MTC in Coventry and Nottingham University were attended by some 98 delegates and 32 delegates respectively. The events were facilitated by Professor Phill Dickens of Nottingham University and Professor Tim Minshall from the Institute for Manufacturing at Cambridge University. The objective of the events was to engage with the UK Additive Manufacturing community to start shaping a national strategy for additive manufacturing. The strategy development work is now on-going with buy in from a number of significant UK operating companies including Airbus, GKN, GSK and Rolls Royce.

Other Outreach

Additive Manufacturing in Healthcare: Joint event with NUH

The aim of the event, held on 25 February 2015, was to bring together academics at the University of Nottingham with key stakeholders within NUH to discuss the potential impact of Additive Manufacturing and 3D-printing in the medical sector. It was intended as an opportunity for participants to explore current capabilities of the technology and contribute their own expertise of clinical needs, in addition to exploring further opportunities for collaborative work.

2nd Mexican Workshop on Additive Manufacturing & 3D Printing: From Aerospace to Bioprinting

Initiated at Newcastle University in collaboration with the British Council, CIATEQ and CONACYT, this workshop and conference brought together academics from the UK and Mexico in June 2015 to discuss the latest development in the field of Additive Manufacturing with a special emphasis on the bioprinting and aeronautical sectors. Martin Baumers, Belen Begines and Qin Hu represented the EPSRC Centre and the 3DPRG at this event which was hosted by the Mexican research organisation CIATEQ in Queretaro, Mexico.

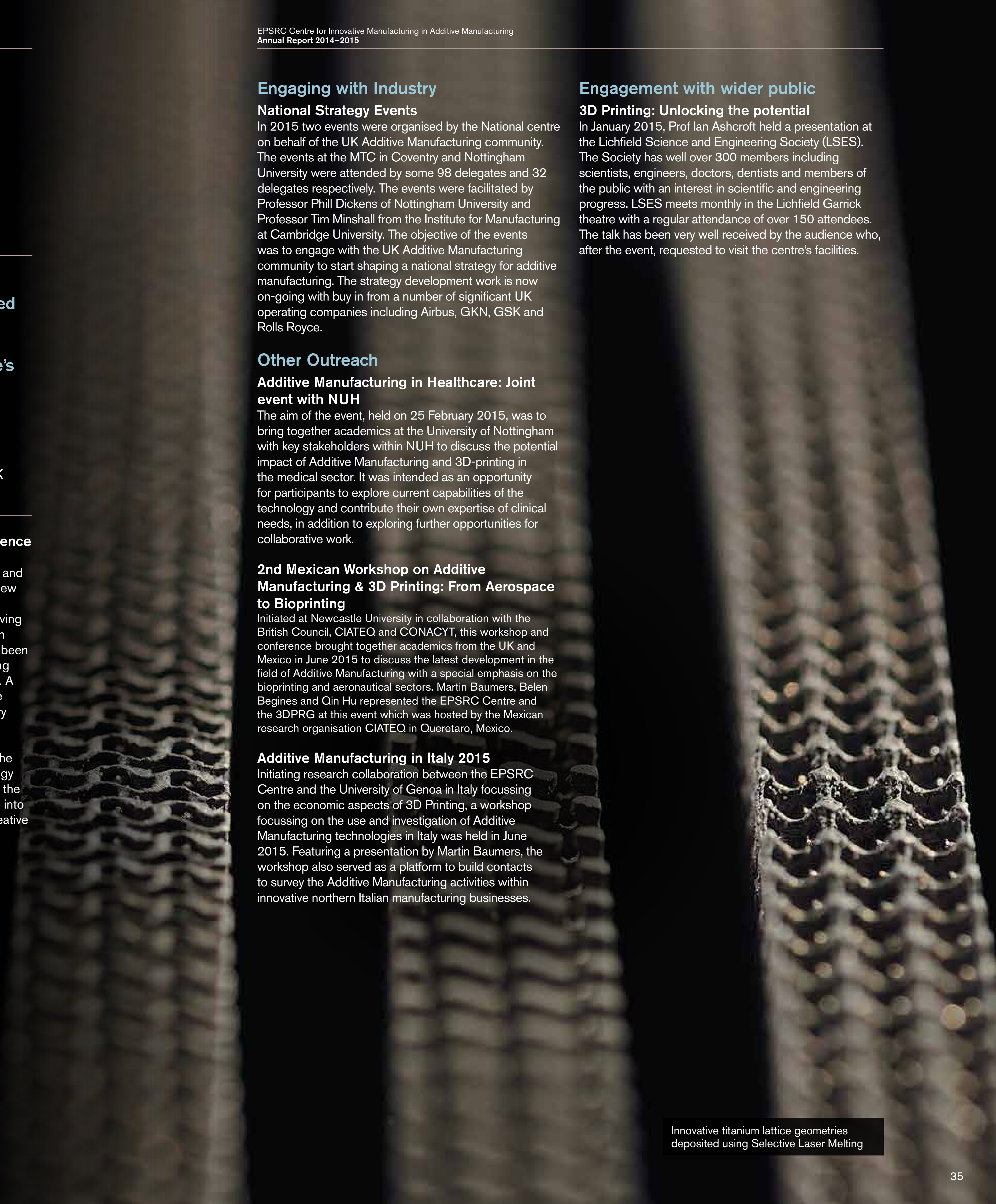
Additive Manufacturing in Italy 2015

Initiating research collaboration between the EPSRC Centre and the University of Genoa in Italy focussing on the economic aspects of 3D Printing, a workshop focussing on the use and investigation of Additive Manufacturing technologies in Italy was held in June 2015. Featuring a presentation by Martin Baumers, the workshop also served as a platform to build contacts to survey the Additive Manufacturing activities within innovative northern Italian manufacturing businesses.

Engagement with wider public

3D Printing: Unlocking the potential

In January 2015, Prof Ian Ashcroft held a presentation at the Lichfield Science and Engineering Society (LSES). The Society has well over 300 members including scientists, engineers, doctors, dentists and members of the public with an interest in scientific and engineering progress. LSES meets monthly in the Lichfield Garrick theatre with a regular attendance of over 150 attendees. The talk has been very well received by the audience who, after the event, requested to visit the centre's facilities.



Innovative titanium lattice geometries deposited using Selective Laser Melting

Doctoral research at the EPSRC Centre

Dr Jayasheelan Vaithilingam analysing surface structures created with Additive Manufacturing

PhD students from a variety of backgrounds are carrying out doctoral research in the context of the EPSRC Centre and at the 3DPRG. The following lists the contributing PhD Students, their academic backgrounds and the topic of their doctoral project:

- **Meisam Abdi (Mechanical Engineering):** Topology optimisation of continuum structures using X-FEM and isovalues of structural performance – Awarded a Research Associate position
- **Nesma Aboulkhair (Mechanical Engineering):** Microstructural and mechanical investigation of aluminium alloys processed by Selective Laser Melting
- **Meisam Askari (Nanoelectronics):** Metamaterial fabrication using two-photon polymerisation and optical trapping.
- **Amir Badiee (Mechanical Engineering):** Examination of the response of ethylene-vinyl acetate film to changes in environmental conditions
- **Sarah Everton (Mechanical Engineering):** Ensuring the quality of metallic components made by Additive Manufacturing for aerospace
- **Michele Garibaldi (Bioengineering):** Impact of Additive Manufacturing on the optimal design of electrical machines
- **Yinfeng He (Materials Science):** 3D printing of biodegradable polymers for stents and implants manufacturing- Awarded a Research Associate position
- **Gunasekera (Deshani) Henadira (Chemical Engineering):** 3D Printing of ionic liquids
- **Dominic Hui (Biomedical Materials Science):** Cytocompatibility of degradable nanostructures materials by Additive Manufacturing
- **Amanda Hüsler (Materials Science):** Polymer particle formation using ink jet printing
- **Farhan Khan (Mechanical Engineering):** Design optimisation for stent manufacture
- **Andrew Knott (Physics):** Fabrication of sub-micron light trapping structures for use in dye-sensitised solar cells
- **Mary Kyobula (Pharmacy):** Manufacturing of personalised solid dosage forms using three dimensional printing
- **Javier Ledesma (Nanoscience):** 3D jetting of functional materials
- **Georgina Marsh (Pharmacy):** Investigation of model carriers and inhalation particles to determine the relative importance of morphology and surface energy for powder interaction
- **You Li (Electrical and electronic engineering):** Inkjet printing of active electronic elements
- **Yaan Liu (Ann) (Polymer Science and Technology; Biofunctional materials):** Multifunctional materials Additive Manufacturing using multi-photon processes
- **Le Ma (Chemical Engineering):** 3D Printing of polyurea by reactive inkjet printing
- **Thuy Trang Ngo (Design Engineering):** Enhanced functionality and customization in prosthetics through Additive Manufacturing and design optimization
- **Luke Parry (Mechanical Engineering):** Simulation and optimisation of Selective Laser Melting
- **Benjamin Paul (Neuroengineering):** Additive manufacture of a neuron biosensor
- **Elisabetta Prina (Biomedical Engineering):** Recreating 3D tissue architectures using Additive Manufacturing techniques for cornea regeneration
- **Craig Sturgess (Mechanical Engineering):** Investigating and modelling the progress of drop on drop mixing and reaction in reactive inkjet printing
- **Qifeng Qian (Chemical and Environmental Engineering):** Fundamental Investigation on Reactive Inkjet Printing of Polycarbonate
- **Zhengkai Xu (Manufacturing Engineering):** Additive Manufacturing using Ni based aerospace alloys
- **Ge Zhao (Mechanical Engineering):** Functional grading and optimization of NiTi by Additive Manufacturing technique
- **Stefan Ziegelmeier (Mechanical Engineering):** Process analysis and material behaviour of thermoplastic elastomers in laser sintering

Students at the Centre for Doctoral Training

EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing

Cohort 1 - Started 2014

- **Hatim Cader (Medical Materials):**
3D Printing of solid dosage forms (Sponsor: GSK, Home Institution: University of Nottingham)
- **Carlo Campanelli (Chemical Engineering):**
Processing of high performance fluoropolymers by Additive Manufacturing, (Sponsor: Fluorocarbon, Home Institution: University of Nottingham)
- **Rebecca Garrard (Mechanical Engineering):**
Process control of EBM by backscatter detection (Home Institution: University of Liverpool)
- **Alexander Gasper (Mechanical Engineering):**
Laser Metal Deposition of Titanium Aluminides and the embedding of fibre optic (Sponsor: TWI, Home Institution: University of Nottingham)
- **Jonathan Goreki (Physics):**
High Throughput Selective Laser Melting (Sponsor: Renishaw, Home Institution: University of Liverpool)
- **Duncan Hickman (Biomaterials):**
SLM of Ti-6Al-4V for Biomedical Applications (Sponsor: Materialise, Home Institution: University of Nottingham)
- **Sarah Kelly (Design):**
Design Rules for Additively Manufactured Wearable Devices (Home Institution: University of Loughborough)
- **William Rowlands (Materials):**
Materials Development for Selective Laser Sintering (Sponsor: Borg Warner, Home Institution: University of Loughborough)
- **Nicholas Southon (Physics):**
Materials Development for Selective Laser Sintering (Sponsor: BMW, Home Institution: University of Nottingham)
- **Adam Thompson (Physics):**
Validation of X-ray computed tomography for Additive Manufacturing (Sponsor: 3T, Home Institution: University of Nottingham)

Internships at the 3DPRG

1. Nataša Mrazovic, PhD student at CEE, Stanford University, Lawrence Berkeley National Laboratory

The aim of this three month research visit was to explore the feasibility of metallic Additive Manufacturing processes for the production of building façades and façade elements. A special emphasis was placed on developing build time and cost models for commercially available metallic Additive Manufacturing platforms to establish an understanding of process scalability.

Visiting researcher: Natasa Mrazovic (Civil Engineering), Stanford University, USA

Main project supervisor: Dr Martin Baumers

2. The study of residual stresses in SLM silicon steel

This project forms a study into the influence of laser parameters, and specifically laser scanning strategies, on silicon steel deposited with Selective Laser Melting. Residual stress is measured using X-Ray Diffraction, on horizontal sample plates. An additional aim of the project is to establish parameters for heat treatment, in order to relieve residual stresses, without modifying the metal's unique microstructure. Differential scanning calorimetry is used to find out the temperature at which phase transition between disordered and ordered state occurs.

Visiting researcher: Alexandre Damiens (Chemical Engineering), Chimie ParisTech, France

Main project supervisor: Prof Ricky Wildman

3. The Effect of Electrical Parameters of Micro-Arc Oxidation (MAO) on Aluminium Alloy which Manufactured by Selective Laser Melting (SLM)

The aim of this project is to find the best electrical parameters of micro-arc oxidation for aluminium and its alloys. The next step after specifying optimum parameters for this process is to apply them with different alloys manufactured by different processes. The parts for this project will be additively manufactured and coated, analysing the surface condition and process parameters relation. The duration of the internship is one year.

Visiting researcher: Mustafa Yilmaz (Material Science and Engineering), Gebze Technical University, Turkey

Main project supervisor: Dr Adam Clare

4. The improvement of the surface of Titanium Carbide (TiC) layers coated by Electrical Discharge Coating (EDC)

In this study, various methods to improve the surface of Titanium Carbide layers coated by Electrical Discharge Coating on 304 stainless steel are investigated. This involves the addition of a second layer with a different material, the use of pulsed large area electron beam irradiation and a combination of both. The resulting surfaces are characterised by SEM, XRD and mechanical testing to determine the mechanism and extent of this surface improvement as well as to obtain an optimum process window for processing.

Visiting researcher: Richard Selo (Materials Science), Polytech Nantes, France

Main project supervisor: Dr Adam Clare

Summer internships 2014-2015

Summer internships for undergraduate students - 2015

Broadening the range of 3D-printable materials: reactive jetting of polymers

The aim of the project is to broaden the range of 3D-printable materials by printing thermoset polymers using reactive jetting. This technique is based on the concept of polymerisation post-jetting, in which the monomers that form the repetitive unit of the final polymer are jetted independently, together with the catalyst.

Summer intern: Zoe Lee (Chemistry)

Main project supervisor: Dr Belen Begines

Single Process 3D Printing Conductive and Non-conductive Materials

This project is to investigate the printing of 3D structures consisting of conductive and dielectric (non-conductive) materials. The method proposed is to use dispensing techniques to deposit different ink pastes by micro-scale nozzles. The key element is to provide repeatable process with clean strand structures free from overflow and tailing effects.

Summer intern: Chen Li (Electrical Engineering)

Main project supervisor: Dr Ehab Saleh

Software development for multi-photon lithography system

This project involves developing software to control the various components of a home-built multi-photon lithography system, including the movement of sample stage, laser power and beam shutter, for the purpose of fabricating arbitrary 3D micro/nano structures.

Summer intern: Louise Wells (Physics and Astronomy)

Main project supervisor: Dr Qin Hu

Liquid metal jetting 3D printing: interface energy and wetting of solder droplets jetted on Cu substrates

The focus of this project lies on the contact angle and reactive wetting in the Sn and Cu system, improving the understanding of the possibilities that lie in the liquid metal jetting variant of 3D printing technology. The deliverable of this summer internship will be a novel and complete dataset indicating the effect of the different Cu substrates on solder jetting.

Summer intern: Daniel Markcoons (Engineering)

Main project supervisor: Dr Marco Simonelli

Optimization of printing parameters for gelatine-based materials for the deposition of vascular structures

This project, concentrates on the investigation of different printing parameters including the influences of printing pressure, temperature, waveform and gelatin concentration on droplet formation as well as deposition with the help of high speed imaging and optical microscopy. At the end of this project, a high quality simple 3D structure should be able to be printed by Gelatin based ink.

Summer intern: Anh Thi Thu Nguyen (Pharmacy)

Main project supervisor: Yinfeng He

Design of impact absorbing lattice structures

This project considers the use of additively deposited structures to protect from projectile and crash impacts. Controlled deceleration, energy absorption, penetration protection and other factors are investigated to define a design optimization problem. Solutions to this will then be explored for specific applications through a combination of design, analysis, manufacture and testing of lattice structures.

Summer intern: Alexandra Hussey (Engineering)

Supervisory Team: Prof Ian Ashcroft, Dr Ajit Panesar, Dr Adedeji Aremu

Investigation into Low Cost Sensing and Intelligent Actuation for Prosthetic Devices

The project aims to progress novel means of actuation for prosthesis to enable higher degrees of freedom without incurring a heavy cost penalty. This project is envisaged to comprise of two stages: the first one will be the literature review, where a survey of the current technologies will be made and the second stage will look into bringing the chosen technologies together into a prototype demonstrator.

Summer intern: Chung Han Chua (Engineering)

Main project supervisor: Dr Ajit Panesar

Comparing the build speed, process energy consumption and cost of entry-level Additive Manufacturing systems to their high-end industrial analogues

This project will compare the resource efficiency, looking in particular at build time, energy consumption and cost, of the new wave of entry-level Additive Manufacturing systems. The project will improve the understanding of novel possibilities and value propositions introduced to the Additive Manufacturing field by such entry-level systems.

Summer intern: Jack Jones (Engineering)

Main project supervisor: Dr Martin Baumers

Centre facilities: equipment and the new lab

The EPSRC Centre's laboratory facilities have undergone a substantial extension over the last year. Originally opened by the University's Chancellor Sir Andrew Witty in 2013, the EPSRC Centre's new laboratory now houses a unique portfolio of developmental and commercially available Additive Manufacturing systems and a suite of state-of-the-art analytical devices in a dedicated 163 square metre materials characterisation laboratory. This section of our Annual Report presents significant individual items of equipment which are pivotal to our research activities.

Multimaterial 3D Ink Jetting System – PiXDRO Toucan

The PiXDRO Toucan system is a custom-built £1M inkjet machine constructed for the EPSRC Centre by the Dutch inkjet specialist Roth and Rau. The advantage of this platform over other available commercial systems is that it has six piezo-electric heads permitting the jetting of six distinct materials within a build process. Additionally, the machine is equipped with an ultraviolet radiation source, with a wavelength of 395 nm and an output of 2W/cm², and an infrared lamp, with a maximum filament temperature of 1500°C and an output of 1 kW, for curing heat/photo-sensitive polymers and conductive materials. This allows the realisation of multi-functional 3D parts in a single step. During the printing process, the substrate moves in the X direction underneath the ink curing devices. The exposure of printed material to radiation can be controlled by altering the process parameters such as energy intensity, curing height and curing speed and the number of passes. The large build volume is another advantage of the Toucan system over other conventional inkjet systems available on the market. The EPSRC Centre's current projects on this novel multi-material inkjet system are primarily focused on jetting of multiple materials to produce multi-functional 3D components for electrical and electronics, pharmaceutical and biological applications.

Liquid Metal Jetting 3D printing

The MetalJet system is a unique bespoke drop-on-demand 3D printing platform based on the Océ MetalJet technology. This technology essentially enables precision jetting of molten droplets of conductive materials with a melting point up to 2,000°C. The MetalJet system has been configured to enable the jetting of liquid metal droplets onto a movable substrate to produce 3D parts from a desired stack of 2D digital patterns. Upon solidification, each layer of jetted droplets acts as a new substrate where new droplets can be dispensed to create the subsequent layer. As the process repeats, complex 3D geometries comprised of individual metals or alloys, or even heterogeneous graded structures of differing metals / semiconducting materials should be possible as the research develops. In contrast to existing powder bed Additive Manufacturing technologies, the MetalJet system features four print-heads that allow to jet four materials independently. This architecture offers printing scalability - as portions of same object can be produced by print-heads that work in conjunction – and, most importantly, the ability to print components consisting of multiple metals. The MetalJet system will thus enable the printing of multifunctional devices and functionally graded materials.

Multi-photon lithography systems

Multi-photon lithography is an advanced Additive Manufacturing technique capable of fabricating arbitrary 3D micro/nano structures with a resolution of around 100 nm using a femto-second laser as the light source. It is based on multi-photon absorption-induced polymerisation, which forms a non-linear optical effect. By tuning the laser beam to let the energy at the centre of the exposure volume peak to overcome the material threshold for polymerisation, it is possible to achieve feature sizes below the diffraction limit of light. As the laser can penetrate into the pre-processed polymer vat, polymerisation can happen within the material volume enabling arbitrary 3D structures at the micro-scale. Two systems are available in our EPSRC Centre.

As a commercially available system, the Nanoscribe platform has the capability of fabricating arbitrary 3D structures with lateral feature size of 160 nm, vertical feature size less than 1 µm, writing speeds up to 10 mm/s, and total accessible writing area up to 100 x 100 mm². Complementing this, The EPSRC Centre has developed its own multi-photon lithography system that has extended capabilities for multi-functional fabrication. By adding optical tweezers, micro/nano-sized objects can be drawn into the vat of material and encased within a matrix or attached to a surface. This offers the potential for functionalising a surface or a material by combining it with particles prepared separately and then brought together. By further coupling multi-photon lithography with stimulated emission and depletion (STED), it is possible to control the fabrication of 3D nano-composite precisely through the selective polymerisation or photo-reduction on demand, thus establishing a new route for metamaterial fabrication.

Liquid Metal Jetting 3D printing

The Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) is a device for surface analysis designed to obtain both elemental and molecular information. ToF-SIMS analysis can also provide image information across the surface of a sample with high lateral resolution and depth profile information. By emitting a pulsed beam of primary ions onto a sample surface, secondary ions are generated by collision, which detach from the surface. The charged species are then accelerated by an electric field. The mass/charge ratio determines the time for these ions to reach the detector. Analysing these secondary ions provides information about the molecular and elemental species present on the surface together with mass spectral information. All the elements in the periodic table are detected, allowing the chemical mapping of the sample surface. ToF-SIMS may be considered a non-destructive technique since only the most external monolayer of the sample is detached from the surface. A large variety of samples may be analysed at extremely small scales down to 100 nm, such as conductors, semi-conductors, insulators, powders, foils, and biological materials.

Atomic Force Microscopy, located at the School of Pharmacy

Atomic Force Microscopy (AFM) is one of the modalities of scanning probe microscopy (SPM). AFM is a high-resolution technique for surface analysis. It allows users to measure simultaneously both topography and physical properties. It incorporates a tip attached to a cantilever, allowing forces between the tip and a surface to deflect the cantilever. A detector measures the cantilever deflections as the tip is scanning the sample. The cantilever deflections allow the generation of a map of surface topography at nanometre resolution. Moreover, the technique is highly versatile regarding the nature of the sample and the measurements can be both in air and liquid phase. The variety of tips available allows users to measure surface energy, electrical, magnetic and conductive properties over a surface. Functionalised tips enable the study of particular or specific surface-tip interactions.

Researchers Hatim Cader and Dr Jayasheelan Vaithilingam at work in the new laboratory

Spin out: Added Scientific Ltd

ADDED SCIENTIFIC

Over the recent years, the academics involved in the EPSRC Centre identified a requirement to meet the needs of potential and active users of Additive Manufacturing technology toward building capability and understanding in this rapidly emerging field. To address this need they have spun out a commercial consultancy business in June 2015.

With a collective 70 years of professional experience in 3D Printing and Additive Manufacturing between them, the founders of Added Scientific share a philosophy of bringing the highest standards of science and engineering to bear on the development and understanding of 3D printing for companies interested in how to best implement the technology.

The team provides consultancy on the future of 3D Printing machinery and techniques, on how to develop materials for Additive Manufacturing, offers services for the design of innovative products and the development of design tools. Added Scientific provides know how and training so that companies can understand the science behind Additive Manufacturing processes and best exploit them for their business. Effectively, the goal of Added Scientific is to support industries keen to adopt and exploit one of the key technologies of the 21st Century.

Added Scientific offers services in four distinct fields to its customers:

- Facilitating understanding and training: Added Scientific provides technical reports and state of the art reviews for industry and government to enable long term strategic planning and technical roadmapping, coupled with performing comprehensive business analysis and developing the skills and working practises required.
- Developing-on existing Additive Manufacturing equipment or bespoke system configurations: Added Scientific provides expertise in optimizing established processes, such as Laser Sintering, for specific materials and applications and in developing novel processes, such as multi-material and multi-functional ink jet printing.
- Materials development and characterization: Added Scientific has considerable expertise in the processing of a wide range of materials, from high performance alloys for the aerospace industry to biological and pharmaceutical materials. Added Scientific can help develop and evaluate new materials that are optimized for specific additive manufacturing processes and their end-use applications.
- Design and design tools for next generation products: Added Scientific provides expertise in developing new design and optimization methods specifically for Additive Manufacturing design and also in the effective use of commercial design software.

For further information, see www.addedscientific.com

Two-photon polymerisation system incorporating optical tweezer technology

What others say about our EPSRC Centre

"HP is the world's largest provider of information technology infrastructure, software, services and solutions. We differentiate ourselves in the market place by combining products and technologies in a holistic way to help our customers turn challenges into opportunities. HP's printing group aligns with these strategies, offering not only world class printers, but also including software solutions and services which allow an integrated end-to-end experience, from content creation to fulfilment.

My 3D research team, within the printing group, recently evaluated additive manufacturing research groups around the world and identified the Additive Manufacturing Research Group at the University of Nottingham as a world leader as well as a potential strategic partner of my group at HP."

Edward D. Davis

CTO and Senior Strategic Technology Manager

"The work initiated with the EPSRC Centre has been both stimulating and scientifically fruitful. This was made possible with the expertise available at Nottingham and is a testament to the advantages gained through collaborations across diverse disciplines. In particular this has enabled my research to spread into new areas where ideas developed in other projects within my group can benefit other projects in new and novel arenas. In addition this funding enabled an ECR to develop new skills and expertise. Finally I am sure the work will flourish in the future with a more extensive collaborative project including Southampton and Nottingham developing the new ideas and concepts formed through this initiative".

Dr Peter Birkin

"I first collaborated with the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing back in early 2012. They funded me on a pump prime project as a post doc, for a project working on novel ink formulations for sinter-free metal inks. This pump prime funding enabled me to obtain valuable results which formed the basis for a larger EPSRC grant which was funded in October 2012 (£700K). The centre has enabled crucial scientific research to be carried out in the area of inkjet printing. It has also helped act as a spring board for my academic career, as the grants obtained due to the centre funded research, has seen me go from postdoc to fulltime lecturer at the University of Liverpool."

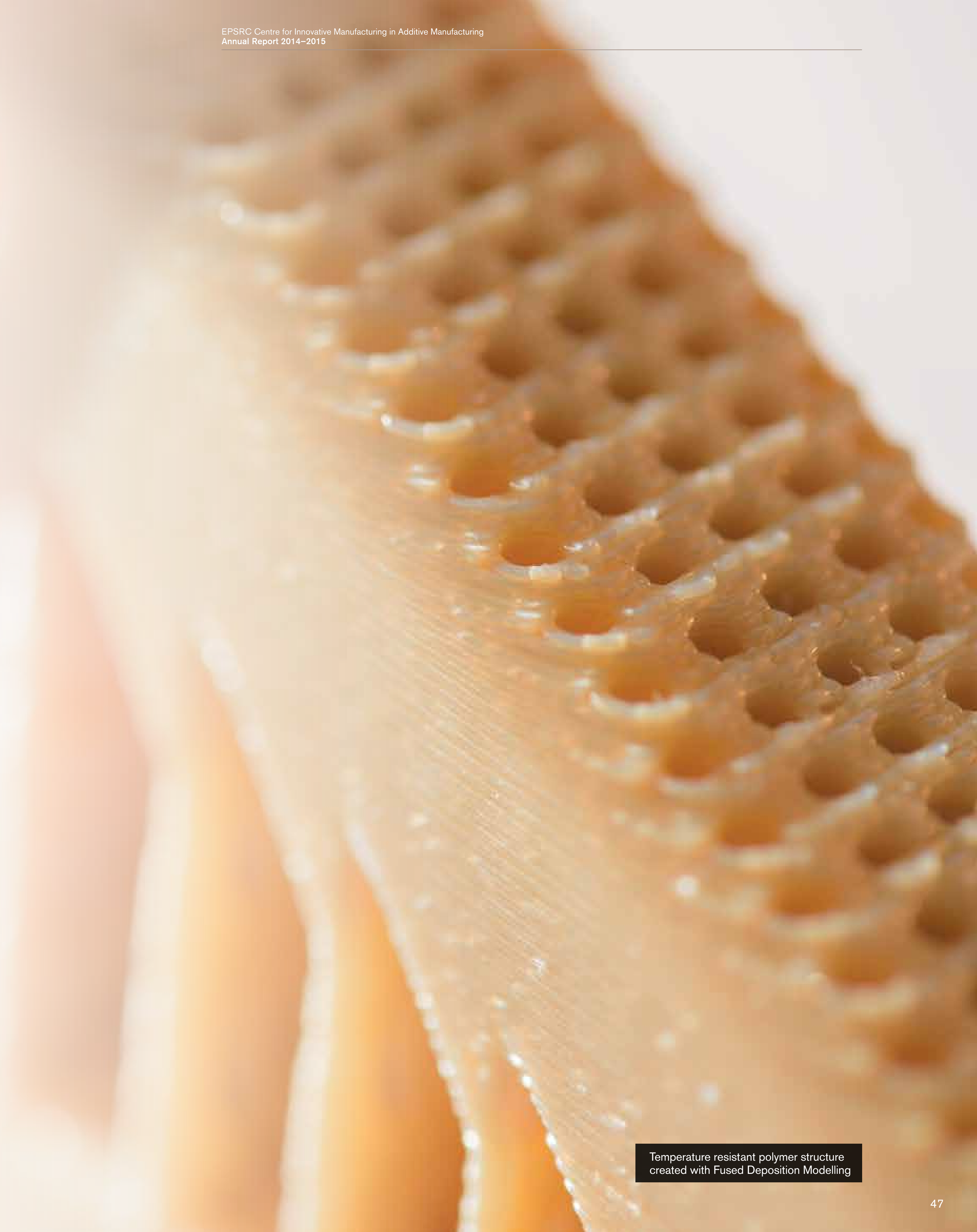
Dr Kate Black

"Our cross-disciplinary collaboration with the Centre unlocked the possibility of generating compound microdrops for next-generation multi-material additively manufactured products. The ambitious proof-of-concept developments in modelling and simulation that led to this breakthrough would have been unattainable without the Centre's funding, broad expertise and enthusiasm. We look forward to working with them on a variety of technology-motivated scientific research."

Dr James Sprittles

"Our recent collaboration with Professor Ricky Wildman and his group at the EPSRC Centre for Additive Manufacturing investigating new polymers for 3D printing has been extremely productive - in this short 6-month long 'Jumpstart' grant we have learned a great deal about the physical characteristics of our materials and how to deposit them successfully in three dimensions. Having access to the world class printing facilities at Nottingham in addition to the technical support and guidance provided by Ricky and his group has proved invaluable."

Professor Wayne Hayes



Temperature resistant polymer structure created with Fused Deposition Modelling

Selected publications in the period 2014-2015

Journal Papers

A Panesar, D Brackett, I Ashcroft, R Wildman and R Hague; Automated Placement and Routing for Multifunctional 3D Printed Circuit Volumes (PCVs); ASME Mechanical Design - Design for AM (Special Issue); 2015

M Baumers, P Dickens, C Tuck, R Hague; The cost of additive manufacturing: machine productivity, economies of scale and technology-push; Technological Forecasting and Social Change, 2015

M Simonelli, C Tuck, NT Aboulkhair, I Maskery, I Ashcroft, RD Wildman, R Hague; A Study on the Laser Spatter and the Oxidation Reactions During Selective Laser Melting of 316L Stainless Steel, Al-Si10-Mg, and Ti-6Al-4V; Metallurgical and Materials Transactions A, 1-10, 2015

S Ziegelmeier, P Christou, F Wöllecke, C Tuck, R Goodridge, R Hague, E Krampe, E Wintermantel; An experimental study into the effects of bulk and flow behaviour of laser sintering polymer powders on resulting part properties; Journal of Materials Processing Technology 215, 239-250; 2015

I Maskery, AO Aremu, M Simonelli, C Tuck, RD Wildman, IA Ashcroft, RJM Hague; Mechanical Properties of Ti-6Al-4V Selectively Laser Melted Parts with Body-Centred-Cubic Lattices of Varying cell size; Experimental Mechanics, 1-12; 2015

J Vaithilingam, S Kilsby, RD Goodridge, SDR Christie, S Edmondson, RJM Hague; Functionalisation of Ti6Al4V components fabricated using selective laser melting with a bioactive compound; Materials Science and Engineering: C 46, 52-61; 2015

NT Aboulkhair, C Tuck, I Ashcroft, I Maskery, NM Everitt; On the precipitation hardening of selective laser melted AlSi10Mg; Metallurgical and Materials Transactions A, vol 46, Issue 8, pp 3337-3341; 2015

S Everton, P Dickens, C Tuck, B Dutton; Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing; SPIE LASE, 935316-935316-8; 2015

M Simonelli, YY Tse, C Tuck; Fracture Mechanisms in High-Cycle Fatigue of Selective Laser Melted Ti-6Al-4V; Key Engineering Materials 627, 125-128; 2015

L Parry, I Ashcroft, D Bracket, RD Wildman; Investigation of Residual Stresses in Selective Laser Melting; Key Engineering Materials 627, 129-132; 2015

M Abdi, I Ashcroft, RD Wildman; Topology Optimization of Geometrically Non-Linear Structures Using Iso-XFEM Method; Key Engineering Materials 627, 121-124; 2015

SS Babu, R Goodridge; Additive manufacturing; Materials Science and Technology (8), 881-883; 2015

A Triantaphyllou, CL Giusca, GD MaCaulay, RK Leach, B Tomita, KA Milne; Surface texture measurement for additive manufacturing; Surf. Topog.: Met. Props 3 024002; 2015

J Vaithilingam, RD Goodridge, R JM Hague; Additive Manufacturing and Surface Modification of Biomaterials using Self-assembled Monolayers; Biointerfaces: Where Material Meets Biology, 30; 2014

J Vaithilingam, S Kilsby, RD Goodridge, SDR Christie, S Edmondson, RJM Hague; Immobilisation of an antibacterial drug to Ti6Al4V components fabricated using selective laser melting; Applied Surface Science 314, 642-654; 2014

S Ziegelmeier, F Wöllecke, CJ Tuck, RD Goodridge, RJM Hague; Aging behaviour of thermoplastic elastomers in the laser sintering process; Journal of Materials Research 29 (17), 1841-1851; 2014

J Bai, RD Goodridge, RJM Hague, M Song, H Murakami; Nanostructural characterization of carbon nanotubes in laser-sintered polyamide 12 by 3D-TEM; Journal of Materials Research 29 (17), 1817-1823; 2014

DJ Brackett, IA Ashcroft, RD Wildman, RJM Hague; An error diffusion based method to generate functionally graded cellular structures; Computers & Structures 138, 102-111; 2014

J Bai, RD Goodridge, RJM Hague, M Song, M Okamoto; Influence of carbon nanotubes on the rheology and dynamic mechanical properties of polyamide-12 for laser sintering; Polymer Testing 36, 95-100; 2014

E Saleh, C Tuck, R Wildman, I Ashcroft, R Hague, P Dickens; 3D inkjet-printed UV-curable inks for multi-functional electromagnetic applications; 2014

NT Aboulkhair, NM Everitt, I Ashcroft, C Tuck; Reducing porosity in AlSi10Mg parts processed by selective laser melting; Additive Manufacturing 1, 77-86; 2014

M Simonelli, YY Tse, C Tuck; Effect of the build orientation on the Mechanical Properties and Fracture Modes of SLM Ti–6Al–4V; Materials Science and Engineering: A 616, 1-11; 2014

M Simonelli, YY Tse, C Tuck; The formation of $\alpha + \beta$ microstructure in as-fabricated selective laser melting of Ti–6Al–4V; Journal of Materials Research 29 (17), 2028-2035; 2014

M Simonelli, YY Tse, C Tuck; On the Texture Formation of Selective Laser Melted Ti-6Al-4V; Metallurgical and Materials Transactions A 45 (6), 2863-2872; 2014

A Badiee, R Wildman, I Ashcroft; Effect of UV aging on degradation of ethylene-vinyl acetate (EVA) as encapsulant in photovoltaic (PV) modules; SPIE Solar Energy+ Technology, 91790O-91790O-7; 2014

JM Huntley, T Tarvaz, MD Mantle, AJ Sederman, LF Gladden, NA Sheikh, RD Wildman; Nuclear magnetic resonance measurements of velocity distributions in an ultrasonically vibrated granular bed; Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences; 2014

M Abdi, R Wildman, I Ashcroft; Evolutionary topology optimization using the extended finite element method and isolines; Engineering Optimization 46 (5), 628-647; 2014

M Abdi, I Ashcroft, R Wildman; An X-FEM Based Approach for Topology Optimization of Continuum Structures; Simulation and Modeling Methodologies, Technologies and Applications, 277-289; 2014

M Khan, P Dickens Selective laser melting (SLM) of pure gold for manufacturing dental crowns; Rapid Prototyping Journal; 2014

TT Nguyen, JM Huntley, IA Ashcroft, PD Ruiz and F Pierron; A Fourier-series-based virtual fields method for the identification of 2-D stiffness distributions; International Journal for Numerical Methods in Engineering; 2014

WA Lughmani, K Bouazza-Marouf, I Ashcroft; Drilling in cortical bone: a finite element model and experimental investigations; Journal of the mechanical behaviour of biomedical materials; 2015

ZR Khokhar, IA Ashcroft, VV Silberschmidt; Three-Dimensional Analysis of the Effect of Material Randomness on the Damage Behaviour of CFRP Laminates with Stochastic Cohesive-Zone Elements; Applied Composite Materials; 2014

AS Alghamdi, IA Ashcroft, M Song; Creep Resistance of Novel Polyethylene/Carbon Black Nanocomposites; International Journal of Material and Science and Engineering; 2014

Conference Papers

J Vaithilingam, E Saleh, C Tuck, R Wildman, I Ashcroft, R Hague, P. Dickens; 3D-inkjet Printing of Flexible and Stretchable Electronics; 26th International Solid Freeform Fabrication Symposium, University of Texas, Austin, USA; 2015

E Saleh, J Vaithilingam, C Tuck, R Wildman, I Ashcroft, R Hague, P Dickens; 3D inkjet printing of conductive structures using in-situ IR sintering; 26th International Solid Freeform Fabrication Symposium, University of Texas, Austin, USA; 2015

M Baumers, C Tuck, R Hague; Selective Heat Sintering versus Laser Sintering: comparison of deposition rate, process energy consumption and cost performance. Proceedings of the Solid Freeform Fabrication (SFF) Symposium, The University of Texas at Austin; 2015

NT Aboulkhair, I Maskery, C Tuck, I Ashcroft, NM Everitt; Nano-hardness and microstructure of selective laser melted AlSi10Mg scan tracks; 4th UK Industrial Laser Applications Symposium ILA 2015 proceedings; 2015

NT Aboulkhair, I Maskery, I Ashcroft, C Tuck, NM Everitt; The role of powder properties on the processability of Aluminium alloys in selective laser melting; 22nd World of Photonics congress: Lasers in Manufacturing conference; 2015

A Panesar, D Brackett, I Ashcroft, R Wildman and R Hague; Design optimization for multifunctional 3D printed structures with embedded functional systems; World Congress on Structural and Multidisciplinary Optimisation; 2015

A Panesar, D Brackett, I Ashcroft, R Wildman and R Hague; Design Optimization Strategy for Multifunctional 3D Printing; Solid Freeform Fabrication; 2014

M Abdi, I Ashcroft , R Wildman; High Resolution topology design using IsoXFEM; Proceedings of the 24th Solid Freeform Fabrication Symposium, Texas, USA, 2014

M Baumers, C Tuck, R Wildman, I Ashcroft, R Hague; Is there a relationship between product shape complexity and process energy consumption in Additive Manufacturing?; Sustainable Design and Manufacturing Conference 2014, Cardiff, UK, 2014

B Liu, C Tuck, E Saleh, R Wildman, I Ashcroft, R Hague; Investigation on the performance of multi-layer printed conductive tracks on multi-layer printed insulator; Annual International Solid Freeform Fabrication Symposium, Texas, USA; 2014

M Fahad, M Gilbert, P Dickens: Ternary Compositions of Methylcellulose in Water and Butylene Glycol as Potential Support Materials for Three Dimensional printing, International Conference on Mechatronics Manufacturing and Automation, Singapore; 2014

Y He, S Kilsby, C Tuck, R Wildman, S Christie, H Yang, S Edmondson; 3D jetting of UV curing bioreabsorbable polycaprolactone; Annual International Solid Freeform Fabrication Symposium, Texas, USA; 2014

Q Hu, M Askari, M Paul, A Knott, M East, R Patel, Z Wang, E Burt, C Tuck, R Wildman, R Hague; 3D micro/nano fabrication by multi-photon lithography; 3rd annual EPSRC Manufacturing the Future conference, Glasgow, UK; 2014

Q Hu, M Askari, P Benjamin, A Knott, M East, R Patel, Z Wang, E Burt, C Tuck, R Wildman, R Hague; Fabricating arbitrary 3d micro/nano structures by multi-photon lithography; International conference on small science, Hong Kong; 2014

H Yang, R Wildman, C Tuck, Y He, I Ashcroft, P Dickens, R Hague; High viscosity multi-material 3D jet printing; ISCIE/ASME International Symposium on Flexible Automation; 2014

M Baumers, C Tuck, P Dickens, R Hague; How can material jetting systems be upgraded for more efficient multi-material additive manufacturing?; Proceedings of the Solid Freeform Fabrication (SFF) Symposium, The University of Texas at Austin; 2014

E Saleh, B Liu, JL Fernandez, C Tuck, R Wildman, I Ashcroft, R Hague, P Dickens; The Optimization of Conductive Inks for 3D Inkjet Printing; NIP & Digital Fabrication Conference 137-139; 2014

Y He, S Kilsby, C Tuck, R Wildman, S Christie, H Yang, S Edmondson; A biodegradable Polycaprolactone Based Ink Developed for 3D Inkjet printing; International Society for the Advancement of Material and Process Engineering; 2014

Book Chapter

Q Hu, C Tuck, R Wildman, R Hague; Application of Nanoparticles in Manufacturing; Handbook of Nanoparticles; 2015

Research Associate Meisam Abdi and PhD student Meisam Askari in discussion

Further information

The EPSRC Centre thanks its collaborators:

3TRPD
Alcon
AWE
Axon
BAE Systems
BMW
Boeing
Centi
Delcam
Delphi
DSTL
Econolyst
ENAS, Fraunhofer
EOS
InnovationLab
Nanogap
National Centre for Printable Electronics
Newcastle University
NPL
Objet
Océ
PEL
Renishaw
SINTEF Raufoss Manufacturing
Smart Fibres
Solidica
TNO
TWI
The University of Bath
The University of Birmingham
The University of Cambridge
The University of Newcastle
The University of Oxford
The University of Reading
The University of Southampton
The University of Warwick
Xaar

Advisory Board

Dr Will Barton - Independent Chair
Dr Jim Fleming (EPSRC)
Dr Karen Brakspear (EPSRC)
Mr Gerard Davies (EPSRC)
Dr Ian Halliday (3T RPD Ltd)
Prof Jean-Pierre Kruth (KU Leuven)
Mr Simon Scott (Renishaw plc)
Dr Brian Henry (Pfizer)
Prof Kenny Dalgarno (Newcastle University)
Prof Will Stewart (Independent Industrialist)
Mr Robin Wilson (Innovate UK)

For general enquiries, please contact EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

Mirela Axinte
Faculty of Engineering
The University of Nottingham
NG7 2RD
United Kingdom

t: +44 (0)115 8466 374
e: 3dprg@nottingham.ac.uk
w: 3DP-research.com

If you require this publication in an alternative format, please contact us.

t: +44 (0)115 951 4591
e: alternativeformats@nottingham.ac.uk