**EPSRC Centre for Innovative Manufacturing in Additive Manufacturing**

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EPSRC Centre for Innovative Manufacturing in Additive Manufacturing

# Annual Report 2013–2014

In partnership with

EPSRC
Engineering and Physical Sciences Research Council

Loughborough University

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PhD Student Amanda Hüsler operating a contact angle measurement system.



# Contents

# Vision

The EPSRC Centre for Innovative Manufacturing in Additive Manufacturing is the core of research activity on multifunctional Additive Manufacturing (AM) in the UK. The fundamental and translational research carried out within this world-class research hub is helping to shape the future national and international AM research agenda. Through deeply rooted technological expertise and research professionalism, the EPSRC Centre's activities will enable the UK to achieve and maintain leadership in the commercial realisation of this next generation of AM technology.



A stainless steel dome structure created via Selective Laser Melting.

# Investigating the next step: multifunctional Additive Manufacturing

**As a manufacturing technology, 3D Printing is based on the principle of adding material, hence it is also referred to as 'Additive Manufacturing'. A relatively recent approach to the manufacture of end-use components, it is based on the creation of parts and products directly from raw material in powder, liquid, sheet or filament form using digital 3D design data. The process operates by depositing material, usually layer-by-layer, without the need for moulds, tools or dies.**

Additive Manufacturing offers several key advantages over other, more conventional, manufacturing techniques. Firstly, it enables the manufacture of products without many of the limitations that are normally placed on designs by conventional processes. Secondly, it enables the cost efficient production of bespoke / low to medium volume products, which can be highly geometrically complex and tailored for a particular function or user.

At the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, hosted by The University of Nottingham in partnership with Loughborough University, researchers are investigating ways of taking this to the next technological level: by depositing more than one material within a single build process, it will be possible to print entire working systems instead of individual parts and components. These could, for example, contain embedded electronics, chemical or pharmaceutical agents or even biological structures.

The research carried out within the EPSRC Centre has shown that the move from single to multi-material Additive Manufacturing gives the potential to move beyond structural applications and create fully functional systems rather than passive individual components. The possibilities of creating added functionality and user value – through the embedding of 3D functional materials within complex structures manufactured from engineering polymers or metals – appear immense. Functional structures that may be built directly into products include electrical circuitry, optical tracks, sensors, conformal batteries, solar cells, LED screens, antennas and other devices.

"This concentrated and unique research focus on multifunctional Additive Manufacturing is why our EPSRC Centre for Additive Manufacturing is recognised as the world's leading research entity in the field and is helping to set the global research agenda."

Prof Richard Hague
EPSRC Centre Director



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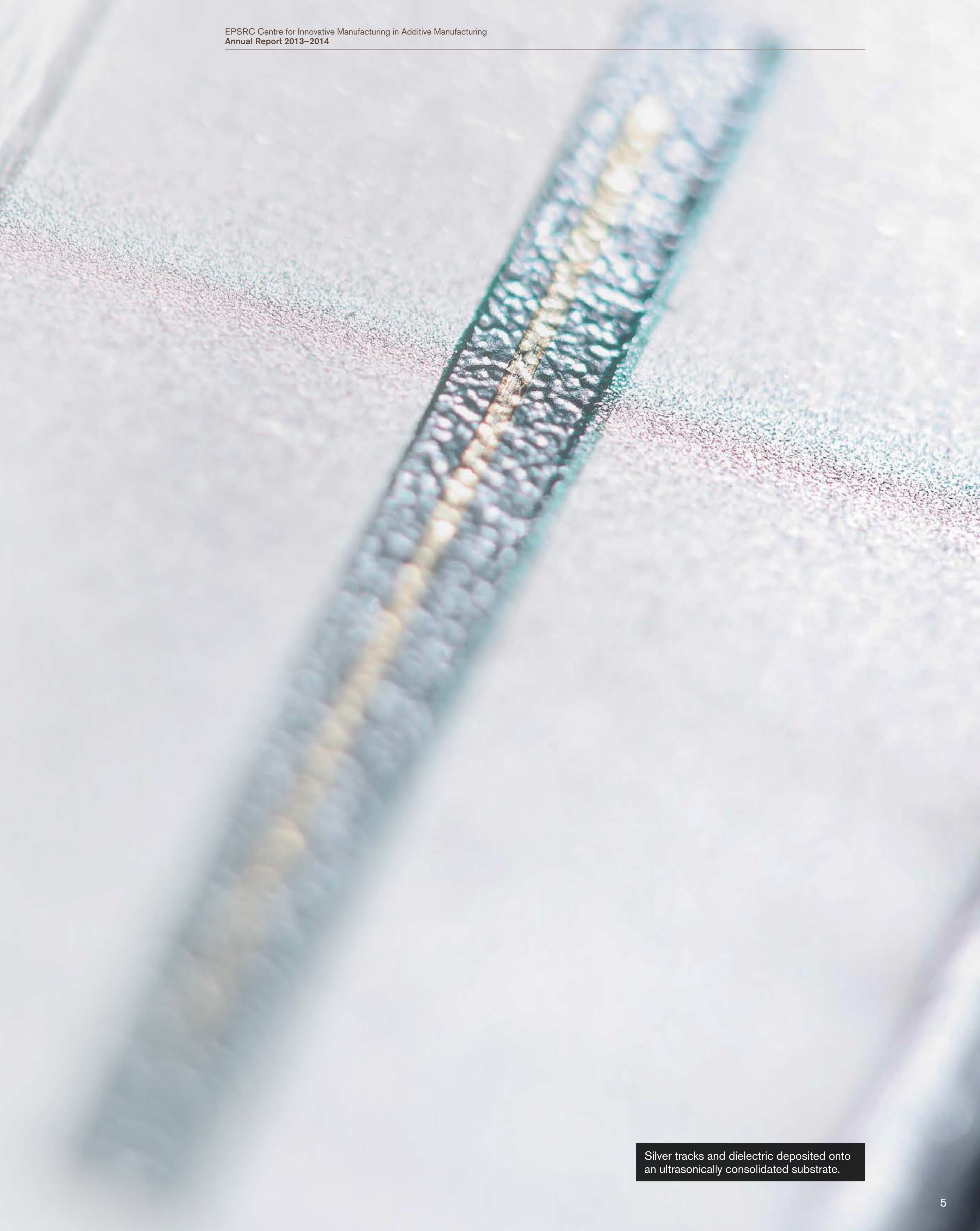

Silver tracks and dielectric deposited onto an ultrasonically consolidated substrate.

# Executive summary 2013–2014

**After the third year of operating the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, we are proud to present a summary of our activities throughout the last year. Based within the Additive Manufacturing and 3D Printing Research Group (3DPRG), this EPSRC Centre is hosted by The University of Nottingham with Loughborough University as a partner institution. Completing our third year in October 2014, also passing the mid stage of the EPSRC Centre's five year period of operation, we are proud to present to you our Annual Report for 2013-2014. Within this report we are covering a period in which significant progress was achieved at our EPSRC Centre, both in our core research themes and also in our collaborations with external institutions and leading industrial partners.**

Over the course of the Centre, our research emphasis has further shifted towards underpinning research and knowledge generation. Our fundamental research activities have gathered considerable momentum over the course of the last year, and we are happy to report that the execution of our Centre's research agenda is progressing well on its trajectory. This was reflected by the Mid Term Review of our EPSRC Centre completed by an independent panel of experts in February 2014. Chaired by Professor Joseph Beaman of the University of Texas at Austin, the review committee concluded that our EPSRC Centre has performed excellently for all assessed performance metrics, including academic research quality, industrial relevance, academic training, added value, strategic planning and execution of the original research proposal. Moreover, the review committee has commented that the EPSRC Centre's academic training plans are exemplary.

Chris Tuck (Deputy Director), Ian Ashcroft (Centre Investigator) and Richard Hague (Director).





In concert with all EPSRC Centres, our Centre is overseen by an Advisory Board consisting of leading international academics, influential industrial players and representatives from UK research funding bodies. Now that we are past the mid term stage of the Centre, we have moved to refresh the Advisory Board to reflect the evolving nature of the Centre and I am delighted to welcome Dr Will Barton as the new Chair of the Board. Having retired recently from the Technology Strategy Board (TSB) where he headed up the High Value Manufacturing portfolio, Will is in an ideal position to provide experienced oversight on the EPSRC Centre's activities and dispense invaluable advice during the second phase of the Centre. I would also like to take this opportunity to thank David Hughes for his contributions as Chair in the early stages of the Centre.

From the outset, it has been this EPSRC Centre's strategic goal to establish a strong research organisation contributing to the vision of turning multifunctional AM technology into a reality. With a strengthened focus on fundamental science and engineering, our activities fall under the overarching strategic imperatives of making a significant scholarly contribution and consolidating a bedrock of intellectual property for UK manufacturing technology integrators to build on. During our third year, the multidisciplinary teams of academics, researchers, students and technical staff working on the EPSRC Centre's flagship projects have demonstrated that the key to achieving scientific impact and high levels of research quality is close collaboration between varied disciplines such as engineering, chemistry, physics, biotechnology and materials science.

In keeping with EPSRC's requirement that Centres for Innovative Manufacturing exert a strong user pull, the core activities undertaken within our Centre have continued to carry high levels of industrial interest and relevance, both within the national context as well as on the global stage. In particular, the ongoing work on the jetting-deposition of engineering polymers via reactive jetting and the newly established jetting of high temperature metals is expected to fill an important gap in the spectrum of existing technologies. Beyond our work on novel processes and materials, industrially relevant research is also progressing in the areas of computational process modelling, optimisation-based design systems, and the creation of functional elements via additive processes at the nano scale, using multiphoton lithography. All of these areas were also commended at the Mid Term Review. The EPSRC Centre also achieves significant industrial exposure through several projects hosted by the 3DPRG. With ASID, ALMER and ALSAM, the research group is currently carrying out three projects funded by the TSB, in collaboration with leading UK industry, including BAE Systems and Rolls Royce. These projects are focused on the use of additive techniques for the manufacture of advanced metallic components for use in high value structural applications. Next to this, the Diginova Project, funded by the EU and coordinated by our industrial collaborator and printhead manufacturer Océ Technologies, concluded in March 2014 with the publication of an innovative technology roadmap exploring the convergence between 2D digital printing technology and Additive Manufacturing.

Alongside the projects carried out by the core Centre partners, we are also continuing to fund external academic research that is complementary to additive technologies. One such ongoing project explores the 3D Printing of tissue engineering structures at Newcastle University. To increase the number of such projects funded by us, a Jump Start event targeted at UK academics was held in February 2014. In this context we are pleased to announce that we have decided to fund five innovative and highly complementary projects at major UK universities looking into multidisciplinary underpinning research.

The EPSRC Centre's ability to attract additional funding has continued in an impressive way over the third year. Throughout the Centre's overall period of operation, we have now levered additional grants in excess of £17M. As part of this, we have received funding of £2.7M for additional equipment in partnership with the School of Pharmacy at The University of Nottingham, successfully illustrating the growing links with basic science provision. Underlining our special emphasis on academic training, we are also delighted to announce that the EPSRC Centre has been awarded the £4.5M EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing. This CDT will train more than 60 PhD students over the coming years at the universities of Nottingham, Liverpool, Loughborough and Newcastle. Led by the EPSRC Centre's Deputy Director, Dr Chris Tuck, this CDT is expected to have significant impact on the UK's Additive Manufacturing skills base, effectively producing a cohort of young AM experts from whom the UK manufacturing sector will benefit for many years.

The third year of operation the National Centre for AM, performing its outreach function for the EPSRC Centre under the ADD3D brand, began with a double presence at the 3D Printshows in London and Paris. As was the case last year, the professional quality of our presence led to significant exposure to industry and media circles and interest from the wider public. Beyond this, the National Centre for AM has taken part in an expanding programme of outreach activities, including its continued hosting of the ASTM and ISO standards committees. As in its previous two years of operation, the EPSRC Centre has organised the highly relevant International Conference on Additive Manufacturing with over 300 delegates in July 2014.

A comparison with the EPSRC Centre's original proposal submitted back in 2011 shows that we have made significant headway in delivering our stated objectives as well as clearly evolving to maximise future potential. The significant public attention now enjoyed by Additive Manufacturing places our work squarely in the focus of the world's technology observers. Over the further course of the Centre, the challenge will therefore be to demonstrate substance behind this exciting technological narrative and define avenues through which multifunctional Additive Manufacturing will lead to applications that are both technologically ground breaking and strategically important.

We cordially thank all those who are contributing to the exciting activities within this EPSRC Centre through their hard work and dedication. We express our gratitude to all of our researchers, our collaborators in industry and the members of our Advisory Board. The EPSRC deserves our special thanks for their continued sponsorship and engagement.

***Richard Hague, EPSRC Centre Director***

# Last year's highlights at a glance

- Successfully completed the EPSRC Centre's midterm review process in March 2014.
- Over the course of 2013-2014 we have secured additional funding of over £10 million, bringing the overall amount of additional funding received over the course of this EPSRC Centre to over £17 million.
- As part of this, we have received funding of £2.7 million for additional equipment in partnership with the School of Pharmacy at The University of Nottingham.
- We have been awarded the £4.5M EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing, which will train more than 60 PhD students over the coming years at the universities of Nottingham, Liverpool, Loughborough and Newcastle.
- Continued recruitment effort for talented new staff: 7 new researchers, 7 PhD starters and one new technician started over the course of the last year.
- Organised the International Conference on Additive Manufacturing and 3D Printing in July 2014, attended by over 360 delegates from 22 countries.
- Held a two-day Jump Start event "Exploring the Science behind AM & 3D Printing" in January 2014, attended by 40 delegates from 27 universities.
- Organised the 3D Printing for Biomedical Applications sandpit at The University of Nottingham in June 2014.
- Collaborated with the London Science Museum to create the influential "3D: Printing the Future" exhibition, running until January 2015.
- Contribution to the Diginova Roadmap for Digital Fabrication, published in March 2014, exploring the convergence of digital printing and AM technologies.
- EPSRC Centre presence at the 3D Printshows in London and Paris in November 2013.
- Successful completion of the second cohort of summer interns from mixed disciplines.

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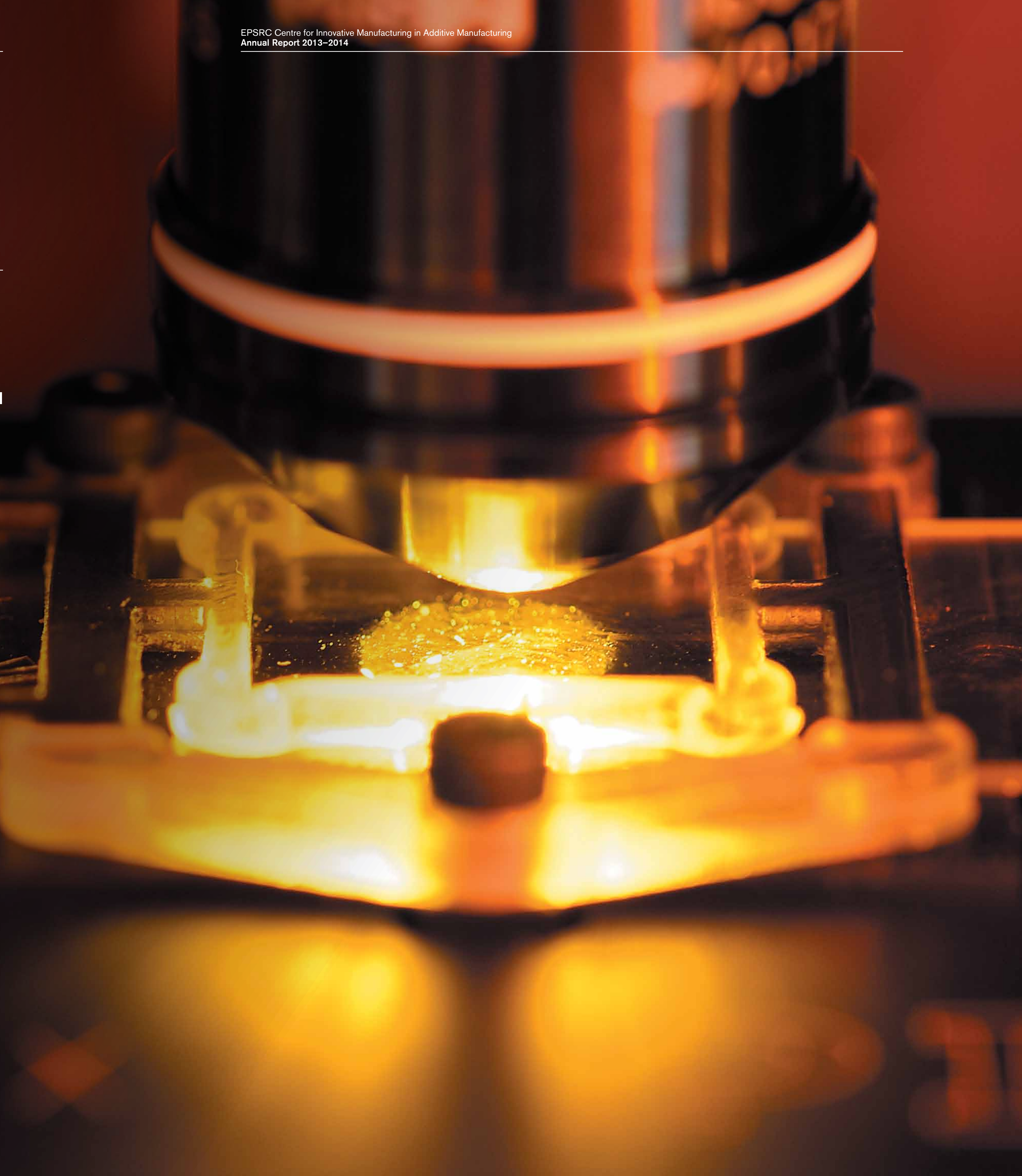

The two-photon polymerisation process at work.

# The strategic environment of this EPSRC Centre

In terms of established manufacturing thinking, the current focus often lies on large numbers of identical products originating from elaborate global supply chains. The key advantages of Additive Manufacturing allow this to be challenged: it is now possible to efficiently create complex and advanced geometries in a single, integrated, manufacturing step with the added possibility of each unit of output being different. This has led to considerable interest among manufacturing experts and designers and opened an opportunity for radical and disruptive product innovation.

It is the strategic goal of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing to push further and establish the scientific groundwork for the exploitation of multifunctional Additive Manufacturing processes.

This will lead to the amalgamation of functional and structural properties within a single manufacturing process, multiplying the benefits available from industrial adoption of Additive Manufacturing technology.



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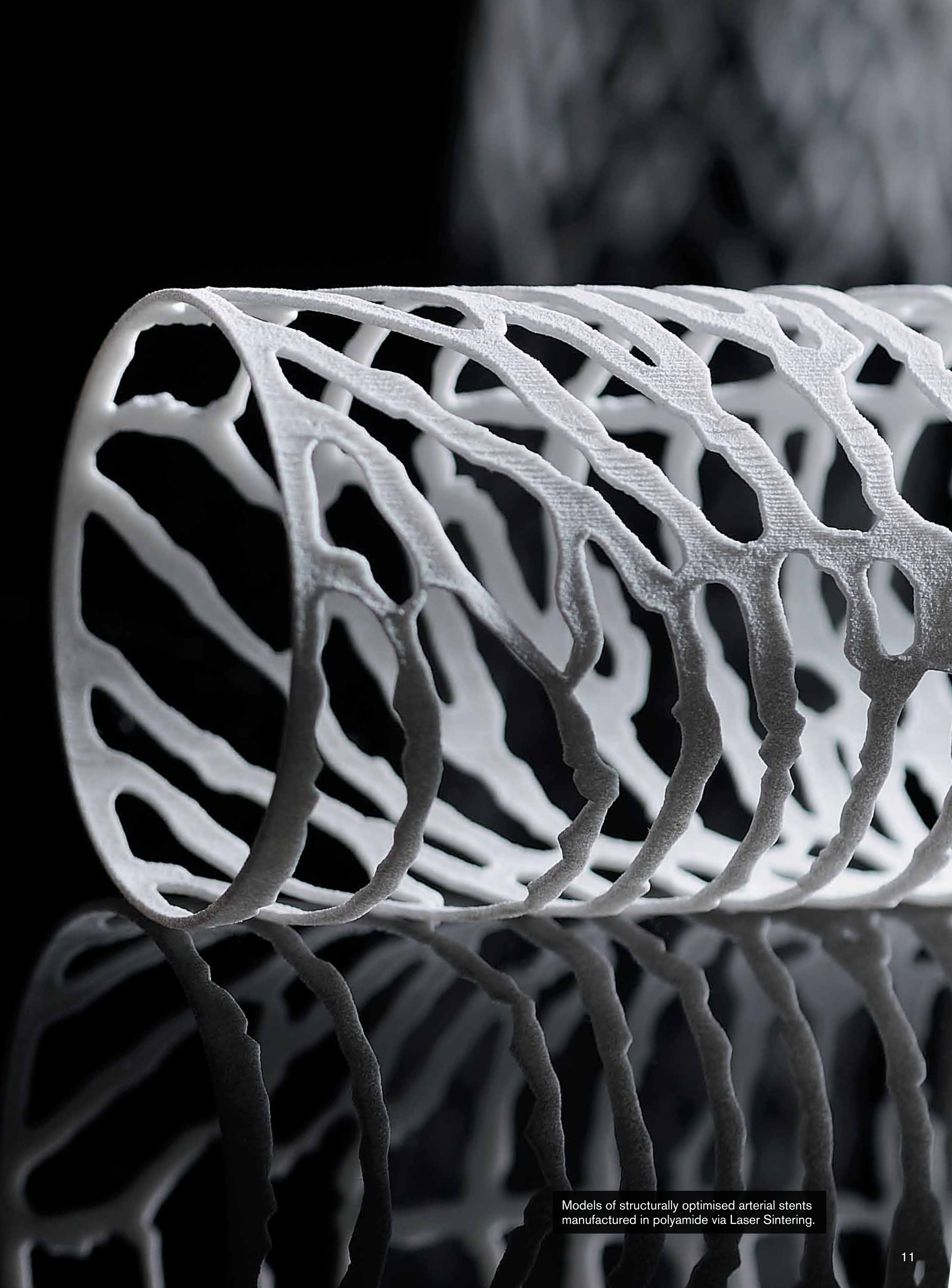
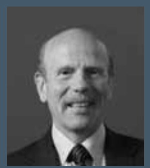


Models of structurally optimised arterial stents manufactured in polyamide via Laser Sintering.

# EPSRC Centre management

**Starting in October 2011, the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing brings together expertise in scientific and engineering research with a strong connection and relevance to industrial reality. Hosting EPSRC Centre at The University of Nottingham, along with colleagues at Loughborough University, we have a strong heritage in Additive Manufacturing research and are recognised as internationally leading this exciting area. The EPSRC Centre's management passionately believes that bringing the disruptive technology of multifunctional AM to fruition will necessitate both substantial fundamental research efforts and also a refined approach required to achieve successful deployment by industry.**



### Dr Will Barton
**Chair, Advisory Board**

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. Will has held leadership roles in multinational organisations ICI, FMC and Flexsys, a joint venture of Akzo Nobel and Monsanto, and a was a co-founder and COO of spin out from the University of Oxford, Oxford Catalysts (now called Velocys). From 2009 until earlier this year, he was part time Head of Manufacturing at the TSB, and was responsible for establishing the UK's first Catapult centre in High Value Manufacturing. In his other time he continued his interest in start-up companies, and now holds the roles of Chairman of the Board of early stage companies Oxford Biotrans and Amalyst and Non-executive Director of NiTech Solutions, as well as being a Director of his own consulting company. 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. He 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 AM 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 AM specific 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 AM 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 AM systems for use in industry. Chris has worked in the field of AM research from 2003, investigating the supply and business effects of Additive Manufacturing on a number of DTI, EU FP6 and EPSRC funded projects. Chris is also an Executive Member of the ASTM F42 AM standards committee and a participant in the BSi initiative of AM standards development. Chris is a regular presenter at numerous international conferences, a panel member for EPSRC and a reviewer for international funding agencies.





### 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 AM 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 a Lecturer 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 Belen Begines**
Research Fellow
The University of Nottingham

**Dr Ross Friel**
Wolfson School
Loughborough University

**Dr Adedeji Aremu**
Research Fellow
The University of Nottingham

**Dr David Brackett**
Research Fellow
The University of Nottingham

**Hagit Gilon**
Research Assistant
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**Mirela Axinte**
EPSRC Centre Research Coordinator
The University of Nottingham

**Dr James Brennan-Craddock**
Research Fellow
The University of Nottingham

**Dr Guangying Guan**
Research Fellow
The University of Nottingham

**Dr Jiaming Bai**
Research Fellow
The University of Nottingham

**Dr Xuesheng Chen**
Research Fellow
The University of Nottingham

**Mark Hardy**
Additive Manufacturing Technician
The University of Nottingham

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

**Mark East**
Head Technician
The University of Nottingham

**Dr Qin Hu**
Research Fellow
The University of Nottingham



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**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.**

**Sophie Jones**
ADD3D Website Coordinator

**Dr Ajit Panesar**
Research Fellow
The University of Nottingham

**Dr Marcin Wegrzyn**
Research Fellow
The University of Nottingham

**Dr Ji Li**
Research Fellow
Loughborough University

**Dr Phil Reeves**
ADD3D Outreach Coordinator
Econolyst Ltd.

**Joe White**
Additive Manufacturing Technician
The University of Nottingham

**Dr Bochuan Liu**
Research Fellow
The University of Nottingham

**Dr Ehab Saleh**
Research Fellow
The University of Nottingham

**Dr Hongyi Yang**
Lecturer
Loughborough University

**Dr Ian Maskery**
Research Fellow
The University of Nottingham

**Dr Marco Simonelli**
Research Fellow
The University of Nottingham

**Dr Tho Nguyen**
Research Fellow
The University of Nottingham

**Dr Saeid Vafaei**
Research Fellow
The University of Nottingham

Projects in core theme 1:

# Multifunctional additive processes, materials and design systems

**To investigate delivery platforms & design systems for multifunctional additive manufacturing**

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## Design Systems Development for Multifunctional Additive Manufacturing

The key to unlocking the user benefits of multifunctional AM lies in the design freedoms that the additive approach engenders; it is this immense design flexibility that gives the potential of multifunctional AM parts. Here, the major challenge is to produce a methodology that enables the design of multifunctional AM parts that are optimised. This optimisation problem must consider: efficient topology generation with integrated lattices and opto-electrical pathways (for embedded functionality). The multifunctional AM 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.

This project has just finished its second year, and progress has been made in several areas of the planned work, specifically in the placement and routing techniques, the efficient meshing techniques and the lattice generation approaches. A framework for automated placement and routing has been formalised and a set of techniques/methods that aid in the design of a multifunctional parts have been outlined. The usefulness of the proposed set of techniques for multifunctional AM design has been demonstrated. Additionally, preliminary investigations into strategies suitable for coupling topology optimisation with the placement and routing methods have taken place. The procedure for transforming the results of the placement and routing tool into a jetting machine-ready state has been defined making use of the direct voxel modelling to bitmap file format relationship; this capability will be exploited by demonstrator parts.

Key next steps are to investigate capability for tackling multi-physics analysis problems and solving multi-objective optimisation problems. The design methods will be evaluated on some demonstrator parts and the software tool evaluated by end users. The lattice optimisation work will be progressed and integrated into the design tool.

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

## Reactive Jetting of Engineering Materials

Creating new materials is vital for widening the applicability of 3D printing for end-use part production. A promising technique is reactive jetting, whereby instead of depositing polymers in solution, prepolymers, potentially in the form of an intermediate state or as a monomer, are deposited and then either combined to produce the final material or induced to react with initiation sources such as ultraviolet radiation. Early work in this area successfully enabled the production of nylon using a reactive jetting approach.

Current work is focussing on the jetting of a number of polymeric materials through reactive inkjet printing. This list includes polymethyl methacrylate (PMMA), polyimides and polysiloxanes, which have significant engineering usage, and biodegradable polyurethane which may have potential as a bioresorbable drug delivery material. Full characterisation of multi-layered deposition is also required, since the degree of cure and therefore mechanical properties will be age dependent. In order to discover the degree of cure throughout manufactured samples, nano-indentation coupled with FTIR microscope and state of the art inverse analysis techniques have uncovered the temporospatial nature of the aging behaviour of ink-jetted materials.

In order to broaden the types of materials that are capable of 3D reactive jetting, a new deposition method based on Nordsen EFD picodot deposition heads, coupled with three dimensional translation stages have been used to develop a printer that has a significantly enhanced viscosity range. This printer extends the printable viscosity range from around 20 cp up to 250,000 cp. Initial work on this system has been demonstrated through the deposition of polysiloxane based structures.

Further materials are being investigated to extend this approach to an ever widening range of applications, with extensive collaborations being developed between Pharmacy, Chemical Engineering and Chemistry at the University of Nottingham to further augment our capability.

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

A 3D printed multi-material demonstration component with embedded functional structures.

## Jetting of Conductive and Dielectric Elements Additive Systems

The move to multifunctionality in AM 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. What is also clear is that current AM technologies such as laser sintering or fused deposition modelling, whilst having some advantages, have some clear drawbacks for the production of multi-material parts. These are namely, in their 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 AM 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, and two based on the PixDro LP50 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 dual 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 vertical direction), as well as the integration of 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. 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.

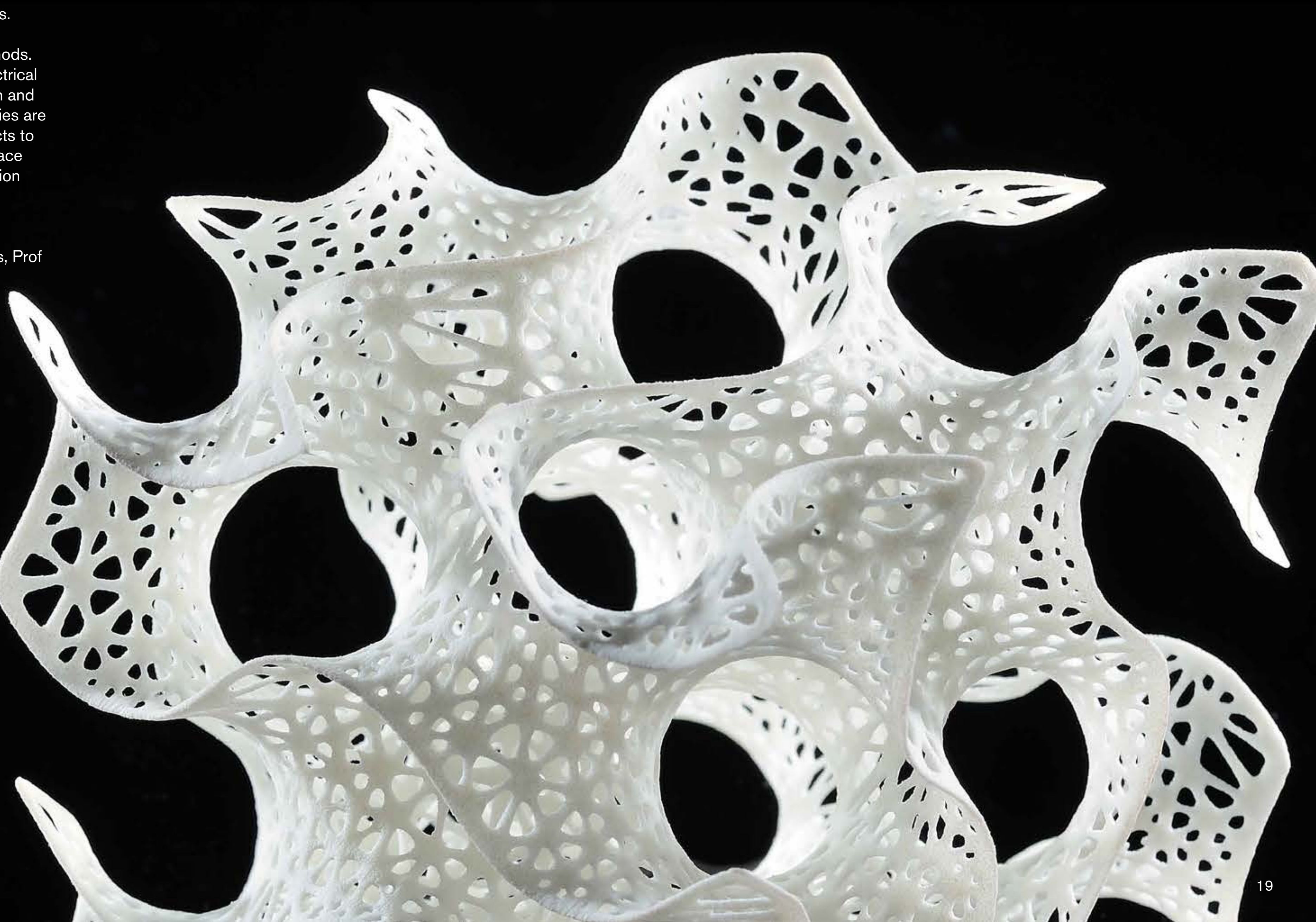
Project Team: Dr Chris Tuck, Prof Ricky Wildman, Prof Ian Ashcroft, Prof Russ Harris, Prof Phill Dickens, Prof Richard Hague, Dr Bochuan Liu, Dr Ehab Saleh

## 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. Elements of the work have been conducted in collaboration with our EPSRC Centre partner, PEL.

Since the last reporting period we have been able to feed into and incorporate the new relevant jetting facilities as they became established at the University of Nottingham, conducted via our link into the JET project. Earlier work demonstrated the fundamental viability of electrical circuitry printing (comprising of dielectric/conductive/dielectric) onto UC surfaces. This has now been extended to incorporate the investigation of undertaking this by freeform methods. Other manufacturing methods for generating electrical pathways have been incorporated for comparison and benchmarking. Experimental results and discoveries are now informing the design of appropriate constructs to obtain electrical functionality of the circuitry. Surface geometry has been identified as a key consideration factor and is undergoing extensive analysis of the varying production stages.

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



A polyamide gyroid structure created via Laser Sintering.



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## Developing Models that can Accurately Simulate the Jetting Process and the Post-Deposition Behaviour of Materials

Jetting is one of the integral AM techniques for the manufacture of the multifunctional devices that are the core deliverable of the EPSRC Centre. In order to understand, develop and optimise the jetting process it is essential to develop models of the process that can accurately simulate the delivery, deposition and post-deposition behaviour of materials. This requires the development of a suite of multiphysics modelling tools.

The modelling techniques required can be divided into two parts. Firstly, those required to model the material deposition process itself, which involve computational fluid dynamics and fluid-solid interactions. Secondly, those required to model the post deposition behaviour of the manufactured devices, which involve multi-physics finite element analysis and multi-scale mechanical modelling.

This project is divided into two stages. The first stage involved state of the art reviews and pilot studies to identify future research directions. This led to combined modelling-experimental investigations into nano-fluid drop formation and the accurate finite element representation of jet printed dielectric and bio-degradable polymers, which are on-going. In the second stage, PhD projects in the two parts introduced above will be used to further develop the models and techniques required to model the deposition of materials via the jetting process and the post deposition behaviour of the manufactured parts. This work underpins and informs work carried out at the EPSRC Centre in the areas of jetting of conductive and dielectric elements and the jetting of biodegradable materials.

Project Team: Prof Ian Ashcroft, Prof Ricky Wildman, Dr Chris Tuck, Dr Xuesheng Chen, Dr Saeid Vafaei

Project in core theme 2:

# Scaling down of additive processes

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



## Nano-functionalised Optical Sensors (NANOS)

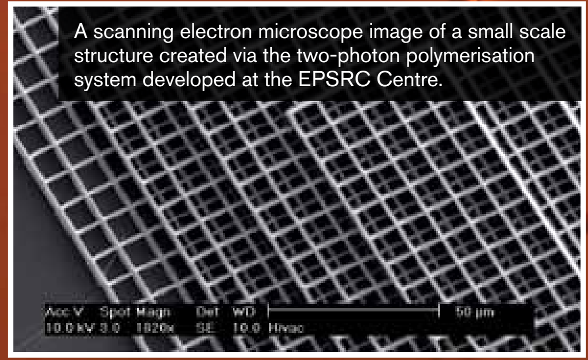
The requirements for future AM systems to produce complex multi-material and multifunctional components are reliant on two aspects; increased material capability and increased resolution. NANOS specifically targets these two aspects through the research and development of nano-resolution manufacturing systems, principally multi-photon lithography, that are capable of producing arbitrary 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 will enable the production of nanoscale structures in new materials that promote the development of new 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.

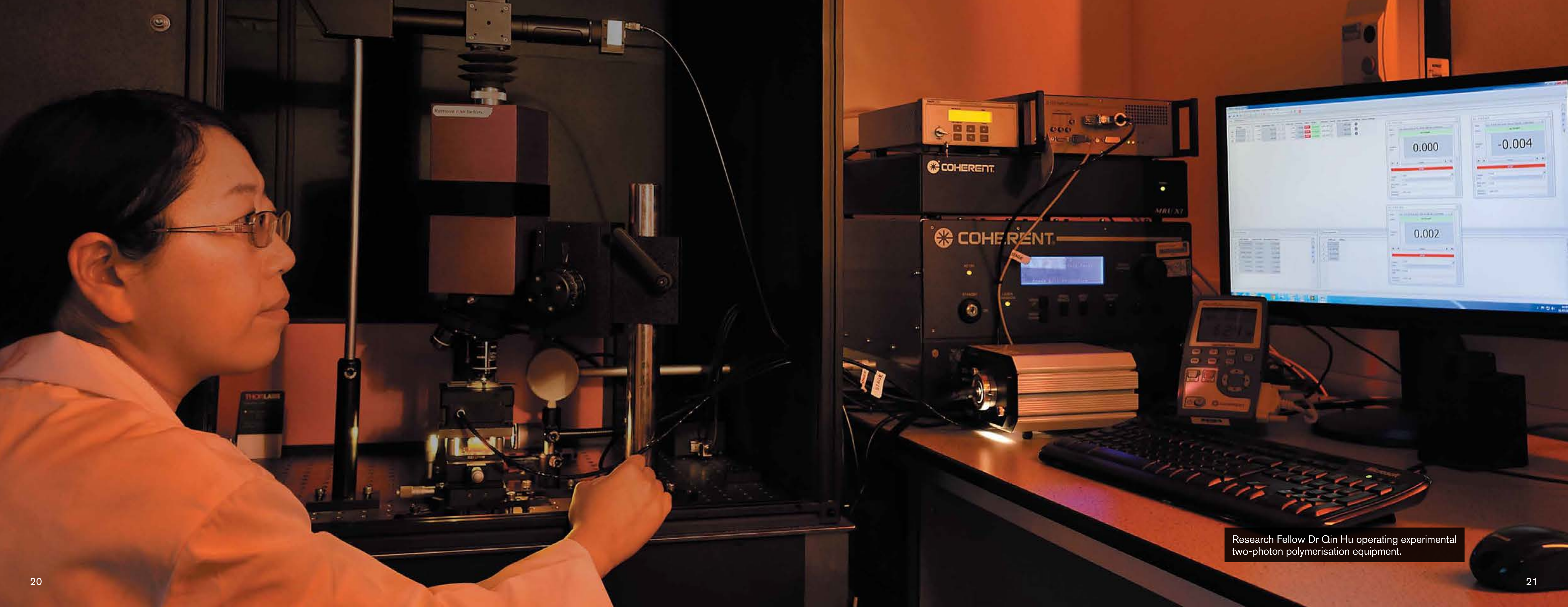
Currently the system is undergoing further testing and optimisation for its capability to process different materials, including polymers and metals, and to increase resolution and component complexity. The next step is to manufacture metal-polymer hybrid nano-composites in a single system with feature resolution less than 0.5 µm.

Since the project's inception, additional funding has been awarded from EPSRC (£250,000) and the United States Air Force's European Office of Aerospace Research & Development ($125,000) for purchasing additional equipment and exploring extended capabilities for the project and machine. Three PhD students are working on spin-off projects that involve collaborations with Nottingham's Electrical Engineering, Biology and Physics Departments. A number of colleagues both internally (biology, pharmacy and physics) and externally have shown great interest in future collaboration.

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



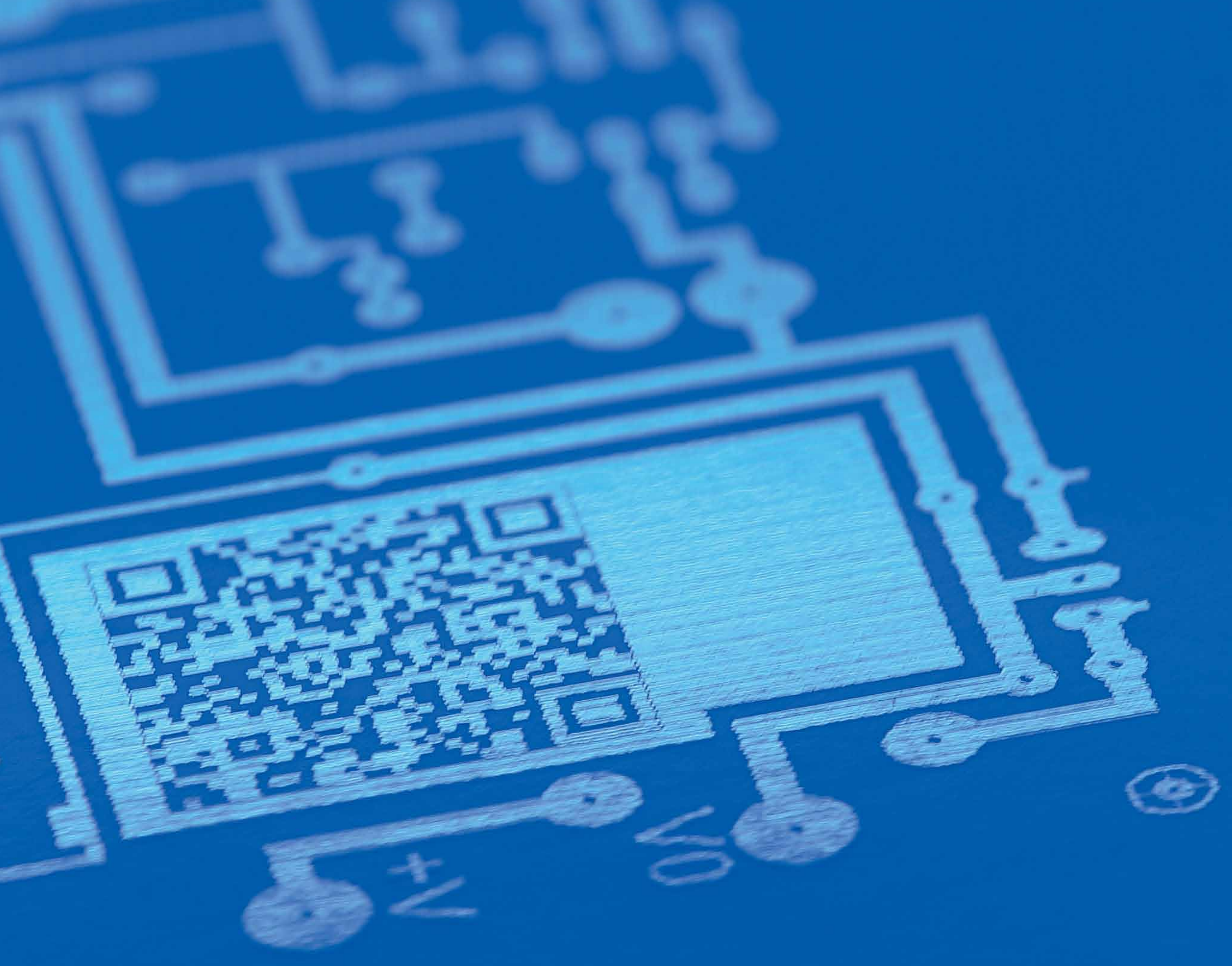

A scanning electron microscope image of a small scale structure created via the two-photon polymerisation system developed at the EPSRC Centre.




Research Fellow Dr Qin Hu operating experimental two-photon polymerisation equipment.

# External Academic research funded by the EPSRC Centre

**The EPSRC Centre is funding a number of complementary research projects at UK universities. These include five projects that were competitively awarded through a Jump Start programme held in February 2014.**



Silver circuitry additively deposited onto a ceramic substrate.





## 3D Printing of Biologically and Mechanically Functional Tissue Engineering Structures (University of Newcastle)

The aim of this project is to evaluate approaches to 3D printing of biologically functional structures allowing for structural biopolymers to be generated in the same processing step. The process consists of primarily three stages: firstly printing a layer of polymer or monomer, secondly crosslinking the polymer or monomer to create a polymer structure, and thirdly printing the cells, proteins and/or pharmacological agents (either together or separately) into the polymer structure, before repeating the steps to create the next layer of the 3D structure. The challenge is that the fabrication of the structural biopolymer should not at any stage expose the biological materials to environmental conditions which will inhibit or destroy their properties. This project explores a number of potential avenues to creating the mechanical structure and to protecting the cells and proteins from damage.

One way of addressing both the potential for damage within the printing process and limiting exposure to a damaging environment is to temporarily encapsulate growth factors and/or cells in a protective shell. The project is examining the use of polyelectrolyte layers and microbubble encapsulation to protect cells and proteins throughout the printing and material consolidation steps of the process.

Further, two approaches to creating a biopolymer structure are being investigated: (i) printing monomers and then polymerising, and (ii) printing linear polymers and then subsequently cross-linking them to create a solid structure. In both cases there is a need to ensure that at neither the printing nor the polymerisation/ cross-linking stages is there any loss of function for the biological elements of the structure.

Ending in September 2014, the project has taken forward the most promising material system and optimised the printing of hard biopolymer structures in that material system, with basic mechanical property testing undertaken. After establishing a consistent processing regime, co-processing of the polymer structure with cells and growth factors has been be undertaken to create a mechanically and biologically functionally gradient structure. This was followed by an investigation of the viability of the processed cells.

Project Team: Prof Kenny Dalgarno, Dr Mark Birch, Dr David Fulton, Dr Matt German, Dr Matt Benning, and Dr Sarah Upson (Newcastle University). The project is overseen by Prof Ricky Wildman and Dr Chris Tuck

Newcastle University

## Self-assembling hybrid jetting inks for regenerative medicine (University of Reading/ Imperial College)

This feasibility project explores and expands the capability of current 3D inkjet printing technologies, particularly in the field of regenerative medicine. It develops new ink formulations that have desired 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. At present, biomaterials do not have ideal combinations of control of mechanical properties, degradation rates and bioactive properties. New advanced materials and new manufacturing methods are needed.

As a result of the unique intimate interactions between bioactive inorganic and biodegradable polymer networks, hybrids are the only type of material that can fulfil the criteria for an ideal scaffold and jetting is the only potential method for the manufacture of complex 3D structures as found in scaffold architectures. The key objective of this feasibility study is to synthesise a new hybrid ink that can be jetted. If successful it will lead to a larger proposal that will explore the several candidate hybrid inks for optimal scaffold production for different tissues.

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.

University of Reading

Imperial College London

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

A critical challenge in AM 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 AM 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 AM techniques) and versatile (different ceramic materials could be printed following this approach).

The overall aim 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).

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.

## 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, would clearly be very beneficial to the industrialisation 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.

The feasibility study proposed here evaluates complementary experimental and modelling techniques which have the potential to step change understanding in this area. The specific objectives of this project are 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.

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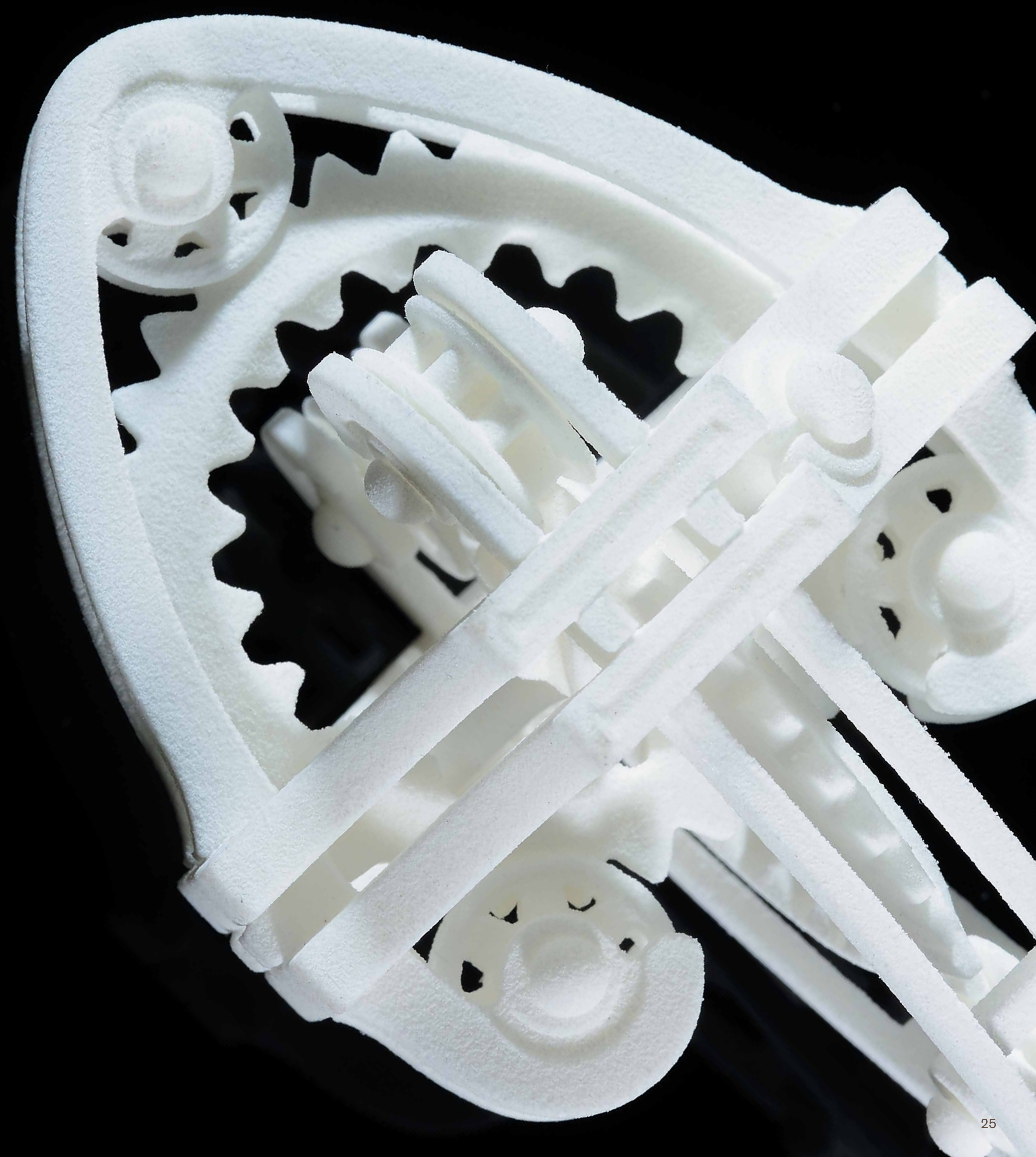
HERIOT WATT UNIVERSITY

UNIVERSITY OF LEEDS



Complex polyamide structure with nine moving parts, manufactured without assembly via Laser Sintering.

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

Cellular materials are an effective solution for impact energy absorption. Dissipation mechanisms and force transmission can be tailored through the choice of material and topology. Established examples include foams (polymer, metallic), honeycombs and lattice materials. Additive Manufacturing (AM) processes are emerging as a route towards novel light-weight cellular structures, with fewer geometric constraints, whose performance can be further enhanced through topology optimisation. Recent research has begun to unlock this optimisation potential at low strain rates; however, the performance of topologically optimised AM components in higher strain-rate applications remains unknown. Subsequently, this project focusses on investigating and validating topology optimisation of cellular materials for high strain rate deformations for applications in AM.

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.

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

In inkjet based AM processes, one of the major limiting influences on resolution and quality, if there is no further processing, is the size of the ink drops used. Conventional inkjet systems are typically operated in the drop volume range 1 pl to 500 pl (drop diameters 12 µm to 100 µm) so surface features less than ~20 µm are hard to achieve and in normal practice are significantly larger than this. The fluid dynamics of conventional inkjet dictates that the diameter of the drop obtained is approximately that of the nozzle. By taking special measures drops can be produced which are smaller than the nozzle but usually at some cost in operating window, drop rate or material range. Hence we see that commercially available inkjets tend to follow the normal rule. Nozzles smaller than 12 µm are difficult to actuate and keep clog-free.

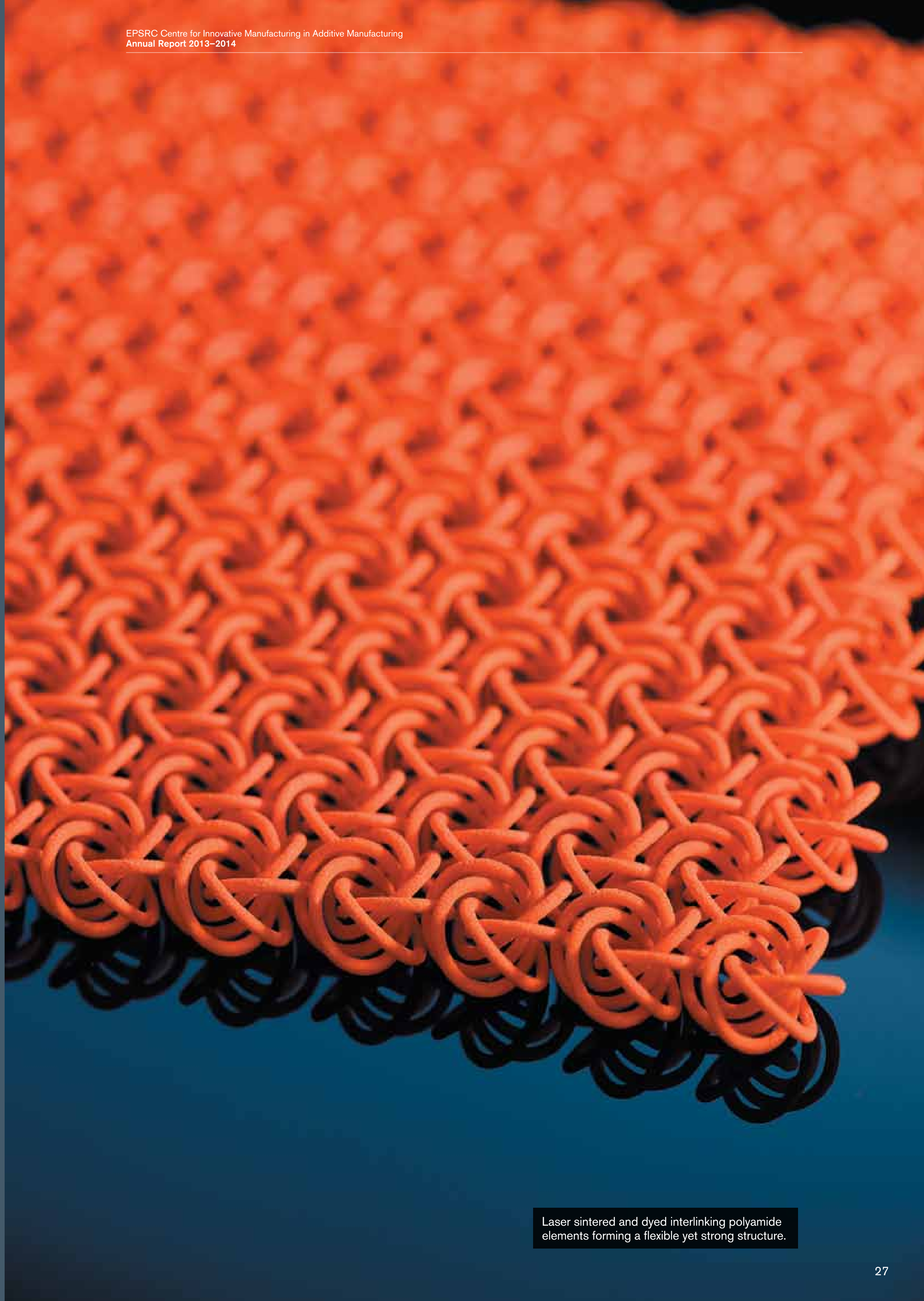
The goal of this project is to gain a better understanding of the process of small droplet generation and deposition to enable improved surface feature definition and reduced surface roughness in AM. Our aim, having optimised the process for AM, would be to print a small structure using a UV curable polymer with a wall thickness of a few microns to demonstrate the potential.

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

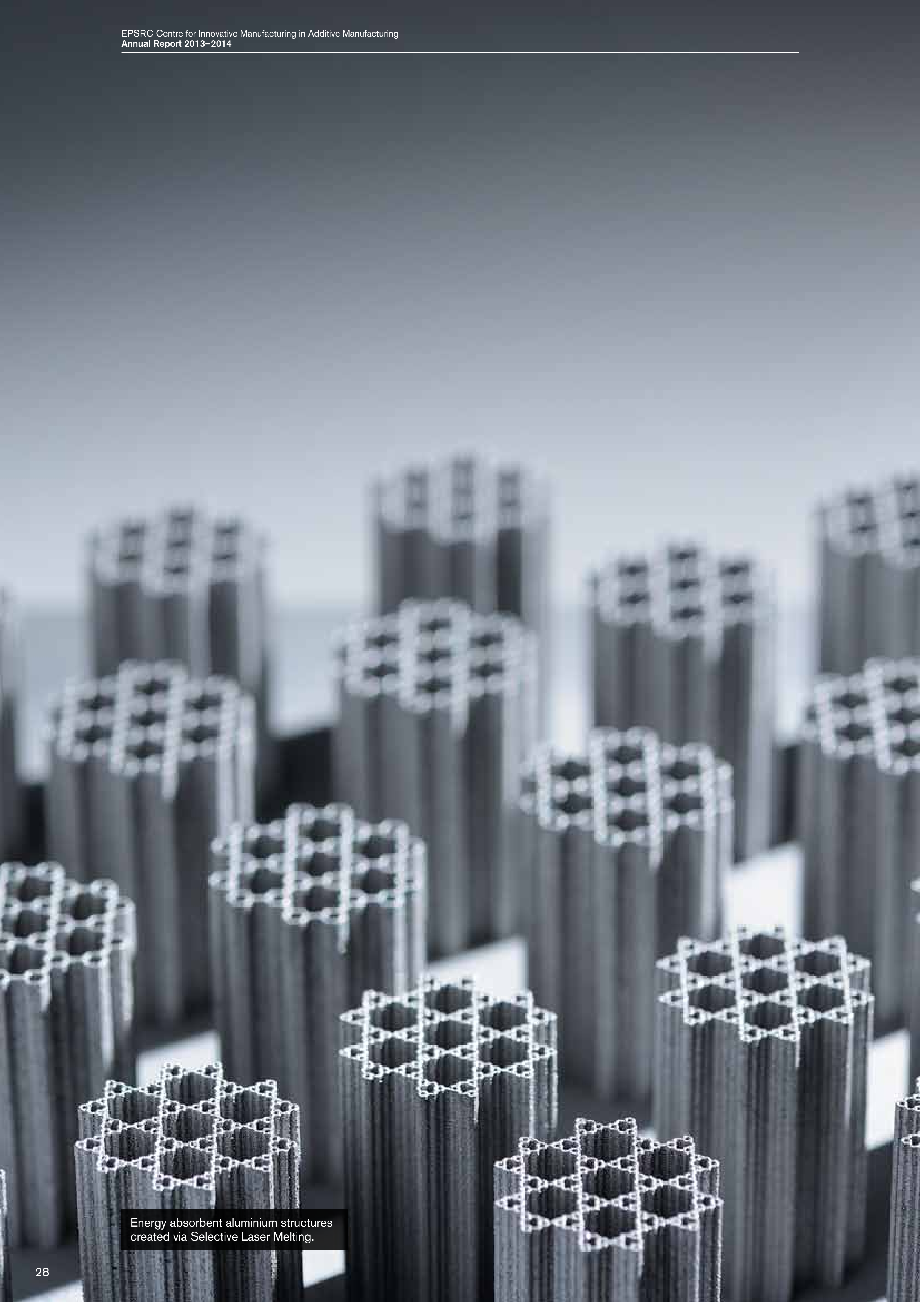
This project is funded through the EPSRC Centre's Jump Start programme.







Laser sintered and dyed interlinking polyamide elements forming a flexible yet strong structure.



Energy absorbent aluminium structures created via Selective Laser Melting.





# Complementary research at the 3DPRG

**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.**

## ALSAM - Aluminium Lattice Structures via Additive Manufacturing

The ALSAM project is structured to realise lightweight end user components composed of aluminium alloys. This is achievable by embedding lattices in these components with the added advantage of achieving multifunctional capabilities. On the ALSAM project, software has been developed to use a broad range of lattices for Selective Laser Melting (SLM) components. This has also been deployed at an industrial partner with commercial interest. Other partners on the project are more interested in improving their components with the lattices. The software is currently been used to achieve this, however, obstacles exists which relate to constraints within SLM and the virtual simulation of the lattices. The need for supports to prevent component distortion on the SLM and the computational expense that is incurred when analysing and optimising these lattices are the most prominent issues.

Initial work has focused on investigating the behaviour of lattices that self-support to mitigate the problem of support removal. The performance of self-supporting topologies were virtually determined and compared. Results for this study were presented at the 25th Solid Free Form Symposium in Austin, Texas, in August 2014 and are currently being validated. Also work is ongoing to understand the behaviour of these lattices under impact loading and efficient analysis and optimisation methods are being developed. A software tool has been developed that can be used to create different unit cells topologies composed of cylindrical struts and some minimal surfaces. This is expected to expedite the design of the latticed components.

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 the Technology Strategy Board.

## Diginova – Innovation for digital Fabrication

The emergence of major societal trends and consumer needs such as customisation, personalisation and on-demand fulfilment will impact the established manufacturing structure. Successful innovation in the digital age requires networked, flexible and open approaches. To an extent, the advent of 'digital fabrication' will enable innovations that bypass the established manufacturing structure.

The Diginova project has helped catalyse the new digital industrial revolution by providing a forum for relevant actors to define and promote advances in innovation for digital fabrication and its use with new materials. As a Seventh Framework funded Coordinated Support Action project, initiated by Océ Technologies, Diginova has brokered collaboration between materials research and industrial representatives in helping to create what could be called "Industry 2.0".

The EPSRC Centre for Innovative Manufacturing at the University of Nottingham led a work package on the identification of key technology challenges and business drivers, successfully concluding the Diginova project at the RapidPro in February 2014 in Eindhoven (The Netherlands). The central deliverable of the Diginova project, the Roadmap for Digital Fabrication, is available for download at: www.diginova-eu.org.

Project Team: The Diginova project team is composed of a large number of industrial and academic partners. At The University of Nottingham, the project team includes Prof Richard Hague, Dr Chris Tuck and Dr Martin Baumers

This project is funded by the European Union.

## 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 art architecture 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 system. AM is expected to provide a platform to introduce such disruptive technology into future products and services. AM 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 AM 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 AM can be exploited fully.

The objectives of the ALMER programme 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 multifunction 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 AM 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 my AM, whilst incorporating the nuances and performance limitations of this modern manufacturing method.

Project Team: The ALSAM 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, Meisam Abdi, Luke Parry

This project is funded by the Technology Strategy Board.

## ASID – Advanced Structural Integrated Demonstrator

Reduction in mass, improved performance, sustainable manufacture 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 AM 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 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 AM, are investigated to join the titanium hinge to the thermoplastic component part.

Project Team: Prof Ian Ashcroft, Dr David Brackett, Dr Tho Nguyen, Prof Richard Hague

This project is funded by the Technology Strategy Board.





## Developing Novel Polymer Nanocomposite Materials for Laser Sintering.

The potential of Laser Sintering (LS) lies in the ability to produce parts without specialised tooling, allowing one-off, customised structures to be easily and economically formed. However, despite the increasing presence of polymer LS in commercial manufacturing, direct production of computer-aided designs carries material limitations that need to be solved.

Polymer nanocomposites (PNCs) are a promising way to improve material choice for laser sintering. Nevertheless, until recently, researchers struggled to achieve the important factors for laser sintered PNCs, the good dispersion of the nano phase in the polymer matrix and the required nanocomposite particle morphology. A previous study within the group showed a significant increase in the mechanical properties of polyamide 12 achieved with a novel method of coating the polymer particles with carbon nanotubes (CNTs). This research is now being explored further with the use of CNTs filled with secondary nanomaterials, to increase functionality (e.g. magnetic). It is also being applied to polymers not currently available for LS to improve processibility and mechanical properties.

Project Team: Dr Ruth Goodridge, Dr Marcin Wegrzyn

## Investigating electrochemical deposition from a light assisted system

Electrodeposition is an attractive technology for the deposition and building of a structure; it offers flexibility in terms of the variety of materials that can be deposited, it can be controlled through the use of appropriate potential/current application and can be applied to a variety of geometric architectures. It can also be interrupted easily to incorporate multi-materials.

The employment of this technology in additive manufacturing of metal parts would hence seem to be appealing. However, high rates of deposition within this arena are desirable as well as control of the 3D architecture and microstructure of the material produced. In order to achieve these goals significant research into 'enhanced jet plating' can be found in the literature and is particularly pertinent. This enhancement is achieved through the application of light or acoustic energy to the system. Most of the relevant work has focussed on the deployment of laser energy. This energy has been suggested to have several effects. These are mostly associated with local heating of the interface although some suggestion of suppression of background parasitic processes (e.g. hydrogen evolution) or increased nucleation rates are also given. However, local heating has been shown to cause acceleration in mass transfer rates (by a factor of 1000 compared to normal conditions), shifts in electrode potentials and even local boiling effects. The combinations of these effects, if used appropriately, can be deployed to deposit metals at high rates. A preliminary study into the application of this technology to the production of a metallic structure will be provided.

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

In collaboration with:

UNIVERSITY OF Southampton

# Reaching out: the National Centre

**After the start of the EPSRC Centre in 2011, funds were awarded to act as a National Centre for AM research. These funds are targeted at supporting the UK Additive Manufacturing 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 develop public facing initiatives such as a comprehensive website, branded as the ADD3D initiative (see www.add3d.co.uk), to promote UK research at trade shows and conferences, and also for the facilitation of regular networking and focus groups.**

The specialist AM consultants at Econolyst continue to support the delivery of much of the National Centre agenda, including the setting up and management of a national AM research web portal, the development and provision of a presence at trade shows and a rolling program of events. Over the course of 2013-2014, a number of targeted outreach events and activities have been organised, designed to engage with the AM community, industry, and the wider public.

EPSRC Centre for Innovative Manufacturing in Additive Manufacturing
**Annual Report 2013–2014**

## Engaging with the AM Community

### International Conference

In July 2014 the EPSRC Centre once again hosted the International Conference on Additive Manufacturing and 3D Printing. The five-day event was attended by over 360 delegates from 22 countries, including the UK, USA, Japan, South Africa and mainland Europe. 17 speakers were invited to attend the conference by the Centre Director and National Centre Coordinator, from organisations including Philips Research, BMW, GE and the Cambridge Institute for Manufacturing.

### ASTM F42 and ISO Standards Committee

Directly following the International conference, the EPSRC Centre played host to the American Society for Testing and Materials (ASTM) F42 committee meeting, which was attended by over 75 international delegates. The ASTM F42 is a global committee of industrialists and academics which meets twice per year to develop and ratify standards relating to Additive Manufacturing & 3D Printing. The ASTM meeting was then followed by a meeting of the ISO Additive Manufacturing standards group, which was attended by over 50 people.

### ADD3D

Over the course of the last year, the ADD3D web site continued to provide information on AM related conferences, seminars and events along with career and funding opportunities. ADD3D includes a number of features aimed at promoting the national AM research community, including a searchable database of research capability and capacity at UK institutions focused on AM.

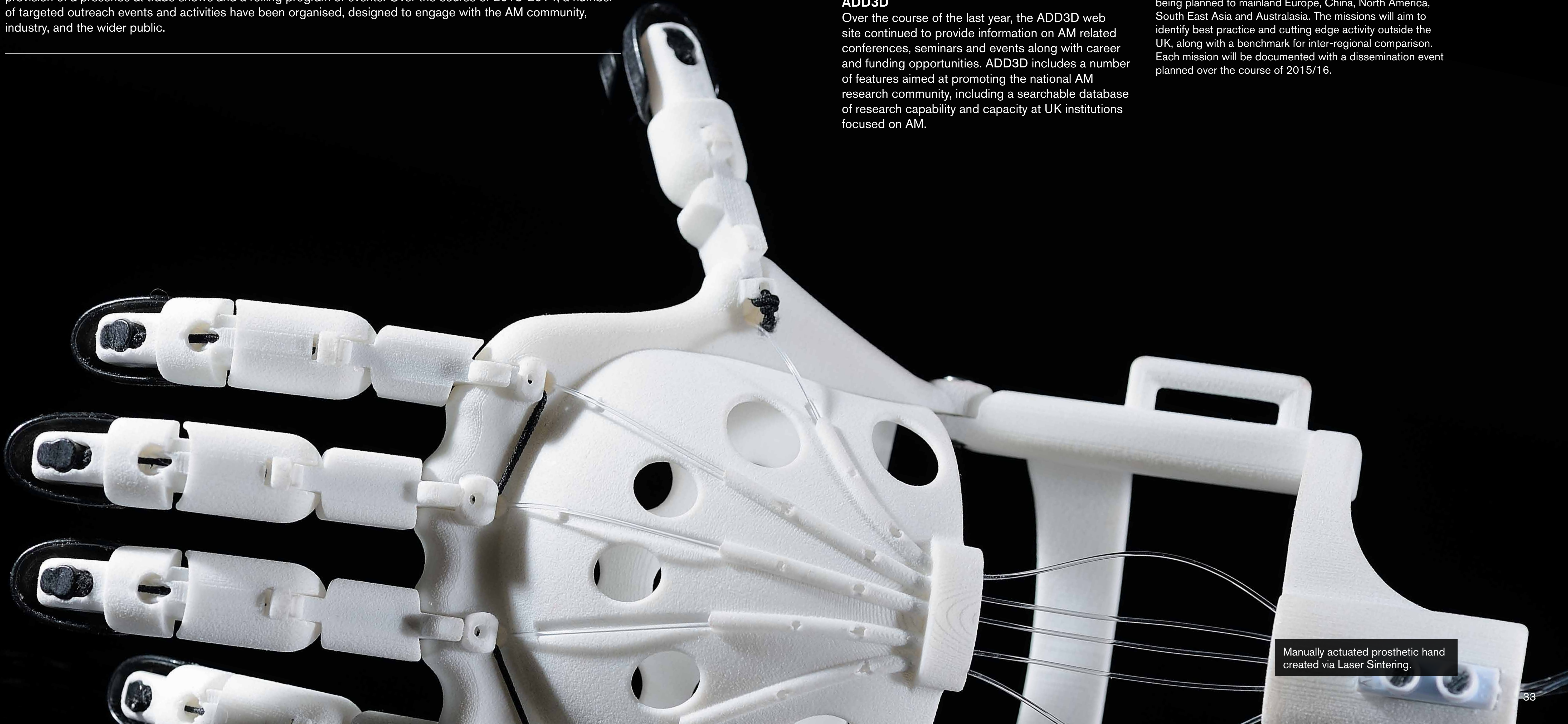
ADD3D also includes a selection of case studies, an industry event diary and a section dedicated to helping companies and academics identify research funding opportunities. Also, a review of AM research activity at leading UK universities was undertaken with high level findings being used to populate a searchable area of the ADD3D website. This enables users to identify research areas of interests, research capability and capacity and also the contact point within universities to engage in specific research activity.

### State of the art review of research competence

A detailed state of the art review of UK AM research competence was initiated during 2014. The review will provide a detailed snapshot of the capabilities and capacity of the UK research base to engage in AM research activity across the Technology Readiness Level (TRL) scale. The review is considering structured research activity funded by UK and EU bodies, along with direct university and industry funded research activity.

### Overseas benchmarking missions

During 2014, a number of overseas benchmarking missions have been designed to compare the capabilities and competence of the UK AM research community against other leading global regions. At this time, overseas missions are being planned to mainland Europe, China, North America, South East Asia and Australasia. The missions will aim to identify best practice and cutting edge activity outside the UK, along with a benchmark for inter-regional comparison. Each mission will be documented with a dissemination event planned over the course of 2015/16.



Manually actuated prosthetic hand created via Laser Sintering.

## Engaging with Industry

### Masterclass

In 2014, a half-day Additive Manufacturing masterclass was undertaken, which was attended by some 70 delegates from academia and industry. Many of the delegates were new to the field of AM and attended this special event to gain an unbiased overview of the current technical and commercial status of AM. The masterclass included session on business models, processes, materials, industrial additive manufacturing methodologies and consumer 3D printing retail opportunities.

### UK University elevator pitches

In 2014, a half-day conference was arranged and attended by over 125 delegates. This event provided a platform for twelve of the UK's most prominent AM research groups to discuss their research portfolios and present methodologies by which industrial organisations and companies can engage in both research but also access research dissemination. The event included presentations from the universities of Nottingham, Loughborough, Sheffield, Birmingham and Cranfield, amongst others.

### Direct company engagement

During 2013 and 2014, the National Centre for AM research and EPSRC Centre staff engaged with a wide range of new industrial contacts looking to understand and implement AM within their value chains. Participant companies included high profile organisations such as Philips, GSK and EON, amongst many significant others. In some cases engagement included simply facilitating visits to university laboratories and meetings with academics and researchers. In other cases, companies engaged in more in-depth AM ideation sessions, workshops and training sessions delivered by National Centre staff.

## Engaging with the Wider Public

### 3D Print Show

In November 2013, the National Centre for AM research and the EPSRC Centre were delighted to exhibit at the 3D Printshows in London and Paris. These events were attended by over 15,000 people, including industrialists, consumers, investors, students and journalists. The University of Nottingham, in conjunction with the National Centre, were the only higher education institution to be invited to participate at this important occasion.

### Physics World article

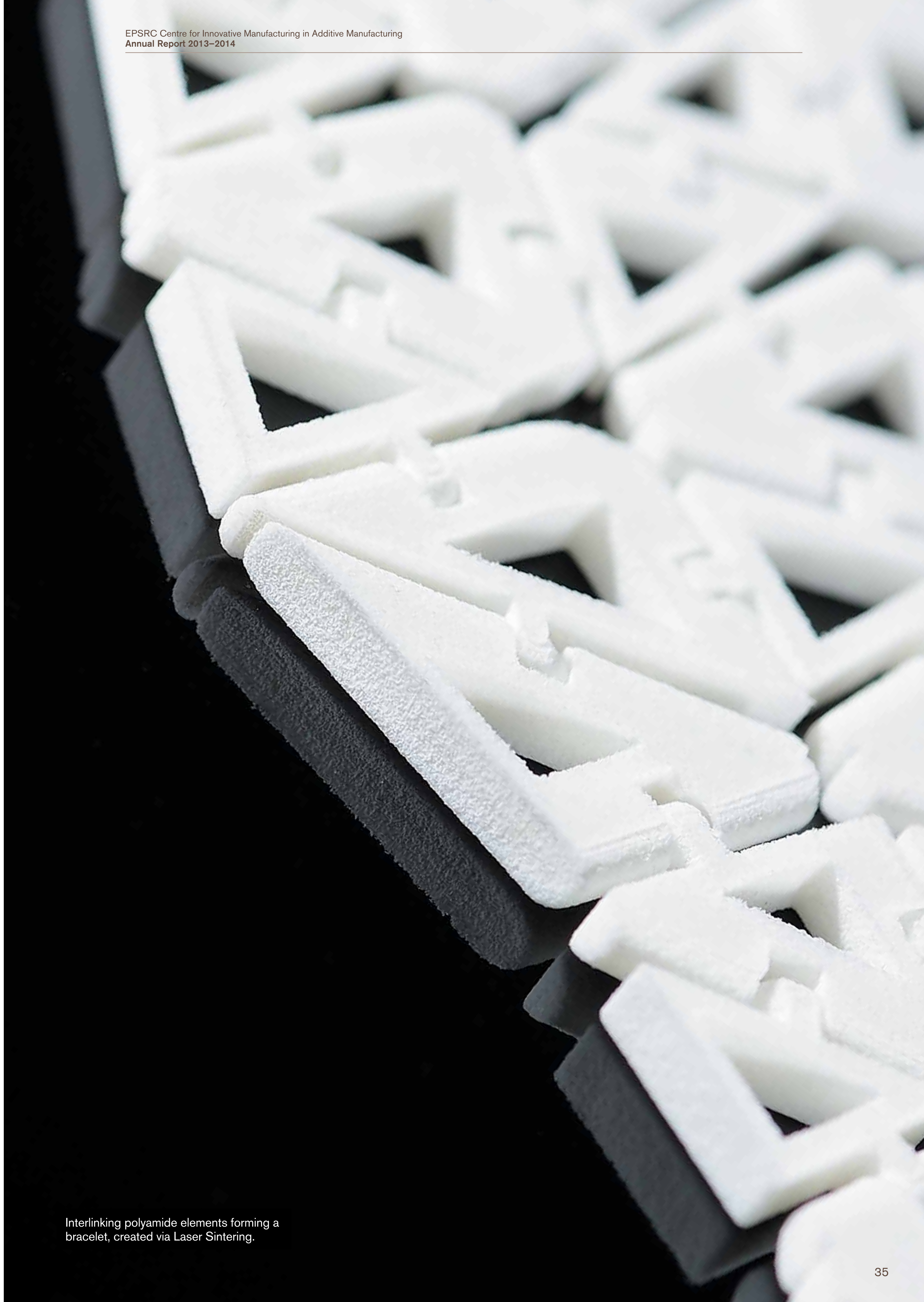
In May 2014, the EPSRC Centre members Prof Richard Hague, Dr Martin Baumers, Dr Chris Tuck and Prof Ricky Wildman published an article titled '3D Printing: The Next Step' in the Focus on: Optics and lasers issue of Physics World. The article explored the relevance of AM for the manufacturing sector in the future, with a special emphasis on multifunctional AM and the Centre's activities toward the use of optical technologies in the additive deposition of nanoscale features.

### Royal Academy of Engineering's Summer Soirée

In June 2014, the EPSRC Centre's academics participated in the Royal Academy of Engineering's Summer Soirée and exhibition, showcasing the activities within the Centre and the 3DPRG. This event was held at the Manufacturing Technology Centre in Coventry in the presence of Royal Fellow HRH The Duke of Kent. The exhibition with the theme 'Manufacturing - at the Heart of the Nation' was followed by a formal evening programme.







Interlinking polyamide elements forming a bracelet, created via Laser Sintering.

# Doctoral research at the EPSRC Centre

PhD Students Meisam Abdi, Javier Ledesma, Craig Sturgess, Yinfeng He and Michele Garibaldi.





## Award of the EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing

**We are delighted to announce that we have been awarded the EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing and 3D Printing, in collaboration with the universities of Liverpool, Loughborough and Newcastle. Being awarded this CDT offers the opportunity to make a very significant impact in terms of the UK national landscape for highly trained individuals.**

The primary objective of the CDT is to produce research leaders to tackle the major scientific and engineering challenges over the next 10-15 years in enabling AM and 3D Printing to play a prominent role in manufacturing, providing the people and talent to fuel this new industrial revolution. These challenges encompass a wide range of scientific disciplines from chemistry and physics to computer science, engineering and bio-materials in order for AM to be successfully adopted as a technology that can enable almost every sector of society and business i.e. aerospace through to medicine.

To fill the available spaces, we are seeking exceptional individuals who are willing and capable of bridging these disciplines to make AM and 3D Printing the enabler for a better economy, environment and society. The distinguishing features of PhDs in this CDT are its four year duration with specific training in AM and 3D Printing methods and techniques, improved stipend, a special link with industrial partners and the requirement that some of the time (a minimum of three months) is spent conducting research in industry.

Fully backed by both the EPSRC Centre and The University of Nottingham, this CDT brings together four of the UK's foremost AM research institutions to generate the coming leaders within this emerging field. The CDT is led by the Director, Dr Chris Tuck, supported by Prof Ian Ashcroft, the Training Programme Director, who, together with colleagues at The University of Nottingham and our partner institutions, have developed an exciting and vibrant training programme intimately linked with industrial sponsors from a wide range of sectors.

## Ongoing doctoral research within the 3DPRG

**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 optimization of continuum structures using X-FEM and isovalues of structural performance
- **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 AM 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
- **Amanda Hüsler (Materials Science):** Polymer particle formation using ink jet printing
- **Luke Parry (Mechanical Engineering):** Simulation and optimisation of Selective Laser Melting
- **Benjamin Paul (Neuroengineering):** Additive manufacture of a neuron biosensor
- **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
- **Adam Naas (Mechanical Engineering):** Investigating the feasibility of radiative area sintering of a uniform polymer powder bed
- **Craig Sturgess (Mechanical Engineering):** Investigating and modelling the progress of drop on drop mixing and reaction in reactive inkjet printing
- **Jayasheelan Vaithilingam (Pharmaceutical Engineering):** Additive manufacturing and surface functionalisation of Ti6Al4V components using self-assembled monolayers for biomedical applications
- **Stefan Ziegelmeier (Mechanical Engineering):** Process analysis and material behaviour of thermoplastic elastomers in laser sintering

Close-up of the surface structure created via a consumer 3D Printer in polylactic acid.





# Summer internships 2014

**Repeating the previous year's successful format, a group of summer interns were supported by University of Nottingham funding to work within the EPSRC Centre at The University of Nottingham throughout July and August 2014. Operating in two small teams and made up from a diverse range of disciplines, the interns were tasked with innovative work in the field of novel additive processes and designs. The objective of the exercise was to demonstrate the attractiveness of AM as a potential postgraduate research topic.**

## 3D printed supercapacitor

Supercapacitors are formed of two electrodes with an electrolyte encapsulated between them. Due to various fabrication limitations, supercapacitors are usually formed into a planar shape limiting the design freedom and the total surface area of the device. Using additive processes, 3D printed structures could achieve an optimal surface area and can be customised to the shape of any device enclosure, which is a key factor for compact electronics. The structural material of the supercapacitor can be a dielectric printed with either the Objet or PixDro printers based in the 3DPRG lab. The internal side of the structure can be carbon coated using graphite ink or exhibits conventional carbon vapour coating to form the electrodes of the supercapacitor. The electrolyte solution can then be purged into the hollow structure making a separator-free supercapacitor featuring reduced weight and volume.

The overarching aim of this project is to print a functional supercapacitor using equipment available in the 3D Printing Research Group labs. Individual objectives include:

- identification of potential materials of the capacitor structure, electrodes and the electrolyte from recently published papers;
- study of the performance of a simple-geometry 3D-printed supercapacitor using the identified materials;
- design of an optimised high surface area geometry to form the final structure of the capacitor;
- characterisation of the electrical properties of the final supercapacitor and evaluation of its performance.

The supervision team includes: Prof Richard Hague, Dr Chris Tuck, Prof Ian Ashcroft, Prof Phill Dickens, Dr Ehab Saleh (as interface with the process-led group), Yinfeng He and Dr David Brackett

The summer interns carrying out this project are: Alex Goodall (Engineering), Kate Harborne (Physics and Astronomy) and Alanna Murphy (Chemistry)

## 3D printing a flexible and durable light-guiding implant

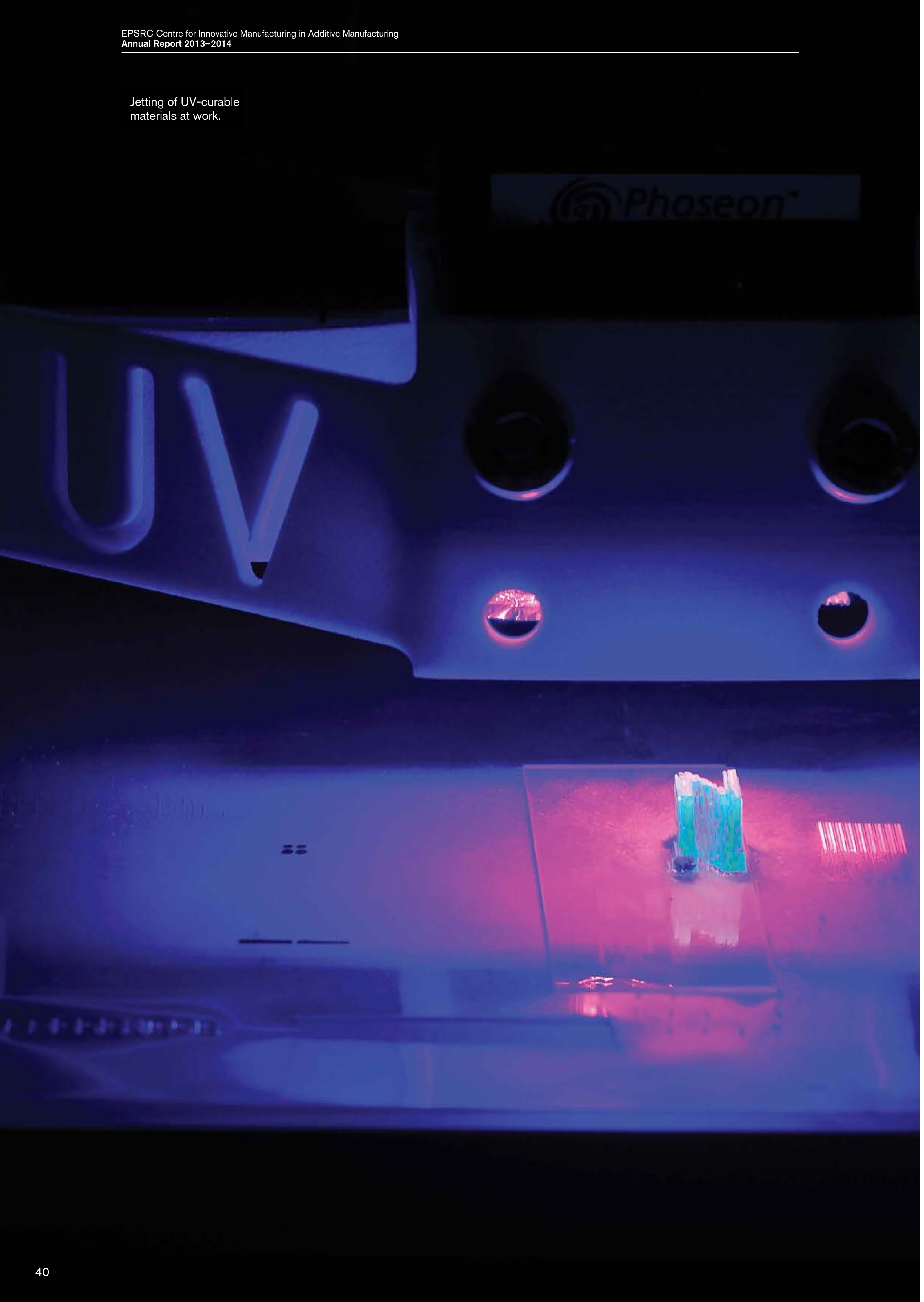
Optogenetics is the combinations of optics and genetics, using light to provoke responses from specific cells or proteins within a complex biological system. The targeted cells or proteins have been genetically modified to be sensitive to light, so the stimulation has a very high spatial and temporal resolution, which cannot be achieved by traditional methods such as electrical stimulation and pharmacological (chemical) stimulation. In 2010, optogenetics was chosen as the 'Method of Year' by Nature Methods. Potential applications include various disease treatments, such as for Alzheimer's, Parkinson's, many cancers, sight restoration and spinal cord injury restoration, as well as regulating the processes of a number of organs, such as the heart and kidney. The demonstrated work about optogenetics shows that currently there is a lack of a well-defined interfaces to connect various targeted cells/proteins with external light sources. A tailorable, flexible and durable light-guiding implant is highly desirable.

The general aim of this project is to develop flexible and durable light-guiding micro/nano structures that could in future be possibly used as implant to connect external light sources with internal genetically modified light-sensitive cells for optogenetic applications. Particular objectives include:

- development of software to operate the two-photon lithography system;
- identification of suitable light-guiding biomaterials;
- design of flexible (stretchable, compressible and twistable) and durable micro/nano structures;
- analysis of fabrication processes using two-photon lithography systems & inkjet printing techniques;
- testing of the flexibility and durability of the fabricated structures.

The supervision team includes: Dr Chris Tuck, Prof Richard Hague, Prof Ricky Wildman, Prof Phill Dickens, Dr Qin Hu (as interface with the process-led group) and Dr David Brackett

The summer interns carrying out this project: Edward Burt (Physics), Rahul Patel (Engineering) and Sara Wang (Engineering)




Jetting of UV-curable materials at work.





# Further information

**The EPSRC Centre thanks its collaborators:**

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