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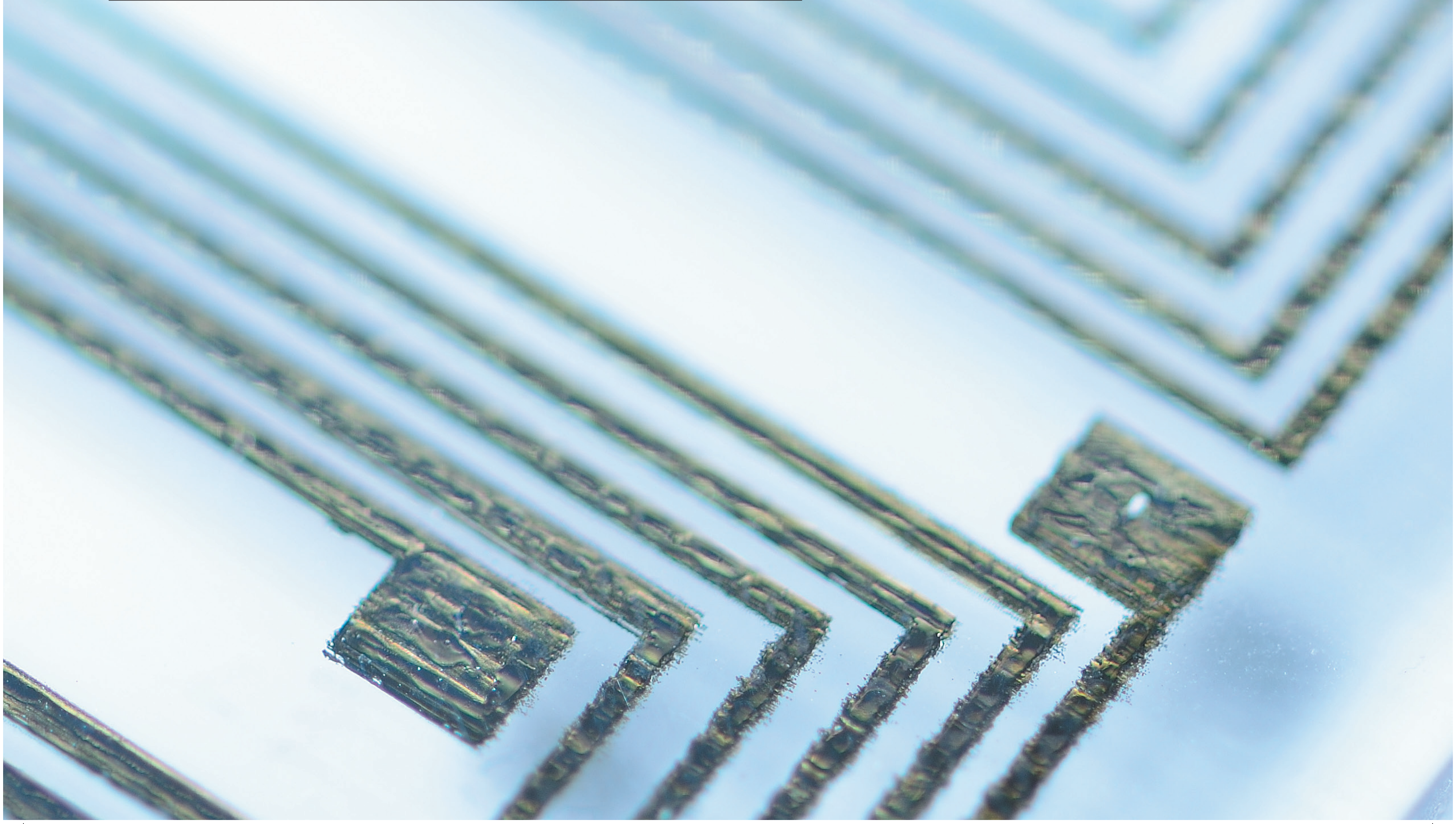
EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing

Annual Report 2014-15

EPSRC
Engineering and Physical Sciences Research Council

EPSRC Centre for Doctoral Training in Additive Manufacturing



Forward by Centre Director, Dr Chris Tuck

Our Centre for Doctoral Training (CDT) in Additive Manufacturing formally began on 1 April 2014, however, the planning and development of both our cohort and teaching programmes started much earlier than this. Our aim was to develop a bespoke programme of challenging modules relevant to the students research and provide experiences to develop a research ethos encompassing integrity, respect and collegiality. Our first year has been incredibly successful; in no small part due to the dedication of the Executive team, comprised of representatives from the four partners, that has led the CDT from a kernel of an idea to reality in a very short space of time. Additionally, our supporting academics and supervisors at all of the partner institutions have played their part in delivering against the CDT's objectives and enabling the taught programme to be both innovative and well-informed. The CDT has been able to draw on world-class research expertise to deliver the experience we aspired to when planning the programme.

I must especially congratulate our first cohort of students. They have all successfully progressed on to the second year of the programme and engaged with the first-year activities with a commendable amount of hard work and enthusiasm. The CDT has also been very successful in identifying and attracting industrial sponsors. We currently have 10 projects in operation, with at least 18 due to commence over the coming year. Each project is supported by an industrial partner, illustrating the applicability of both the CDT programme and the subject area across a wide range of sectors. From automotive to plastics and metrology, the CDT is attracting a wide range of companies, SMEs and large Original Equipment Manufacturers (OEM).

Following a highly enjoyable and successful trip for our students to the Solid Freeform Fabrication Symposium in Texas, USA, the second year of operation finds the CDT in a good place to accelerate our plans. Recruitment has continued throughout the first year and we are expecting a significant increase in the number of students starting in October 2015. We look forward to working with the new student cohort and a new set of industrial sponsors.

Dr Bochuan Liu operating a Diamatix inkjet 3D printer.

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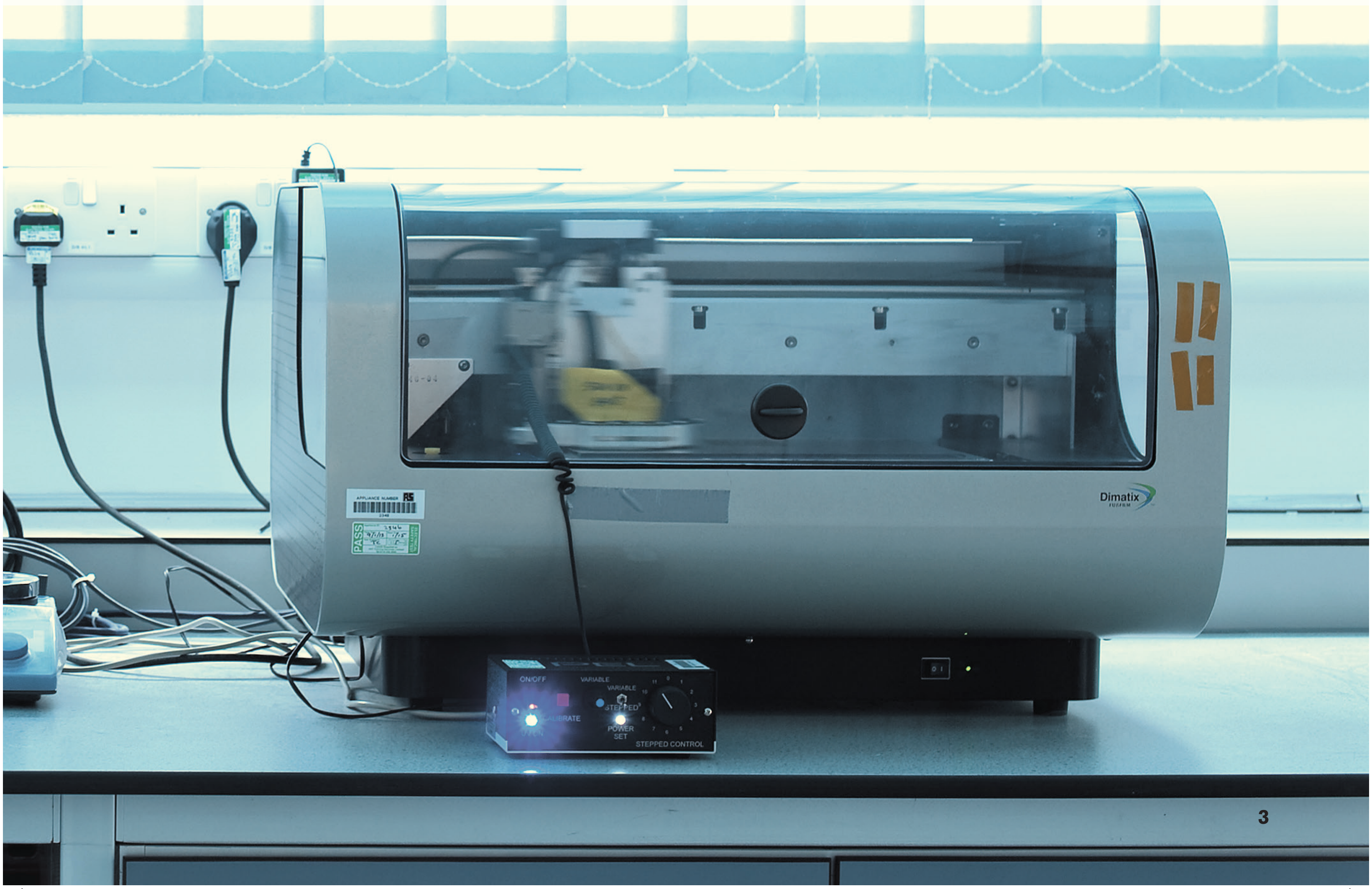


CDT researcher Hatim Cader operating the Dimatix material jetting platform.

Introduction

The EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing and 3D Printing was established in April 2014.

Led by The University of Nottingham, in partnership with Loughborough University, Newcastle University and The University of Liverpool, the CDT provides a world-class collaborative training environment in the multi-disciplinary field of Additive Manufacturing (AM). It aims to deliver 66 researchers over the course of the grant who will have the necessary technical understanding and transferable industry-facing skills to become future leaders in this field of research.

The CDT receives funding from the Engineering and Physical Sciences Research Council (EPSRC) with contributions from each of the four partner universities. Every research project is also supported by an industrial partner, ensuring the research conducted within this CDT is highly relevant to industry. This combined financial support will allow the CDT to provide specialist AM training to PhD students until 2022.

The first cohort of CDT students was welcomed in October 2014. As part of the training programme, students have covered in-depth topics, including materials used for AM, computer-aided engineering for AM, commercial 3D printing, and considered the wider implications of AM technology such as intellectual property and ethics. They have also received training on a range of specialist laboratory AM equipment, as well as attending international conferences, participating in professional skills training and assisting with outreach activities.

During this past year, all students have successfully completed 130 credits of training modules and have progressed into their second year of study. Primarily, they are now working towards their defined PhD project but will continue to complete taught modules and transferable skills training throughout the remainder of the CDT programme.

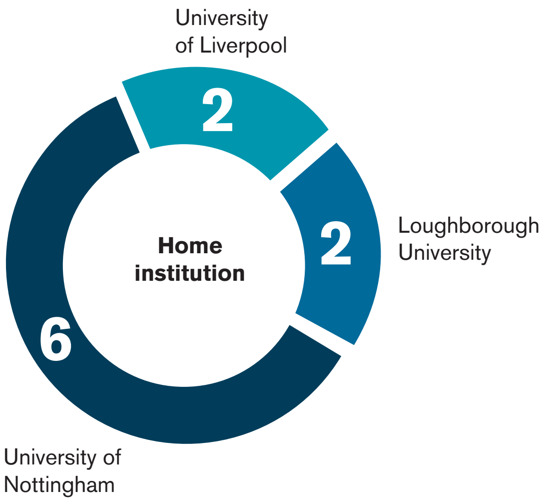
Partner	**The University of Nottingham**	**Loughborough University**	**Newcastle University**	**The University of Liverpool**
Expertise	Multi-material AM	Hybrid and multisystem AM	AM Ceramics and Glass	Metallic AM
	New AM materials	Solid state AM	AM Biomaterials and structures	Spiral growth
	Design	Structural Monitoring	Medical devices	Medical implants
	Jetting systems		Digital fabrication	Atomic layer deposition
	Digital fabrication			
	Polymer AM			

Recruitment

The CDT aims to recruit the highest calibre students from across engineering and the physical sciences. At the heart of this is the firm belief that recruiting from a range of disciplines will add depth and value to the student's cohort learning experience. In October 2014, the CDT welcomed 10 highly motivated students who were registered across three of our partner institutions.

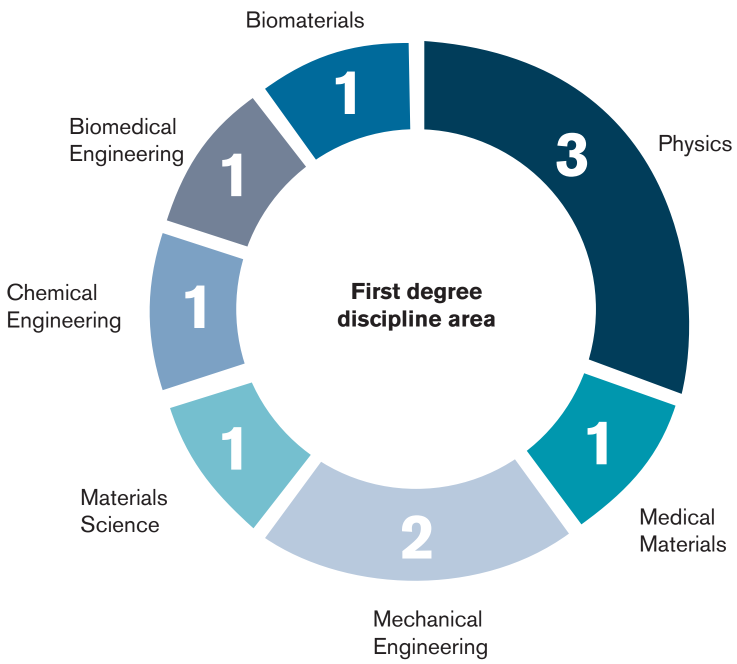
Recruitment for Cohort two has continued throughout the 2014/15 period. Interest from prospective students has been high from across the globe and the CDT expects to register at least 18 highly qualified students in October 2015.

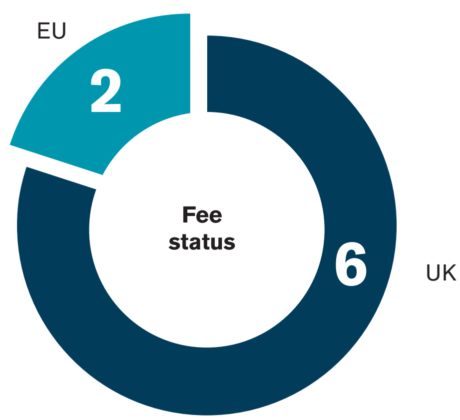
Cohort 1 Student Demographics



"I like the multidisciplinary nature of the group, and the sense that there is always something exciting and new happening"

Nicholas Southon
CDT student





Building a cohort

For the first nine months of the CDT programme, all students are based at The University of Nottingham. However, student visits to partner institutions are organised so that they are familiar with the staff, infrastructures and the research taking place across the CDT. In 2014/15, there were group visits to Newcastle University and Loughborough University.

The taught training programme plays a key role in laying the foundations for students to form a solid cohort. There is strong emphasis on collaboration and multi-disciplinary group-work through a series of tasks and assignments. As a result, students have formed excellent working relationships within the group and have a ready-made network of Additive Manufacturing colleagues to consult, both during their programme and beyond.

Team building

Additional events have been organised on campus and externally to help develop team-building skills, both across the cohort and alongside non-CDT researchers. Activities have included raft building, abseiling and problem-solving challenges in the Derbyshire dales, as well as a team go-karting competition.

Student charter

In 2014, a CDT student charter was published for use across the CDT. It was developed with input from institutional partners and current students to ensure that the charter clarifies the expectations of students and supervisors, while capturing the ethos of the CDT.

"The CDT focuses fairly heavily on the building of a cohort, which allows for what I feel is a friendlier and more productive atmosphere than a standard PhD. We are encouraged to solve problems and work together"

Adam Thompson
CDT student

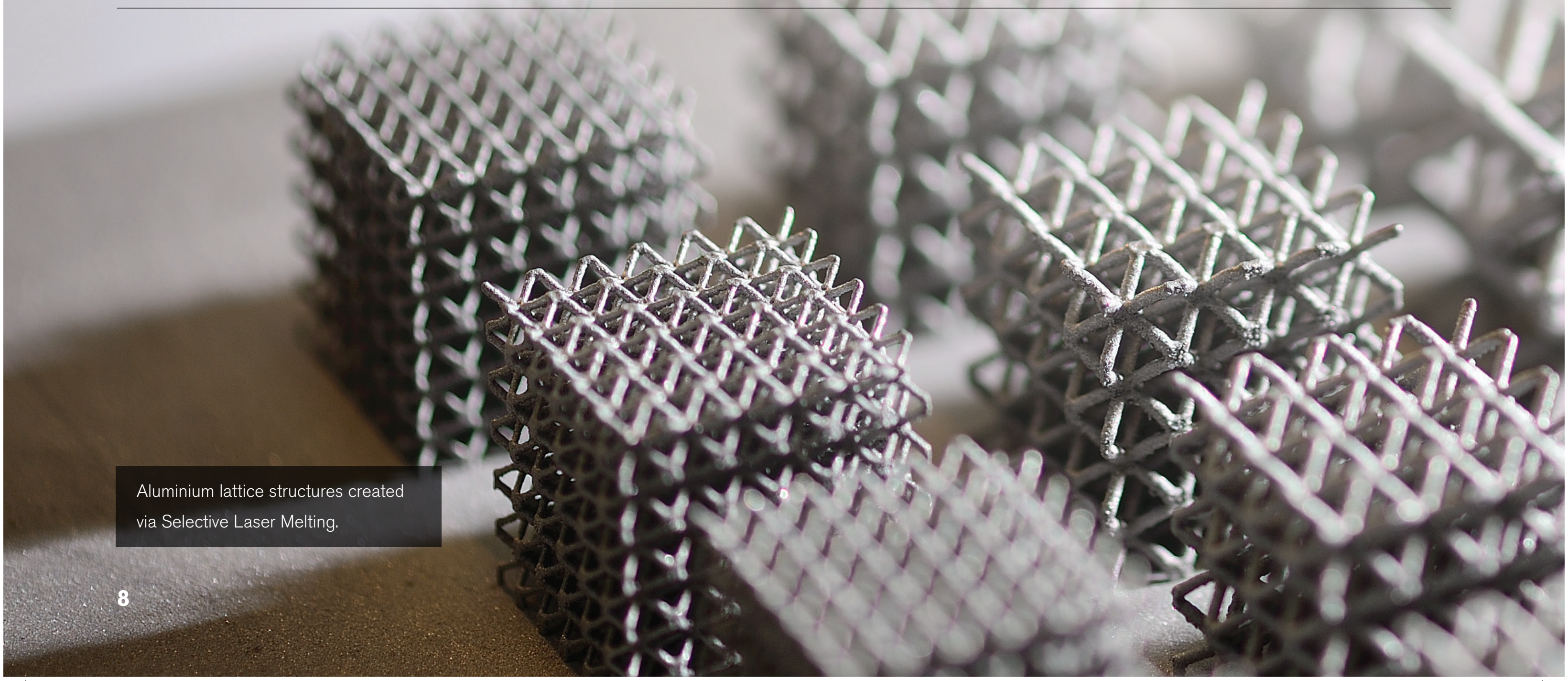
Training programme

The CDT provides specialist training using the very best facilities in AM

The training is arranged into credit-bearing modules. Some of these are traditional classroom-based taught modules, delivered in week-long intensive blocks. Traditional lectures and seminars are complemented with hands-on laboratory practicals.

Alongside taught modules are research modules which provide a continuous stream of activity throughout the first nine months of the programme. These include the Group Grand Challenge in Semester one (see page 10) and the Individual Project module in Semester two (see page 11).

YEAR ONE: modules (credits)	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Group Grand Challenge (40)									
Introduction to AM 1 (10)									
Introduction to AM 2 (10)									
Individual Project (40)									
Materials in AM (10)									
Computer Aided Engineering in AM (10)									
Professional Skills (10)									
PhD (-)									



Aluminium lattice structures created via Selective Laser Melting.

Specialist taught modules

Introduction to Additive Manufacturing 1

This module provided an overview and introduction to AM which included up to date relevant examples from both industry and research. Briefly it covered the seven ASTM process categories of AM, product development, reverse engineering applied to AM and rapid tooling.

Introduction to Additive Manufacturing 2

Modern AM techniques that are currently being researched and exploited within both academia and industry, resulting in net shape parts were considered. Topics covered included; commercial 3D printing, experimental systems for AM, material requirements for AM, inkjet materials, software and systems, impact of AM and 3D printing, case studies of AM in industry and the future for AM.

"Although they were taught modules, they were unlike any previous modules I had taken. The teacher student dynamic was more relaxed, allowing for a greater learning and stimulating discussions"

Sarah Kelly
CDT Student

Computer Aided Engineering for Additive Manufacturing

This module described the various computational methods available to engineers and how they can be used in a manufacturing environment. Attention was focused on the subjects of computer aided drawing (CAD), finite element analysis (FEA) and computer aided manufacture (CAM). In particular, CAM for additive manufacturing was considered with teams competing to design and manufacture the most efficient AM structure.

Materials for Additive manufacturing

The requirements, formulation and processing of raw materials for modern additive manufacturing and 3D printing techniques that are currently being researched and exploited within both academia and industry were examined. It included analysis techniques for polymers and metallic materials, material formulation and post-deposition analysis.

The Group Grand Challenge

Research modules

Module Organisers: Professor Richard Hague and Doctor Adam Clare

During the very first week of the CDT programme, students were placed into small groups of three to four and given a challenge which would immerse them in AM research at Nottingham. Each group member had a different discipline background ensuring that everyone was able to contribute to the project with a different perspective. This was a semester-long challenge resulting in the production of a final report, a group presentation and a poster. Each group presented their poster at the 2015 Solid Freeform Fabrication Symposium held in Austin, Texas.

Challenge 1:

To Investigate Novel Designs of Auxetic Structures of Metallic Materials.
Sarah Kelly, Alex Gasper, Duncan Hickman, Jonathan Gorecki

Summary: This project considered the design, fabrication and testing of novel 3D auxetic lattice structures in Stainless Steel 316L using Selective Laser Melting (SLM). The research developed along three themes; auxetic foam structures, re-entrant bowtie structures, and a novel auxetic ring design. An auxetic foam structure was produced and using Computer Tomography, a computer model was created that allowed the tailoring of key parameters to greatly increase the capability and usability of the structure. It was possible to create 3D re-entrant bowtie structures within the parameters SLM; however issues arose on creating curved struts on a small scale. Design variations were created to assess the effects of curving the re-entrant struts on a bowtie lattice structure and varying this curve. A novel auxetic ring design was created that produced a width reduction due to the relative rotation of the top and bottom surfaces under compression. The design was investigated for a range of parameters and manufactured using Laser sintering and SLM.

Challenge 2:

To Investigate the use of Hot Melt Inks for the Manufacture of Complex Micro-lattices.
Adam Thompson, Rebecca Garrard, Carlo Campanelli

Summary: This project investigated hot melt inkjet printing of 3D microlattices. The authors reviewed relevant literature around the fields of hot melt ink-jetting, ink composition and development, and lattice design. Utilising Océ hot melt TonerPearls™, deposited material was evaluated mechanically by DMA and compression testing. Using the PiXDRO LP50 printing system, design restrictions were identified through variation of relative layer offsets and an angle of ~45° was found for maximum overhang, relating to a layer offset of 10 μm. The process of lattice development was articulated, including voxel CAD development, slicing software and lattice iterations.

Challenge 3:

To print a Functional Supercapacitor using equipment available in the 3D Printing Research Group labs.
Hatim Cader, William Rowlands, Nicholas Southon

Summary: Supercapacitors were successfully produced using ink jet printing. Through a critical literature review of past research, relevant materials and production methods were investigated. After thorough ink characterisations, the final electrode composition was determined to be graphene oxide, 30wt% polyethylene glycol and 0.5wt% TWEEN20. The ink was jetted onto a gold-sputtered and ink-jetted silver current collector, followed by thermal reduction to produce reduced graphene oxide. A novel method of reducing graphene oxide was also investigated through the use of UV light, followed by numerous characterisations confirming the success of the process.

First year individual projects

In semester two, students were given the opportunity to undertake an in-depth individual project on a topic associated with their future interests in AM. On completion, they were asked to present their work at an internal CDT symposium, and to write a paper to the standard of a peer-reviewed journal publication.

Selected examples:

The use of an Error Diffusion Based Method (Dithering) to produce a Functionally Graded Cellular Structure for an Orthopaedic Hip Implant

Duncan Hickman, David Brackett, Ian Ashcroft, Doctor Ruth Goodridge

This project looked into improving the design of hip prostheses as revision surgeries of Total Hip Arthroplasty (THA) are often caused by the poor mechanical compatibility of the implant with the surrounding bone. This mismatch in properties results in bone resorption and interface instability caused by stress shielding. Current hip replacements aim to address these issues through careful material selection and the use of porous structures. The use of Additive Manufacturing (AM) technologies allow for the creation of complex and highly customised porous structures.

2D representation of a femoral stem component designed with an intelligently distributed material density.

Using these technologies this project utilised a novel method of creating a functionally graded porous implant consisting of a lattice structure with a nonhomogeneous distribution of material properties. The design was subsequently manufactured using Laser Sintering and a simple cantilever bending experiment was conducted comparing the results of the functionally graded design to a fully dense implant and an implant made with a regular lattice structure, in order to provide a comparison of the stiffness provided by the different designs. The results of this study provide an insight into the potential for the application of the new method to improve the design of orthopaedic implants through the reduction of stress shielding while also minimising stresses at the interface.

Fabrication of 3-Dimensional Ceramic Parts by Micro-Extrusion: Feasibility Study

William Rowlands, Professor Bala Vaidhyanathan, Yumeng Chen, Robert Kay

Industrial alumina paste was additively manufactured via a computer numerically controlled 200um diameter nozzle micro-extruder. Cuboid samples 7.5mm x 7.5mm x 5mm were produced with varying parameters that found a speed of 1.2mm/s with a flowrate of 50ul/min to be optimal. Investigation of the process showed that the use of a fan to reduce drying time of extruded paste had mixed results. The surface smoothness of extruded samples could only be improved with loss of geometric structure – more vertical walls resulted in greater stair-stepping. With greater flowrates during extrusion the deposited layers would contain a greater volume so the structure loses its shape. With faster drying with fans or lower flow rates the stair-stepping effect is most pronounced although the sample shape is closely retained. There was also a 'twirling' effect from the extrusion which affected the accuracy of the deposition and was likely caused by the screw mechanism used to pump the paste through the nozzle. The high binder content required for the paste resulted in a porous sintered microstructure whilst the process resulted in a number of large voids within the sample too. Overall this process can produce non-conventional ceramic shapes but with a poor surface finish and poor tolerances up to +2mm extra. The green density of the paste is comparable to that dye-pressed from powder at 54% and a good sintered density of 98%.

Sintered samples extruded at 50µl/min dried in air (left) and with a fan (right).

PhD Projects

Hatim Cader
The University of Nottingham

Supervised by Professor Ricky Wildman, Doctor Chris Tuck, Professor Clive Roberts and Professor Morgan Alexander

PhD project: 3D Printing Solid Oral Dosages

This project involves the development of processes specifically for the 3D printing of solid dosage forms. The key focus will be on the optimisation of 3D printing based processes to scope out the range of qualities achievable (for example, in appearance, repeatability and speed), identify the relationships and trade-offs inherent in the process and achieve optimal process conditions. The form and distribution of the Active Pharmaceutical Ingredient (API) will be assessed in situ within the formulation. Mechanisms of drug release will be established for the different printed dosage forms. A focus will be to characterise and understand the possibility of crystal form control in the printed dosage forms and to evaluate potential in-line tools that could be used to monitor key parameters during manufacture by 3D printing.

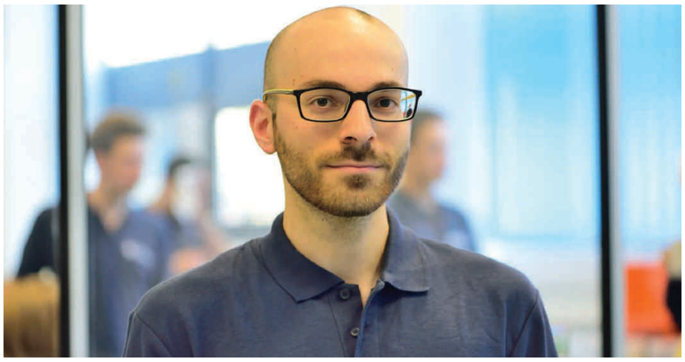
Rebecca Garrard
The University of Liverpool

Supervised by Doctor Chris Sutcliffe and Doctor Peter Fox

PhD project: Process Control of Electron Beam Melting

The proposed research is to develop an in-situ monitoring system to be used in metallic 3D printing, so part quality can be checked during manufacture; the user will be alerted to any defects that occur during processing, and the build process may be stopped if defects exceed acceptable limits. 3D printing is the process of building solid objects as a stack of 2D layers; this allows constant smart monitoring and control systems to examine every layer as it is built. This monitoring can be used to create consistently high quality parts, potentially reducing manufacturing costs by minimising post build inspection.

Metallic 3D printing is used for the production of components for the medical, aerospace and other industries. Customised orthopaedic implants are made, tailored to patients' measurements, using this technology. Well-developed process monitoring systems could allow the parts to be made at a reduced cost by allowing for the in-process validation of as-built components.



Carlo Campanelli
The University of Nottingham

Supervised by Doctor Chris Tuck and Professor Ricky Wildman

PhD project: Processing of High Performance Fluoropolymers by Additive Manufacturing

Polymers are used in different additive manufacturing (AM) techniques such as material jetting, material extrusion, binder jetting, vat photopolymerisation, sheet lamination, and powder bed fusion. In general, they are all suited for low-volume production/prototyping, complex geometry, bespoken parts, avoiding the losses of expensive materials (usually involved in traditional fabrication), rapid tooling/mould manufacture, and reverse engineering.

Only a small percentage of the available polymers on the market are suitable to be processed with an AM technique as particular material properties are required for each method. The lack of a diversified portfolio of materials is one of the main limitations of AM, thus research in this field is essential for the advancement of the technique and to reduce the gap between AM and the traditional manufacturing industry.

This project will focus on fluoropolymers, a particular family of polymers with outstanding properties such as high thermal stability (service temperature up to 300°C and down to -250°C), high chemical resistance, high purity, flame resistance, low permeability, low surface energy (non-stick), low dielectric constant (insulating), low refractive index, and good transparency to UV, Visible, and IR light. Any one of these properties can be found in other materials, but fluoropolymers are unique when two or more of these properties are required in the same application. Still, all these qualities come with a price, they require particular manufacturing processes, where some of these processes are highly wasteful and do not allow complex geometries. Special recycling systems are also required to reuse fluoropolymers. Therefore, as aforementioned, AM could decrease the amount of wasted material and simplify the manufacturing process.

Jonathan Gorecki
The University of Liverpool

Supervised by Doctor Chris Sutcliffe and Doctor Stewart Edwardson

PhD project: High Throughput Selective LaserMelting

Additive Manufacturing methodologies are beginning to achieve commercial uptake due to the advantages they bring in terms of part complexity, design freedom and material economy. Selective Laser Melting is one such technology which utilises a scanning galvanometer system to divert a process laser across a metallic powder bed creating complex 3D components.

In order for the uptake of this technology to continue, improvements in build speed and material microstructure coupled with a reduction in part defects and process uncertainties must be achieved. As affordable high power fibre lasers with excellent reliability become commonplace, their integration into AM systems should allow for some of the stated issues to be resolved. However, current optical configurations cannot readily accommodate increases in optical energy provided by these lasers. We propose the development of a proof-of-concept high power laser scanning Selective Laser Melting system to allow for increased build rates and novel scanning strategies aimed at improving surface finish and reducing component residual stresses.

Duncan Hickman
The University of Nottingham

Supervised by Doctor Ruth Goodridge, Professor Ian Ashcroft and Professor Richard Hague

PhD project: Selective Laser Melting of Functionally Graded Lattice Structures with Intelligently Distributed Material Density for Biomedical Applications

This research will develop new methods to produce novel, functionally graded lattice structures. The use of Additive Manufacture (AM) enables the creation of novel lattice structures that are difficult and expensive, or not currently possible, using conventional manufacturing methods. By varying the density of a lattice its mechanical properties can be varied across the structure to provide a more optimal design solution. This has applications in many research areas, notably in biomedical implant design, where it has been identified as a key means to reduce an issue known as stress shielding in orthopaedic implants. Stress shielding is a primary cause of implant failure, due to its detrimental effect on the remodelling of the surrounding bone. Therefore the research aims to improve the design of implants through developing new methods to produce functionally graded lattice structures in order to overcome these effects.

Orthopaedic implants are primarily made of metallic materials; therefore the research will focus upon design for manufacture using Selective Laser Melting (SLM). SLM is an AM process specifically designed for the processing of metals and has advantages over other metallic AM processes, e.g. Electron Beam Melting (EBM) and Direct Energy Deposition (DED), such as superior mechanical and surface properties. For biomedical applications SLM currently provides better component characteristics compared to both EBM and DED, and is already being used in implants. However, SLM can limit design freedom due to certain aspects of how the process operates, most noticeably the need for support material. The limitations in design freedoms will be incorporated into the design methodology to ensure the structures can be manufactured using SLM.

William Rowlands
Loughborough University

Supervised by Professor Bala Vaidhyanathan and Doctor Robert Kay

PhD project: Additive Manufacturing of Advanced Ceramics for Demanding Applications

This additive manufacturing project will investigate various Borgwarner products to potentially replace one or more component manufacturing methods with AM techniques. The primary goals of the project are to reduce the weight of a number of current automotive products while improving product functionality.

Sarah Kelly
Loughborough University

Supervised by Doctor Abby Paterson and Professor Richard Bibb

PhD project: Design Rules for Additively Manufactured Wearable Devices

The aim of this research is to develop robust design rules relative to the structural integrity of Additive Manufactured (AM) wrist splints, in order to bring the digitised splinting process closer to realisation. This research is to follow on from previous research carried out at Loughborough University by Paterson in 2013.

The main objectives of this research are to perform mechanical testing on samples made using low cost 3D printing (PLA, ABS) and high-cost Material Jetting (acrylic-based photopolymer Digital Materials) to gather local base data, analyse how build orientation affects the mechanical properties of an artefact (specifically splint designs), identify optimum geometric properties of pattern cut outs and wall thickness to mechanical strength ratio using FEA, validate findings and establish conclusions.

Adam Thompson
The University of Nottingham

Supervised by Professor Richard Leach and Doctor Ian Maskery

PhD project: Validation of X-ray Computed Tomography for Additive Manufacturing

This PhD project will entail a number of research topics, focussed around the validation of x-ray computed tomography (XCT) for the purposes of metrology for additively manufactured components. XCT is widely used in medical applications for volumetric scanning, but recent work is beginning to integrate the technology into the industrial setting as a precision measurement tool.

Additive manufacture is capable of producing complex internal geometries that are not measurable using traditional metrological techniques, and the volumetric scanning offered by XCT proposes a potential method of successful measurement of these geometries. This PhD is planned to contain the design of an XCT validation artefact for comparison between XCT and traditional measurement data, as well as similar comparisons of industrial case studies. The research will then likely address imaging and measurement of porosities and unsintered powders in additively manufactured parts, to verify the use of XCT for the measurement of production defects.

The project further aims to form part of an industrial XCT “Good Practice Guide” and the applications of this project are heavily focussed towards industry. The work produced during the PhD intends to forward the usage of XCT as an industrial metrological technique, which should lead to the production of more accurate parts and benefit many areas of manufacture.

Alexander Gasper
The University of Nottingham

Supervised by Doctor Adam Clare, Professor Ian Ashcroft and Professor Phill Dickens

PhD project: Laser processing of Titanium Aluminides for Additive Manufacturing of Aerospace Components

Titanium Aluminides offer great potential as a lightweight alternative to the Nickel-based superalloys currently used in many aerospace applications. This research will look into processing Titanium Aluminides through the Direct Metal Deposition process to produce near-net shape aerospace parts. The research will also investigate the capabilities of functional grading, Oxide Dispersion Strengthening, and the ability to embed sensors within components during processing.

Nicholas Southon
The University of Nottingham

Supervised by: Professor Richard Hague, Professor Ian Ashcroft and Doctor Ruth Goodridge

PhD project: A Predictive Tool for Material Suitability for Polymer Laser Sintering

Polymer Laser Sintering is the most widely used Additive Manufacturing process in industry, but almost all use is with either nylon 11 or 12. It is also recognised that the lack of materials, measured both in quantity of options and their quality, is one of the main barriers to the more widespread adoption of the process in industry. Improved materials for Laser Sintering could make Laser Sintered parts a possibility in a wider range of more demanding applications.

The literature shows that there is no single analytical technique which definitively shows how a polymer will perform in the Laser Sintering process. However, models based on computational fluid dynamics (CFD) for the related processes of Laser Melting and Electron Beam Melting have been developed and demonstrate the potential for extension to modelling polymer laser sintering.

This project aims to develop a predictive tool for Laser Sintering using CFD simulations. This requires two strands, one practical and one computational. The latter requires the development of software since no commercial or free software with the required capabilities exists. The former requires the development of a measurement setup that can measure the fluid properties of the polymer melt. These properties are required for input into the simulations, and it is rare for them to be well characterised for a large range of polymers. The desired goal is to predict the suitability of arbitrary polymers for Laser Sintering, and therefore potentially find a novel polymer to improve the material selection available for Laser Sintering.

CDT equipment

The CDT was awarded a capital equipment grant in order to purchase new laboratory equipment for use by CDT students across the four partner institutions and other CDTs based at The University of Nottingham. This equipment forms part of the resources available to all students within the CDT as well as those currently studying on standard PhD programmes.

The new equipment was selected to complement existing equipment and capabilities, and to add to the capacity of equipment to ensure timely use for the students.

Much of the new equipment will enable our students to gather more in-depth data, as well as providing platforms for research outside of the normal environment. The University of Liverpool has purchased equipment to enable material-laser interactions to be more discretely controlled outside of standard selective laser melting equipment thus enabling the researcher to understand the mechanism of powder melting more thoroughly. It will also allow process researchers to study the optical delivery of high power laser radiation. The equipment installed at Newcastle University includes 3D scanning for geometry capture and X-Ray Fluorescence for elemental analysis of powder and other forms of materials. The equipment delivered to The University of Nottingham complements an existing capability in inkjetting (Dimatix) and significantly enhances a suite of materials characterisation equipment already available. Loughborough University has added inverted microscopy capability to their equipment which enhances their ability to monitor in-situ reactions and materials changes during AM processing.

Equipment purchased

Newcastle University

- X-ray Fluorescence (XRF, Bruker S2 Ranger)
- Handheld 3D scanners and software

The University of Liverpool

- Renishaw Fusion Optical Systems
- SPI 1kW Laser
- Laser Beam Alignment
- Optical Beam Monitoring

The University of Nottingham

- Dimatrix Ink Jet System

Thermal Imaging Suite:
- Gas Chromatography Mass Spectrometer
- Differential Scanning Calorimeter (DSC) with photocalorimetry extension
- Fourier transform infrared spectrometer (FTIR) for use with DSC
- Dynamic Mechanical Analyser with humidity generation
- Thermogravimetric Analyser System

Loughborough University

- Inverted Microscope

Industrial Partnership

In the initial funding bid to EPSRC, 25 industrial companies offered letters of support to the CDT. Since then, this has increased to more than 35 interested companies, at least 19 of which are supporting one or more projects across cohorts one and two.

Industrial involvement offers an invaluable addition to the CDT experience. It ensures that the PhD projects are relevant to industry and capable of having a significant impact on the way products are currently manufactured. Students will complete a three-month internship with their project sponsor, giving them the opportunity to understand the industrial environment that their research will directly impact.

For Industrial partners, the benefits of being involved in the CDT include access to a high calibre graduate with the time and skills to concentrate on an industrial project, access to academic AM specialists and access to University facilities. It is a cost-effective method of funding research and helps Industry to develop strategic links with the University.

The CDT's advisory board has a strong industrial presence, with membership from a range of AM relevant companies. Further details can be found on page 23.

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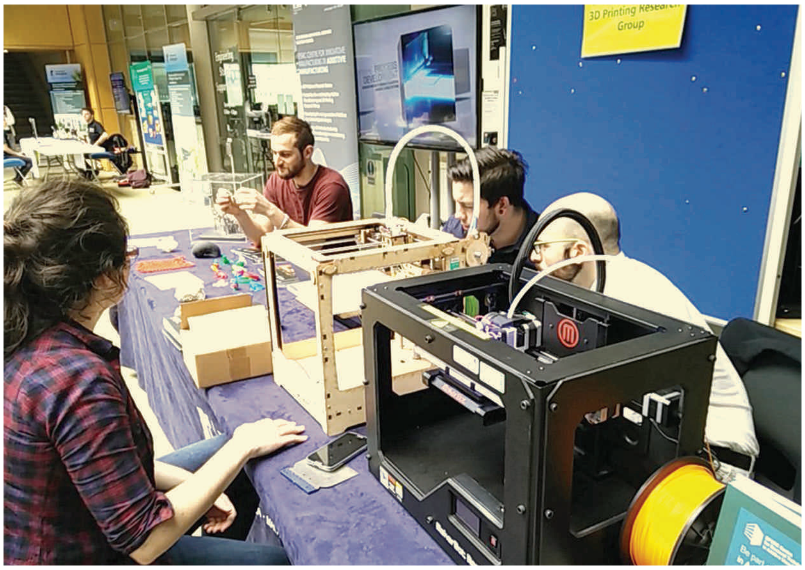
Laboratory technician Mark Hardy sieving metal powder.

International Experience

All CDT students attended the 2015 Solid Freeform Fabrication (SFF) Symposium held in Austin, Texas (10-12 August 2015). Participation in this conference formed part of the International experience module which is a compulsory training element of the programme. All students presented findings of their Group Grand Challenge research as poster presentations, with one student, Alexander Gasper, also making an oral presentation on his individual project research.

The SFF Symposium is held at one of the founding universities for 3D Printing, The University of Texas in Austin, where the technology laser sintering was invented. SFF is currently in its 26th year and the symposium attracts researchers and students from around the globe to a principally academic focused meeting, enabling students and academics to network, discover and socialise with those most closely related to their discipline. International meetings such as SFF are an important part of understanding the research landscape that researchers exist in and enable future collaborations and relationships as well as acknowledgment of competing work and groups. The CDT students were fully immersed in this culture for four days with papers being delivered across five parallel tracks each day, including work on software, modelling, simulation, materials, processes and applications.



CDT students preparing the 3D Printing stand at May Fest 2015.

Outreach Activities

May Fest 2015

May Fest is the The University of Nottingham's community open day, packed full of scientific displays, interactive activities and topical debates, and brings a wide range of local people to engage in the University's research activities. The CDT hosted a stand at May Fest 2015, which featured a number of desktop additive machines producing small toys throughout the day for the younger visitors. Members of the CDT spent the day discussing additive manufacture and the CDT with members of the public of all ages, providing interesting information about AM and 3D printing, and informing those interested in the technologies of how to get involved.

"It was great to be helping out with this event because it gave us an opportunity to engage with the local community and promote our research, as well as developing our skills in discussing our work with a wider audience".
Adam Thompson, CDT researcher.

NUAST

In June 2015, the CDT played host to the Nottingham University Academy of Science and Technology (NUAST). A total of 40 students, aged 14-15 took part in this event which involved an introduction to the work being carried out by our research group and a brief overview of what each of the CDT students were undertaking for their PhDs. After this they broke into smaller groups, where topics like materials, design, applications, sustainability and process limitation were discussed.

The next day the students from NUAST came back for a tour of the labs. This allowed the groups to link what we discussed with the actual machines and allowed the students to see what the daily life of a researcher might involve.

"It was great to be part of this activity as it allowed us to give the students an insight into the world of The University of Nottingham with the hopes that one day they might follow in our footsteps".
Sarah Kelly, CDT researcher

Looking ahead

The CDT is proud of its achievements and the hard work of its students during the first year of operation. Preparations for the next student intake has been ongoing for some time and the CDT looks forward to welcoming cohort 2 in October 2015.

Throughout 2014-15, the CDT has received invaluable feedback from current students. The student feedback panel was set up specifically for this purpose, and as a result, next year's programme should deliver an even better CDT experience for all.

The research currently being conducted by students is already showing promise with some students making presentations at international conferences before the end of their first year. The CDT therefore has very high expectations of quality publications, further collaborations with industry and real impact in the future.

Watch this space!

From left to right Carlo Campanelli, Duncan Hickman, Hatim Cader, William Rowlands, Sarah Kelly, Jonathan Gorecki, Rebecca Garrard, Alexander Gasper.

Management Team

Doctor Chris Tuck
CDT Director
The University of Nottingham

Professor Ian Ashcroft
CDT Programme Director
The University of Nottingham

Doctor Daniel Engstrom
Co-investigator
Loughborough University

Professor Kenny Dalgarno
Co-investigator
Newcastle University

Doctor Chris Sutcliffe
Co-investigator
The University of Liverpool

Current supervisors and other key individuals

Romina Davoudi	CDT Centre Manager	The University of Nottingham
Professor Morgan Alexander	Supervisor	The University of Nottingham
Professor Richard Bibb	Supervisor	Loughborough University
Doctor Kate Black	Key contact	The University of Liverpool
Doctor Adam Clare	Supervisor	The University of Nottingham
Professor Phill Dickens	Supervisor	The University of Nottingham
Doctor Stuart Edwardson	Supervisor	The University of Liverpool
Doctor Daniel Engstrom	Key contact	Loughborough University
Doctor Peter Fox	Supervisor	The University of Liverpool
Doctor Ruth Goodridge	Supervisor	The University of Nottingham
Professor Richard Hague	Supervisor	The University of Nottingham
Doctor Robert Kay	Supervisor	Loughborough University
Professor Richard Leach	Supervisor	The University of Nottingham
Doctor Ian Maskery	Supervisor	The University of Nottingham
Doctor Javier Munguia	Key contact	Newcastle University
Doctor Abby Paterson	Supervisor	Loughborough University
Professor Clive Roberts	Supervisor	The University of Nottingham
Professor Bala Vaidhyanathan	Supervisor	Loughborough University
Professor Ricky Wildman	Supervisor	The University of Nottingham

Research fellow Doctor Marco Simonelli operating a selective laser melting system (Realizer)

Advisory Board members

Doctor Will Barton	Independent Chair
Doctor Karen Brakspear	EPSRC
Gerrard Davies	EPSRC
Professor Kenny Dalgarno	Newcastle University
Doctor Ian Halliday	3T RPD Ltd
Doctor Brian Henry	Pfizer
Professor Jean-Pierre Kruth	KU Leuven
Professor Graham McCarthy	Independent CDT Co-director
Simon Scott	Renishaw PLC
Professor Will Stewart	Independent industrialist
Robin Wilson	TSB

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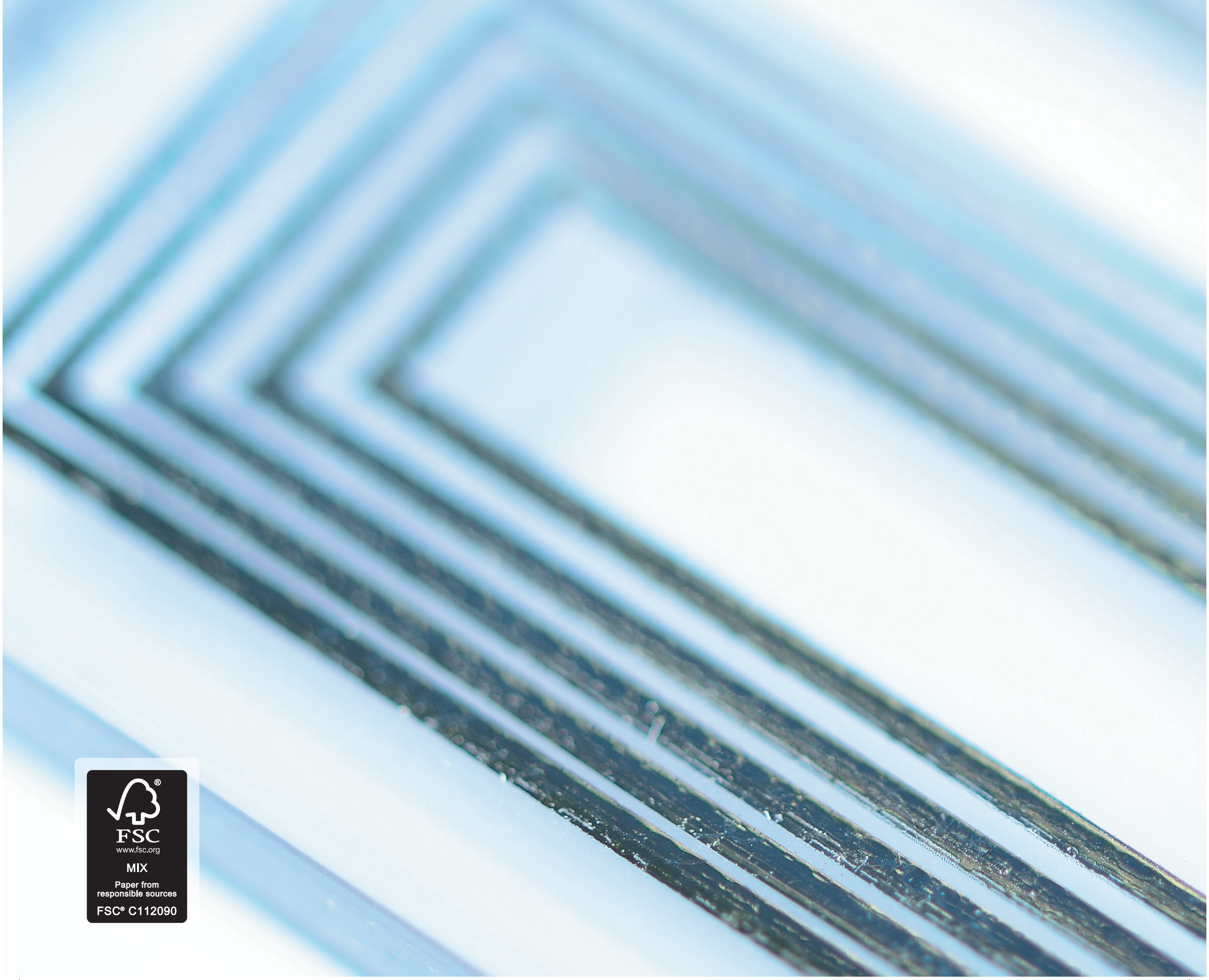

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