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

Annual Report 2015-16

UNIVERSITY OF LIVERPOOL

Loughborough University

Newcastle University

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 Centre of Doctoral Training (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 sponsored by an industrial partner, ensuring the research conducted within this CDT is highly relevant to industry. These, combined with financial support, will allow the CDT to provide specialist AM training to PhD students until 2022.

The first two cohorts of the CDT were welcomed in October 2014 and October 2015. As part of the training programme, students have covered in-depth topics, including materials used for AM, computer-aided engineering for AM, and commercial 3D printing. In addition, they have 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 taking part in outreach activities.

During the past two years, cohort 1 and 2 students have successfully completed their credit requirement and have progressed into the second and third year of their study. They are now working towards their defined PhD project, but will continue to complete taught modules and transferable skills training throughout the remainder of their studentship.

Table of Contents

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Update on the Centre's Progress

The second year of operation for the CDT in AM and 3D Printing was a big one. Building on our successful first cohort of students, we welcomed 20 students to the CDT in October 2015, building on our aims to develop a bespoke programme of challenging modules relevant to the students' research and providing experiences to develop a research ethos encompassing integrity, respect and collegiality.

The CDT has undergone a number of changes to enhance the experience for all the cohorts, including the establishment of a dedicated AM laboratory to support practical work. In addition, the CDT has established a knowledge sharing network through a CDT and PhD seminar series to help understanding and provide a collegiate environment to problem solving. This has been coupled with a newly instigated seminar series for esteemed academics and industrial figures to discuss their take on this growing industry.

The executive team, comprised of representatives from the four partners, has seen changes with the addition of Dr Daniel Engstrom at Loughborough University, who brings with him a new vision for AM applications. Additionally, our supporting academics and supervisors at all of the partner institutions have grown significantly to deliver against the CDT's objectives and enabling the taught programme to be both innovative and well-informed. These include the provision for new modules and supervisors from different fields offering a new perspective to students.

As with cohort 1, I must congratulate cohort 2 in their significant academic and professional growth over their first year; they have contributed and added much to the learning experience, supporting each other and participating in a number of outreach events to capture the imagination of younger generations in the world of AM. 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.

Once again, recruitment maintains its strength with a further eight projects already identified for the third cohort. Each project, supported by an industrial partner, illustrates the validity of the CDT programme and highlights the added value that PhD training can have on businesses from a wide and disparate range of sectors. We look forward to working with cohort 3 and a new set of industrial sponsors and maintaining our impetus for the years ahead.

Professor Chris Tuck
Director of the EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D Printing

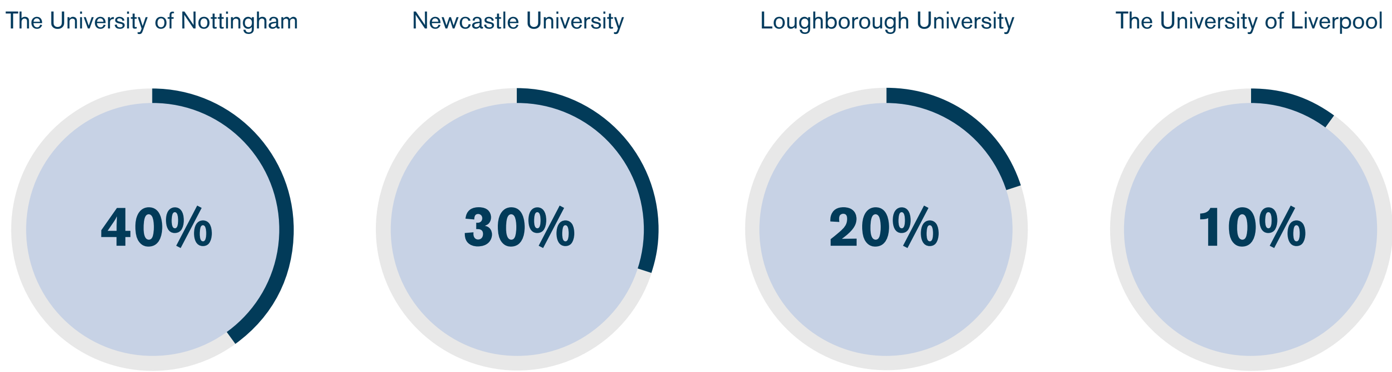
Cohort 2 Recruitment

The student intake for cohort 2 was considerably higher than the first cohort of 10 students. In the true multi-disciplinary nature of the Centre, our second cohort of 20 students are from Physics, Chemistry and Engineering backgrounds.

Across the CDT's academic partners, two University of Liverpool, four Loughborough University, six Newcastle University and eight University of Nottingham students were recruited.

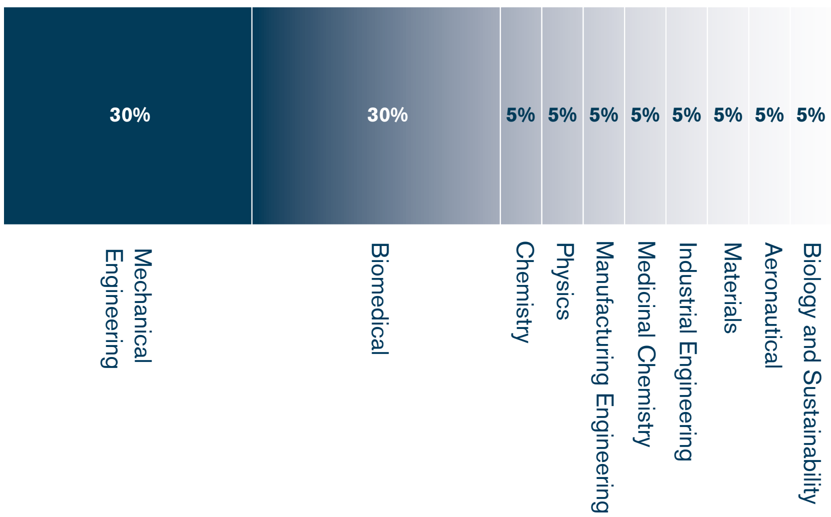
Cohort 2 Student demographics

Home institution

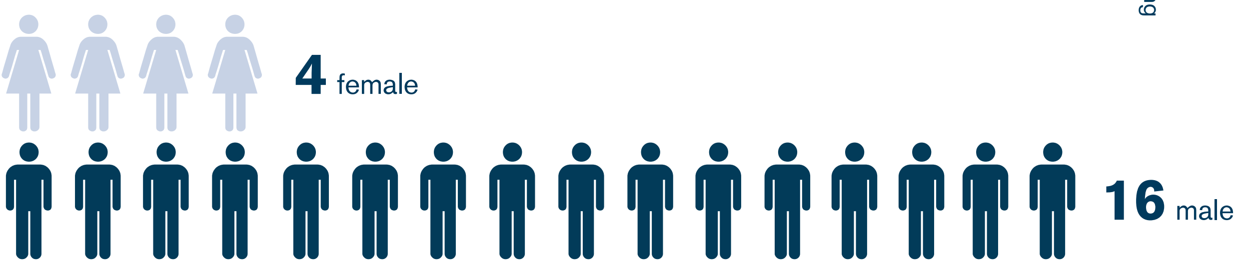


Fee status

First degree discipline area



Student gender ratio



Cohort 2 – Student Profiles

Lewis Newton
The University of Nottingham

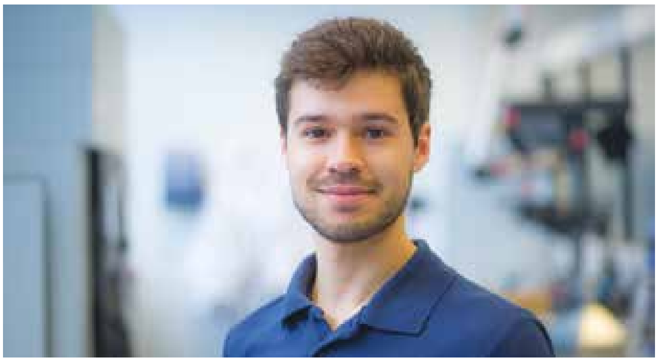
Project title: Development of Methods for Measuring the Surface Topography of Additive Manufactured Parts

Methods will be developed to measure the surface topography of additive manufactured parts. Commercial measurement techniques will be used, such as stylus profilometer, focus variation, confocal microscopy, interferometry and electron microscopy. This is to assess the appropriate measurement spatial bandwidths to be used and appropriate parameters to control manufacturing or correlate to function. A number of industrial case studies will be investigated to formulate ways to control the surfaces during manufacture and finishing.

Nathalie Sallstrom
Loughborough University

Project title: Directed Neural Cell Growth in Additive Manufacturing Systems for Applications in Next Generation Prosthetics

At Loughborough University, research in the field of next generation prosthetics and the additive manufacturability of these devices is being conducted. One of the objectives of this work is to establish an interface between the human body and the prosthetic device. This essentially aims to connect the prosthetic device to the wearer's nervous system, which will provide both signals from and to the wearer. This will improve the wearer's control of the prostheses since the device would be thought controlled, like a natural limb. Furthermore, this project will be focusing on the bridging from a residual nerve to the electrode/prosthetic interface. To do this, the neurons need to be guided and directed effectively towards a surface. This project will first focus on conditions required to direct neuronal growth and subsequently to adapt current AM systems to successfully manufacture the neural guide.

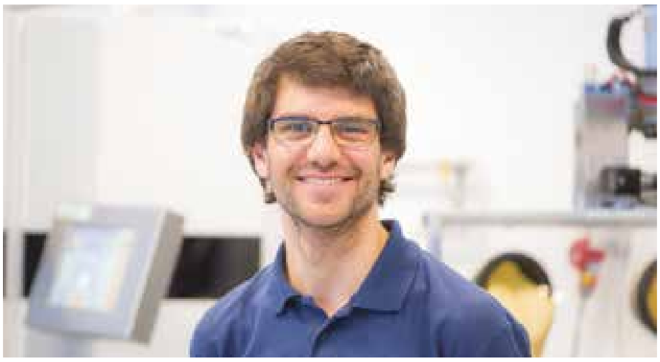


Yazid Lakhdar

The University of Nottingham

Project title: Additive Manufacturing of Advanced Ceramic Materials

This project aims to use colloidal processing and AM technologies, such as inkjet printing and binder jetting to develop the routes to controlled-density and fully dense advanced ceramic parts. The project will also evaluate the use of laser sintering to further the understanding of its use on advanced ceramic materials. By firstly developing the processing routes and then exploiting the materials they yield so as to better understand the potential engineering application, the project aims to make advanced ceramic materials much more accessible in the AM world. Using alumina as the starting point, the project will develop the techniques and explore the equipment and characterisation required to deliver material for testing. AM of non-oxide ceramics will also be investigated, as the project develops a broader understanding of the processing techniques most applicable to each type of ceramic material.



Xabier Garmendia

The University of Liverpool

Project title: Functional Coated Powders for Selective Laser Melting

The project will start once the powder recirculation rig is finished at Renishaw Stone facilities and shipped to the University of Liverpool. The rig will need some structural aluminium profile reconfiguration in order to be shipped and located at its final destination. Previous to the initial test on the rig at Liverpool, I will be trained on the PLC software to be the person operating the machine. After the installation of the machine at Liverpool, some initial recirculation test will be run, until the machine is perfectly set up. Later, a long period will be used for the design and implementation of an ALD chamber in the powder recirculation rig. At this stage, various chamber configurations will be tested for optimising the process. Finally, some ALD thin film coating on Al alloys will be tested on the rig and the results will be characterised.

Sam Morris

The University of Nottingham

Project title: Process, Microstructure and Property Relationships in Inconel 718 Produced by Selective Laser Melting

High thermal gradients and cooling rates are present in the selective laser melting (SLM) process, resulting in the as-built microstructure of SLM parts being drastically different to that of parts produced by conventional methods. Applying post-processing techniques developed for use with conventional methods to SLM parts may therefore not result in the desired final structure and mechanical properties. Work is needed to better understand the influencing conditions on the as-built structure and its response to post-processing. This project addresses areas to this end for Inconel 718 by:

- Comparing the as-built structure of SLM IN718 to traditionally manufactured IN718
- The effect of composition on the structure of SLM parts.
- The structural response of SLM IN718 to heat treatments to determine an optimal post-process treatment to achieve a desired final structure
- Mechanical testing of parts as-built and post treatment

Sam Catchpole-Smith

The University of Nottingham

Project title: Selective Laser Melting of Lattice Structures for Heat Transfer Applications in Gas Turbine Engines

Working in partnership with Siemens Industrial Turbomachinery, the research is based upon the development of nickel alloys for use in high temperature and high performance environments, specifically for industrial gas turbines. Nickel alloys with a high percentage of aluminium and titanium are susceptible to cracking if the thermal profile during manufacture is not carefully controlled. This is a particular problem for the SLM process due to the very high cooling rates involved during material deposition. Hence, careful consideration of the process steps and how the thermal profile will affect the material in question is required. Commercially available machines have little room for flexibility in this regard and so alternative techniques, such as altering the laser scan strategy, are necessary to enable manufacture in these high performance alloys. Once the processing steps have been optimised and verified, more complex geometrical parts can be designed and tested. Lattice structures, particularly for thermal transfer, have been discussed for further work.

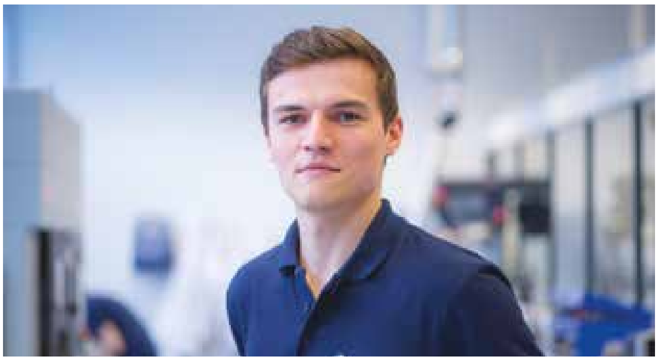
Babis Tzivelekis

Newcastle University

Project title: Polymer-based Additive Manufacturing for Microfluidic Diagnostic Devices

Microfluidic technology has attracted research community interest due to simplified fabrication technique via additive manufacturing (AM), which became more accessible to a wider range of research disciplines. However, AM requirements that most microfluidic devices impose (and issues related to the nature of AM processes), constitute a considerable challenge in an attempt to widely employ AM for microfluidic devices. This project attempts to study the performance of different polymer-based additive and conventional manufacturing techniques in microfluidic cartridges fabrication.

Building experiments will be exclusively focused on on-chip nucleic acid amplification microfluidic chips with embedded fluoresence detection function. Chosen materials can be categorised in thermoplastic and thermosetting materials with enhanced functional properties for thermal stability, transparency and biocompatibility in terms of microfluidic DNA amplification and fluorescence detection. Testing parts will be produced to evaluate achievable accuracy and building time of each process, while surface modification techniques will be investigated. The aim of this project is to build a low-cost, disposable, functional microfluidic chip for nucleic acid amplification and optical detection function, exploiting design freedom of AM systems, while maintaining desired requirements.



Joseph Dudman

Newcastle University

Project title: Bioprinting Osteoarthritic Joint Co-Cultures

This project will focus on the development of reliable procedures to print precise numbers of cells resident within the articular joint in order to manufacture co-culture models of osteoarthritis. Following characterisation and optimisation, these models can then be used to replicate the pathophysiology of osteoarthritis to further understand disease progression and screen potential drug candidates in vitro.

The optimised printing technology and co-culture conditions may also be used to generate living tissue from patient cells that can be transplanted into the body within next generation surgical procedures, such as autologous chondrocyte implantation.

Kegan McColgan-Bannon

Newcastle University

Project title: Synthesis of Natural/Synthetic Hybrid Polymers

Using synthetic techniques to modify the structure of currently available biocompatible polymers to enhance the surface characteristics for cellular adhesion. Current focus is the synthesis of PCl-collagen hybridised material, performing analytical groundwork (physicochemical, mechanical and cell work), and developing a methodology to take the materials from ground state to a filament that can be extruded into a scaffold for bone tissue regrowth.

Other targets of interest are PHBV-Collagen hybrids that have shown promise as replacements for tendon tissue. Similar to the PCl-Collagen work, a synthetic route will be established and a considerable amount of analytical work will be performed to establish the viability of the material in animal/medical trials.

Priscila Melo

Newcastle University

Project title: Binder and Powder Blend Formulation for Porous Apatite-Wollastonite Implants

The main goal of my PhD project is to optimise the printing and processing of Apatite-Wollastonite/Maltodextrin (AW/MD) powder blend scaffolds. A primary approach to the project was studying the influence of moisture on Maltodextrin powders in the first year's individual project, alongside the study of thermal properties of this material under different environments. This study continues further on, with the study of particle size and shape influence on packing and part density of the AW/MD printed parts, before and after sintering. New powder formulations will be worked out to optimise the powder for bioapplications and AM. In a further stage, the produced scaffolds containing the optimised material will be tested in vitro as a platform for bone tissue regeneration. A study on a new method to process GTS's AW powders, in order to make them commercial for AM purposes, completes my project goals.

Liesbeth Birchall

The University of Nottingham

Project title: Quantum Dot – Silicone Nanocomposites via Reactive Inkjet

All current AM used for silicones produce elastomers from viscous precursors which react in situ. However, the strength of elastomers which can be produced via standard inkjet is severely limited by two main factors. Long polymer chains are required for good elastomers, which means viscous reagents beyond the operating range of inkjet printing. Additionally, silicone elastomers are intrinsically weak compared to organic rubbers, and reinforcing fillers are employed in industry; a strategy towards good particle loading in inkjet is therefore of interest. Silicone resins are strong without the need for high viscosity reagents, and are relatively unexplored within inkjet. Fluorescent nanoparticles require low loading for functionality and complement the optical clarity of silicones. This project aims to print quantum dots in silicone matrices via reactive inkjet, exploring MDTQ composition for polymer properties and suitable solvent systems to aid dispersion. These nanocomposites would be developed for application in sensors or electronic displays.

Greg Murray

Loughborough University

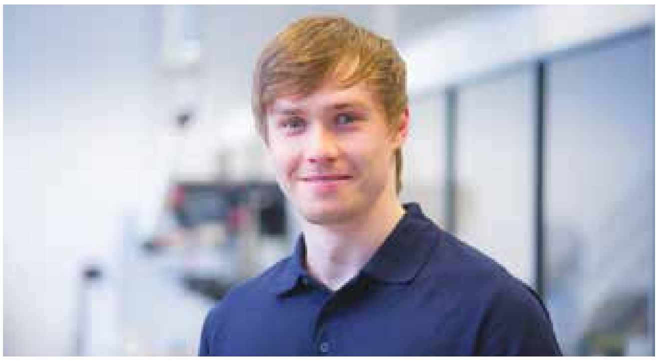
Project title: Manufacturing of ‘Smart’ Footwear Components

‘Smart’ footwear products are those which meet the current standards and needs of the industry, while also providing some additional functionality beyond the basic criteria. This project will consider the feasibility of using various manufacturing methods, including 3D printing, for the efficient manufacturing of ‘smart’ footwear parts which include embedded functional materials that respond to external stimuli, such as temperature, mechanical stress, light intensity, etc. The project will comprise of investigations into material properties and formulation, as well as different processing opportunities. Integrated manufacturing will also be a prime consideration. Screen printing, tape casting, and 3D printing methods in conjunction with laser/microwave/infrared/UV processing will be examined for the fabrication of these multilayer structures.

Niloufar Hojatoleslami
Newcastle University

Project title: Additive Manufacturing of Bioactive Composite Scaffolds for Osteochondral Implants

The general aim of this PhD project is to make bioactive composites for osteochondral implants. This is quite a broad aim and requires some particular subjects to be addressed, developed and optimised. A number of AM techniques will be exploited throughout the project to determine the best method of acquiring the required scaffolds, and to incorporate biomaterials and cells together to develop the osteochondral implant. The scaffold material will be developed significantly throughout the project to ensure optimum conditions for cell growth and development. Mechanical testing and in vivo testing of materials and printed scaffold will be performed throughout the project. Many new skills will be acquired and developed which will aid successfully fulfilling the overall aim.



James Smith
Loughborough University

Project title: Investigation into the Additive Manufacture of Intramedullary Caps to Provide Mechanical Support & Alleviate Soft Tissue Pain in Transfemoral Amputees

Unlike knee and hip arthroplasty, transfemoral implants have received limited attention, yet patients requiring such surgery continue to swell. This is primarily due to cardiovascular disease, diabetes and osteoarthritis becoming prolific amongst ageing and growing populations. Prominent complaints of such trauma include residual limb pain and extensive skin breakdown caused by appositional bone growth. In order to alleviate pain presently, osseous tissue must be mechanically removed (filed) which requires additional surgery, money and can lead to infection. It is therefore proposed to design and manufacture an implant which is able to be surgically integrated into the patient, reducing pressure and minimising appositional bone growth. 3D Printing and AM technologies could offer the potential to manufacture advanced, designer implants that are able to provide a better quality of life.

Michael Ward
The University of Liverpool

Project title: Additive Manufacturing of Life-like Prosthetics

Traditional engineering techniques, such as material characterisation, numerical analysis and manufacturing will be combined with social factors in a medical setting to improve prosthetic design and production by 3D additive manufacturing. The project goals will incorporate:

- Developing biocompatible materials and macro-level prosthetic structures based on known anisotropic, hyper-elastic and viscoelastic biomechanical properties of skin. Therefore optimising (a) interfacing with the patients natural features, (b) tactility, (c) deformation under normal physiological conditions; and consequently, the prosthetics biomechanical mimicking abilities
- 3DMD camera systems (IPHS) will be used to obtain colour-calibrated high-resolution 3D facial images and 3D numerical models which will be used numerically assess the effect of material and structural variation against suitability criteria
- Materials need to be measured, and their colour optimised, to match human skin tones and refractive properties based on the existing multi-ethnicity skin tone database
- Tolerance limits for the prosthetics acceptability will be established using standard appearance metrics and end-user based qualitative evaluation

Iliya Dimitrov
Loughborough University

Project title: Additive Manufacturing for Quantum Systems

The goal of this project is to create a 3D printer that will serve as laboratory equipment for exploring micron and sub-micron systems. Such a machine can benefit researchers by offering an accurate and affordable way to reproduce theoretical models. Electronics has brought a revolution to human technology and its limits continue to be explored. While trying to exploit the already observed quantum phenomena, such as particle-wave duality, entanglement, etc., reproducing complicated three-dimensional features is crucial. The obvious advantage that 3D printers can provide is further underlined by the relatively low cost for manufacturing individual items. Research-tailored 3D printers can serve teaching purposes, as students usually need to break their equipment to understand how it works. Another desired output of the project is the ability to restore damaged RLC-circuits in teaching laboratories. The question therefore is how to utilise AM in research facilities without shifting their focus to manufacturing.

Lars Korner
The University of Nottingham

Project title: Development of XCT Techniques to Measure the Internal Dimensional Properties of Additive Manufactured Parts

Due to the large design freedom offered by AM, conventional metrology systems are being challenged. X-ray computed tomography (XCT) has been identified as a potential metrological system, which allows the measurement of a part's geometrical conformity, while also analysing some aspects of the parts material, such as porosity and inclusions. A special focus of this project is the measurement of internal geometries, as these geometries are feasible using AM. This project aims to use information-rich metrology approaches to improve the XCT process. The area of research currently explores the measurement chain of XCT to identify the possible stages where information-rich metrology can improve the performance of the system or of the software.

This project is part of the CDT in additive manufacture and 3D printing, and it is sponsored by Nikon Metrology.

Vicente Rivas-Santos
The University of Nottingham

Project title: Design for Metrology in Additive Manufacturing

The aim of the project is to research the use of the capabilities of the AM processes to include reference geometries in the fabricated pieces to help their dimensional metrology characterisation. These references can include datum references, parallel planes and other markers to clearly identify the dimensions of the piece. These kind of designs are already in use in conventional manufacturing processes in the automotive, aerospace and semiconductor industries, but no adaptation has been done to AM. The dimensional metrology is an important part of quality control, as it thoroughly checks product characteristics against specified dimensions and tolerances.

Mahid Ahmed

Newcastle University

Project title: Bioprinting Skin Equivalents for Toxicity Testing

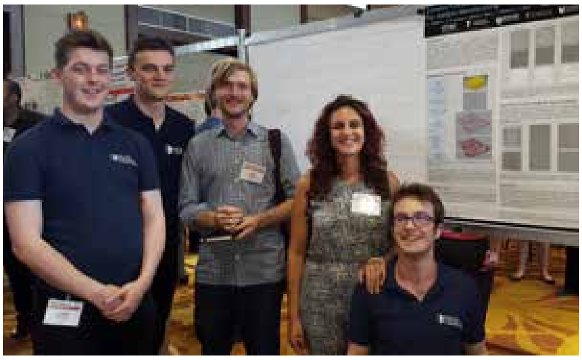
One of the common limitations of medical research is the availability of tissue for in vitro studies. Human tissue has many research applications, ranging from the modelling of diseases to testing drugs at pre-clinical trial phases. The use of human tissue in vitro can provide researchers with an insight into human responses and can therefore be used as a suitable alternative to animal testing. Conventionally, tissue equivalents are developed for use to overcome the lack of available tissue. However, traditional tissue engineering methods for tissue equivalents can often be lengthy procedures which may lack compositional complexity and scalability.

This project aims to reliably bioprint human skin equivalents while maintaining tissue viability. The bioprinting of human tissue equivalents will provide researchers with a method to scale up current tissue engineering of the skin equivalents for the application in vitro toxicity testing of chemical compounds.

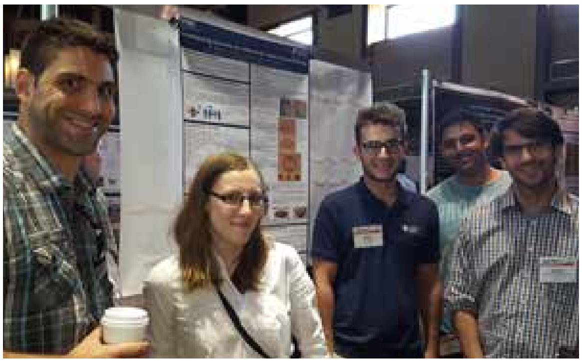
International Experience MM4INE Module

This module provides an opportunity for the students to understand the scope of AM in an international context by attending the Solid Freeform Conference in Austin, Texas. The conference was held in August 2016 with cohort 2 students presenting their posters from the MM4GGC (Group Grand Challenge) module, with one resulting in publication.

This is a two-part, 10-credit module with one international trip scheduled for year one and year two of the CDT studentships. To obtain the credits, students must submit a 2000-word essay for each international conference, which will be assessed and moderated by the academic colleagues in the Centre.

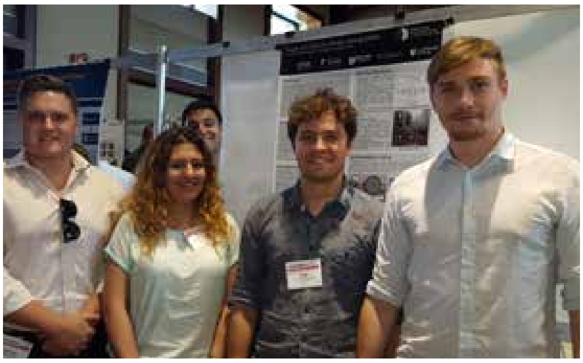


Enhancing Tissue Scaffolds via Fabrication of Normally Distributed Surface Features onto Inkjet Printed Substrates using 2-Photon Lithography



Investigating Chocolate as a Material for Additive Manufacturing

Inkjet Printed LFP and LTO Electrodes for Llithium Microbatteries

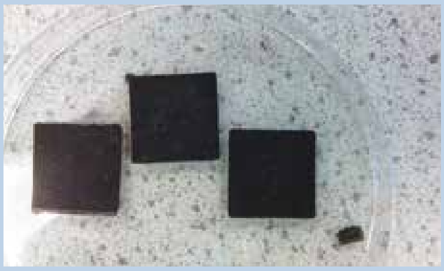


Designing and Building a Custom Binder Jetting Printer

Cohort 1 – Student Project Updates

Carlo Campanelli

Processing of High-Performance Fluoropolymers by AM



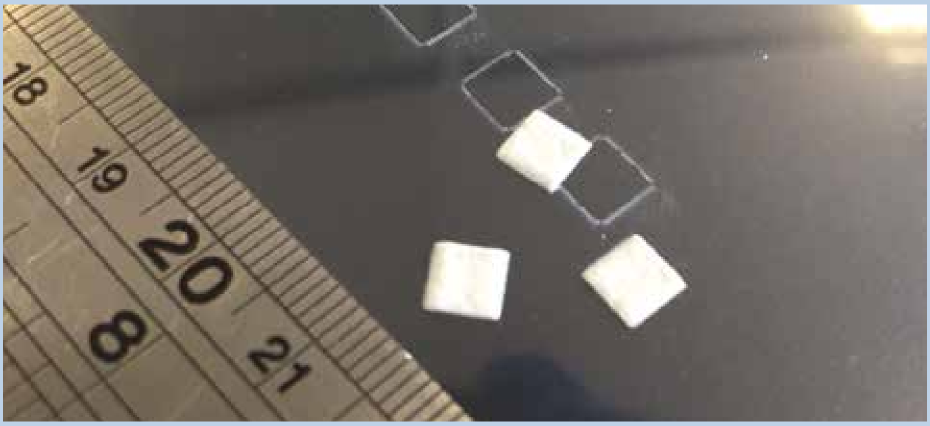
Only a small percentage of the available polymers on the market are suitable to be processed with an AM technique, as particular material properties are required for each method. The lack of a diversified portfolio of materials is one of the main limitations of AM. Thus, research in this field is essential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

This PhD focus on fluoropolymers, a particular family of polymers with outstanding properties, such as high thermal stability (service temperature down to -250 °C and up to 300 °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.

Two grades of PCTFE have been used; one grade, named NEOFLON M-400H PCTFE Granular Molding Powder, produced by Daikin and provided by my industrial sponsor Fluorocarbon, having high molecular weight (ZST ~350) and big coarse particles, and a second grade bought from Chemical Point (a German company) having lower molecular weight (ZST~128) and fine particles. PCTFE does not decompose at the chamber temperature (guaranteeing a high ZST, namely high molecular weight and potential for high physical properties), and the processing windows are wide enough to avoid curling and distortion (processing window similar to PA12, which is the most performing polymer for LS), and it shows a high absorbance in the wavelength of the CO_2 laser. Still, while the Daikin powder is too big to be processed, the Chemical Point powder, despite the low surface energy and non-stick ability of fluoropolymers, shows a not ideal powder flow due to the small particle size distribution. Still, this flow issue has been solved by the addition of a small % of carbon black and a series of small test parts have been successfully laser sintered in an EOS Formiga P100. The polymer powder has a particle size distribution of less than 1 μm and, although this is less than the recommended value (~50 μm), the success of laser sintering PCTFE can illustrate the potential of sintering a wider range of polymers outside the recommended parameters.

Hatim Cader

Inkjetting of Solid Oral Dosage Forms Processing of High-performance Fluoropolymers by AM



This investigation will involve the manufacturing of solid oral dosage forms (more commonly referred to as tablets) through the AM method of inkjetting. The project will take advantage of inkjetting's numerous advantages, including creating precise complex geometries and printing multiple inks at the same time. For the pharmaceutical industry, this can translate to highly precise and accurate drug loadings and customisable tablets with a controlled drug release, leading to the prospect of personalised medicines and therapies. The overall aim of this PhD will be to successfully inkjet a reservoir device dosage form, where a polymer-drug matrix is surrounded by a release controlling membrane.

Over the last year, two inks have been formulated; the polymer-drug core, which on its own would be rapid release dosage form, and the membrane formulation. The development of these two inks primarily consisted of investigating its surface tension and viscosity - two key properties for successful and reliable jetting of material. Once appropriate properties of the ink were achieved, printing was carried out using the Dimatix Materials Printer DMP-2850. After printing the entire dosage forms, drug release was characterised through dissolution tests. Current work involves further investigating the actual mechanism of drug release and how it can be controlled, through the use of modifying materials or the printing process.

Future work will involve investigating different materials and drugs for new inks and the development of a modelling programme, which can predict the release of a specific drug through a specific material taking into account the properties of the drug and dosage form. The programme can act as part of a manufacturing system, where drug delivery devices with a pre-programmed release can be printed to illustrate the potential of sintering a wider range of polymers outside the recommended parameters.

Alex Gasper

Advanced Powder Feedstock for Metal Additive Manufacturing

My project has taken twists and turns on its journey to where it is now. My project was initially an investigation of Direct Metal Deposition of Titanium Aluminides with TWI as a sponsor. Work for this project from my first year led to a publication in the *Journal of Materials Processing Technology*. TWI pulled out and my sponsor company then changed to Oerlikon Metco. The project direction then moved to 'AM processing of difficult to cast alloys' with more focus on crack susceptible nickel superalloys and leaning more towards processing with selective laser melting. I felt the project was veering towards an area which was preventing me from utilsing my skills and knowledge in the best way. I then steered the project towards a focus on material systems and processing for nickel superalloys for selective laser melting, and this is the current direction of the project. Initial characterisation of bulk powder properties of these materials has been undertaken and the future direction is in investigating new material systems and effects of processing.

Duncan Hickman

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

During the first year of the CDT programme I conducted an individual project as one of several components that make up the first year of the CDT. During this individual project, I conducted some initial work using the error diffusion design methodology for creating functionally graded lattice structures. This project allowed me to familiarise myself with many concepts and tools that would later become useful in my PhD research, including FEA, Matlab and mechanical testing. From this initial work, opportunities to develop the error diffusion method were identified and formed the start point for work in year two and for proposed future work. In summary, this initial project investigated the use of the error diffusion method in a 2D form to assess its suitability along with potential advantages and disadvantages for its use in load bearing metallic biomedical implants.

Initial investigations in year two commenced with the aim of developing the error diffusion method to work effectively in 3D for a range of geometries. In order to achieve this aim a series of goals were set out. These goals focused upon coding-based challenges, including generating both Delaunay and Voronoi lattice structures in both 2D and 3D, investigating how the 2D and 3D error diffusion filters behave, controlling this behaviour through calibration of inputs to outputs, and applying the method to curved geometries. Over the course of my first year, I aimed to work through all of these goals to evaluate the suitability of the method for the production of lattice structures in 3D. In carrying out these investigations, a series of challenges arose and the strengths and weaknesses of the initial design methodology became apparent. In working towards this initial aim, a 'Toolkit' of computational methods was developed to enable future work.

Nicholas Southon

Process Monitoring for Laser Sintering

The groundwork for the project has progressed well with the review of literature identifying fringe projection as a key potential process monitoring technique for laser sintering. Thermal monitoring will also be incorporated to enable data fusion which will improve the diagnostic value of the process monitoring. Commissioning and process mapping of the laser sintering system that will be monitored has been completed. This includes measuring the surface topography of interrupted builds at different parameter settings. Simulations of the measurement process have been developed and image analysis software is being written to reliably extract 3D data from the measurements taken. Characterisation of the measurement process will be made before incorporation into the laser sintering machine.

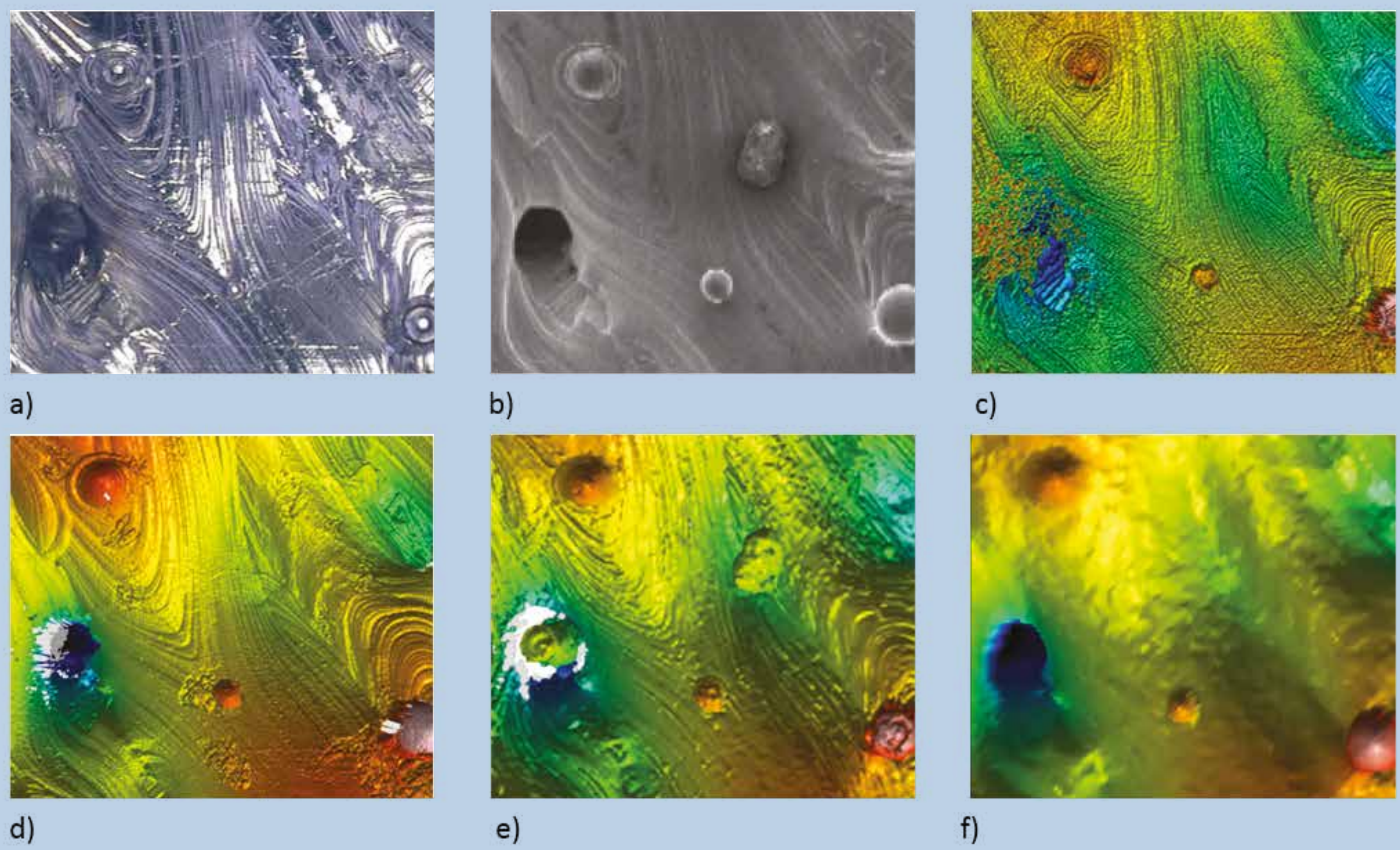
Adam Thompson

Surface Texture Measurement of Metal Additively Manufactured Parts by X-ray Computed Tomography

During the second year of my project, I began work towards my eventual PhD qualification, initially producing an extensive review of the available literature. This review was divided into two separate parts focusing specifically on industrial and medical applications of X-ray computed tomography with AM, and two review papers have been produced. The first of which has been published in the journal *Measurement Science and Technology*, while the latter is in preparation for an upcoming submission.

Following the review stage, I undertook initial experiments towards completion of this PhD. This work was presented at the ASPE/euspen 2016 Summer topical meeting: dimensional accuracy and surface finish in additive manufacturing, and is currently under review by the journal *Scientific Reports.* The work sought to answer the question of the surface topography features of an additive manufactured metal part, for the purpose of optimising the manufacturing process for high-value part production. Such an apparently simple question is surprisingly difficult to answer, as AM processes generate complex structures with relevant topographic detail spanning multiple scales, which makes these structures challenging to measure. In this work, a selective laser melted Ti6Al4V component surface was measured using an array of measurement technologies and setups. Conventional methods of surface inspection, such as optical and scanning electron microscopy, were juxtaposed with cutting-edge topography acquisition technologies, such as focus variation microscopy, coherence scanning interferometry, confocal laser scanning microscopy and X-ray computed tomography. Stylus profilometry was also used to measure the surface. Results showed that no single technology provides a completely trustworthy measurement and that agreements between technologies provide a useful starting point towards the understanding of surface features, while disagreements provide hints as to why measurement technologies react differently to topographic features.

I am currently in the process of producing a series of measurement artefacts to examine X-ray computed tomography measurement of internal surfaces, and my intention is for this work to be presented at the International Conference on Industrial Computed Tomography (iCT) 2017 and subsequently published in a journal.



Topography details of a Ti6Al4V SLM sample (field of view approximately 0.3 mm × 0.3 mm) captured with different measurement solutions; a) digital optical microscope at 500× magnification; b) scanning electron microscope at 61× magnification; c) confocal microscope with 20× objective lens; d) coherence scanning interferometry with 20× objective lens; e) focus variation microscopy with 50× objective lens; f) XCT at 44.1× magnification.

Rebecca Garrard

Process Monitoring of Electron Beam Melting by In-situ X-ray Detection

My project is focused on in-situ chemical composition monitoring of material in EBM. When material is irradiated by the electron beam, inner shell ionisation can occur. When the atom relaxes from the excited state, an X-ray is released. The energy of this X-ray is characteristic of the species of the atom. By detecting the energy and number of X-rays emitted when the material is irradiated, its composition can be calculated.

In order to learn more about the state of the art and other research efforts, a literature survey on X-ray detector types, soft X-ray spectroscopy, electron-matter interactions, process monitoring in EBM and metallisation has been conducted.

To aid the integration of a detector into the EBM chamber during processing, a study into factors that could affect readings or damage the detector has been planned. The main factors that have been identified are temperature, metallisation build up and the amount of radiation released during processing. Experiments have been undertaken to quantify these factors. Temperature during processing has been measured in three locations. Metallisation has been collected during a build – further experimentation will be conducted to determine the rate of build up with respect to location and melt volume. Investigation into radiation activity are in progress of being planned.

Currently, an extreme UV and soft X-ray photodiode is in progress of being developed for soft X-ray detection. Using X-ray sources (radioisotopes), the response of the photodiode is passed into an amplification circuit. Observation of this output allows the circuit to be optimised. Once the circuit is fully optimised, a housing will be designed to protect the photodiode in the chamber, and software will be written to collect the output and calculate composition.

William Rowlands

Additive Manufacturing of Advanced Ceramics for Demanding Applications

A thorough literature review of various AM methods and their material handling capabilities was conducted. Ceramic pastes are able to be deposited via extrusion freeforming as the best solution to fabricate functional ceramic components.

This project aims at making a detailed investigation into AM of various ceramic and metal-based engineering products relevant to the industrial sponsor (BorgWarner). These products could potentially replace one or more conventional component manufacturing methods with AM techniques, and achieve multi-material 3D printing of lightweight components whilst retaining device functionality. Suitable Positive Temperature Coefficient (PTC) ceramic heater materials are investigated through AM methods in particular along with metal electrodes.

A wide range of experimental parameters affect the AM processes and final manufactured components. This is true for micro-extrusion of high solids loading pastes also, which was chosen as the route to fabricate automotive heater components. Specifics that have to be accounted for include shear rate, shear thickening and rheological characteristics, printing speed, flowrate, nozzle distance throughout the build and drying rates. The extruded ceramic layers were found to blend together well, leaving zero weakness between layers, although the structural geometry of the three-dimensional extrusion required controlled in-situ drying to retain accuracy. Within the preliminary sintered bodies micropores were found and occasional larger voids, however, 98% density was achieved of the provided alumina paste, comparable to the >99% from conventional manufacture, a good trait for taking things further.

The AM process can fabricate composite ceramics as the extrusion does not affect the mixing of the material components significantly. Further improvements on the green forming and sintering processes will be investigated in the future.

Sarah Kelly

Design Rules for Additively Manufactured Wearable Devices

Currently, patients with wrist ailments might be prescribed wrist splints to aid their treatment. The traditional fabrication process of custom-made splints is skill dependent, time-consuming and the splints themselves pose numerous problems with regards to patient compliance. To overcome this, the use of AM has been proposed in recent years and there has been an increase in public awareness and exploration. Many of these developments have been as a result of the Maker-movement, the Internet of Things and development of more accessible technologies and infrastructures to enable production of AM builds; hobbyists, industry and academia are exploring the use of AM creating splints, all with strengths and weaknesses. One of the main weaknesses of most developments is the lack of acknowledgement of structural integrity of the splints. Because of this lacking, this research aims to generate and evaluate design rules that allow for the creation of safe splints through a digitised splinting process for production using AM. To date, a literature review and an initial study looking at the feasibility of digitised splinting has been conducted. A study has been started to look for links between the structural integrity of a splint and its geometric properties. It is hoped that this study will produce some strong findings on which further research can be conducted.

Outreach

The primary goal of our outreach activities are to encourage the CDT students to engage with the members of the public and to promote STEM which will also provide an opportunity to raise the students' research profile.

The main purposes of these activities are:

- Increase knowledge and awareness about AM and 3D printing
- Encourage younger generations to study STEM (Science, Technology, Engineering and Maths)
- To promote science in areas with low output of students
- Recruit high-calibre students
- Attract industrial sponsors
- Promote the Centre

Pint of Science Festival Nottingham

23-25th May 2016

- Presentation by Adam Thompson (CDT student) on "Making stuff in the 21st century: the need for verification" to an audience of members of the general public, including members of the industrial and academic communities.
- Stall at the event, displaying a 3D printer producing parts, as well as an array of additive manufactured parts, discussing with attendees the concepts and processes behind AM and advanced metrology.

Christmas lecture ‘Sound and Light’ The University of Nottingham

17th December 2015

This event involved an interactive foyer demonstrations and a lecture that was aimed at year 9-11 students with an interest in science and engineering. The theme of the lecture ‘Sound and Light’, was designed to enhance the national curriculum and show how exciting and diverse the world of engineering is.

The CDT contributed to the event by presenting demonstrations with FDM printers, discussing AM with the general public and handing out 3D-printed objects.

Tech Me Out

24th May 2016

The event was organised based around computing and engineering, with presentations on Metrology and 3D printing by CDT students and academic colleagues. It also involved demonstrations on 3D printers. This was very well received and resulted in positive feedback from both the public and presenters.

Family discovery day The University of Nottingham

7th May 2016

CDT students spent the day discussing AM with members of local primary schools and their families, providing interesting information about AM and 3D printing, and informing those interested in the technologies, of how to get involved.

STEM Outreach in Mansfield

16th March 2016

To enthuse and encourage the school children with 3D printing and AM technology, the Centre presented a Star Wars themed stand with many printed Star Wars characters and figurines and a large 3D puzzle Darth Vader head, which served as an interactive way to demonstrate the fundamental ideas behind the technology of 3D printing or AM.

Stafford College visit to the AM labs

27th January 2016

The day involved a visit from a group of 25 students (level 2 BTEC) from Stafford College, with presentations by the staff on AM and a tour of the AM labs by CDT/PhD students.

Publications

A N D Gasper, S Catchpole-Smith, A T Clare. In-situ synthesis of titanium aluminides by direct metal deposition, Journal of Materials Processing Technology. Volume 239, Pages 230-239, ISSN 0924-0136, January 2017.

Abstract:

This study explores the capabilities of methods for in-situ synthesis of titanium aluminides using the Direct Metal Deposition process. This allows for the functional grading of components which will be required for next generation aerospace components. The feasibility of three techniques are explored here; firstly, a new process of powder preparation for AM, satelliting, in which a larger parent powder is coated with a smaller powder fraction. Here, Al parent particles are satellited with fine TiO2 to produce an intermetallic matrix composite with Al2O3 particulates. The satelliting procedure is shown to increase capability and mixing of in situ synthesis. Secondly, combined wire and single powder feeding is explored through the use of Ti wire and Al powder to create Ti-50Al (at%). Finally, a combination of wire and loose mixed powders is explored to produce the commercially deployed Ti-48Al-2Cr-2Nb (at%) alloy. The simultaneous wire and powder delivery is designed to overcome issues encountered when processing with single powder or wire feedstocks, whilst allowing for on-the-fly changes in elemental composition required for functional grading. Characterisation of the deposits produced, through OM, SEM, and EDS, reveal the influence of key processing parameters and provides a meaningful basis for comparison between the techniques. Results show that it is possible to produce $\alpha 2+\gamma$ two-phase microstructures consistent with previous studies which have relied upon more expensive and harder to obtain pre-alloyed feedstocks. This represents a move forward in manufacturability for an emergent process type.

Thompson A, Maskery I and Leach R K 2016. X-ray computed tomography for additive manufacturing: a review. Measurement Science and Technology, 27 (7). 072001/1-072001/17. Volume 27, Number 7. ISSN 1361-6501, June 2016.

Abstract:

In this review, the use of X-ray computed tomography (XCT) is examined, identifying the requirement for volumetric dimensional measurements in industrial verification of additively manufactured parts. The XCT technology and AM processes are summarised, and their historical use is documented. The use of XCT and AM as tools for medical reverse engineering is discussed, and the transition of XCT from a tool used solely for imaging to a vital metrological instrument is documented. The current states of the combined technologies are then examined in detail, separated into porosity measurements and general dimensional measurements. In the conclusions of this review, the limitation of resolution on improvement of porosity measurements and the lack of research regarding the measurement of surface texture are identified as the primary barriers to ongoing adoption of XCT in AM. The limitations of both AM and XCT regarding slow speeds and high costs, when compared to other manufacturing and measurement techniques, are also noted as general barriers to continued adoption of XCT and AM.

Thompson A, Senin N and Leach R K 2016 Towards an additive surface atlas. Summer topical meeting: dimensional accuracy and surface finish in additive manufacturing, ASPE/Euspen 2016 Rayleigh, NC, USA.

Abstract:

What is the surface topography of an additive manufactured metal part? Such an apparently simple question is surprisingly difficult to answer, as AM processes generate complex structures with relevant topographic detail spanning multiple scales; making these structures challenging to measure. Topography is a rich source of information that can be used to optimise a manufacturing process for high-value part production. In this work, some of the most popular mainstream measurement technologies are used to measure a region of interest on the top surface of a Ti6Al4V cube fabricated by selective laser melting. Notable topographic formations are identified and their digital reconstructions in the different measurement configurations are compared via visual inspection. Qualitative results allow the identification of some key aspects in regards to agreement and disagreement of measurement results, as well as advantages and weaknesses specific to each measurement technology and configuration. Additional research work is needed to complete the experimental campaign by adding more measurement technologies, and to provide a more theoretically sound and quantitative approach to the comparison. Future work includes also the extension to different types of surfaces, materials and AM processes.

Charalampos A Tzivelekis, Lazaros S Yiotis, Nikolaos A Fountas, Agathoklis A Krimpenis. Parametrically automated 3D design and manufacturing for spiral-type free-form models in an interactive CAD/CAM environment. International Journal on Interactive Design and Manufacturing (IJIDeM). doi:10.1007/s12008-015-0261-8.Page 1-10. February 2015.

Abstract:

For product lifecycle management reasons, research trends impose the need of automated engineering tasks, such as computer-aided design and manufacturing. This paper proposes a novel approach of automating both the design and manufacturing processes of impeller-type geometries, when CAD/CAM technology is employed. To do so, a newly developed application was built; exploiting application programming interface objects of parametric instances, in order to automate time-consuming repetitive tasks for the preparation of 3D models and their direct manufacturing process. The developed application incorporates Simpson's method, Bezier-Bernstein equation and Non-Uniform Rational B-Spline for curve approximation describing blades of centrifugal impellers, as a representative case study. The machining technology is that of 3-axis CNC, thereby; each curve extends along a constant x-y plane. In the first step of the application, the entire 3D model of the impeller-type model is automatically generated according to variable values taken as user-defined entities from the interface. The application then carries on by automatically modelling the manufacturing process and ultimately generating the NC programme from the cutter location data for a given CNC machine tool.

Andrew J. Cummings, Francesco Ravelico, Kegan I.S. McColgan-Bannon, Olga Eguaogie, P. Alain Elliott, Matthew R. Shannon, Iris A. Bermejo, Angus Dwyer, Amanda B. Maginty, James Mack, Joseph S. Vyle. Nucleoside Azide–Alkyne Cycloaddition Reactions Under Solvothermal Conditions or Using Copper Vials in a Ball Mill. 34(5):361-70 • DOI: 10.1080/15257770.2014.1001855. May 2015.

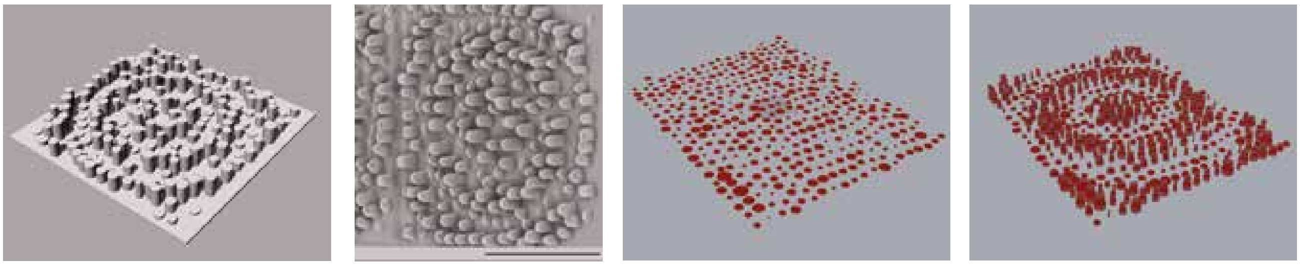
Abstract:

Novel nucleoside analogues containing photoswitchable moieties were prepared using 'click' cycloaddition reactions between 5'-azido-5'-deoxythymidine and mono- or bis-N-propargylamide-substituted azobenzenes. In solution, high to quantitative yields were achieved using 5 mol% Cu(I) in the presence of a stabilizing ligand. 'Click' reactions using the monopropargylamides were also effected in the absence of added cuprous salts by the application of liquid assisted grinding (LAG) in metallic copper reaction vials. Specifically, high speed vibration ball milling (HSVBM) using a 3/32(″) (2.38 mm) diameter copper ball (62 mg) at 60 Hz overnight in the presence of ethyl acetate lead to complete consumption of the 5'-azido nucleoside with clean conversion to the corresponding 1,3-triazole.

Samuel J. Morris, Joseph P. R. Dudman, Lars Korner, Priscila Melo, Lewis H. Newton, Adam T. Clare. Complex Functional Surface Design for Additive Manufacturing. Annual International Solid Freeform Fabrication Symposium, 8-10 August 2016, Austin, Texas.

Abstract:

This paper presents a new methodology for the creation of advanced surfaces which can be produced by AM methods. Since there is no cost for enhanced complexity, AM allows for new capabilities in surface design. Micro-scale surface features with varying size, shape and pitch can be manufactured by Two-Photon Polymerisation (2PP). Computer-Aided Design (CAD) tools allowing for this variation to be incorporated into the surface design are only just emerging. With the presented methodology, surfaces are created from a single feature design. Variation is applied to the surface features through algorithmic design tools, allowing for arrays of hundreds of unique features can be created by non-CAD experts. The translation of these algorithmic expressions from CAD to a physical surface is investigated. Using the proposed methodology, 2PP is used to create quasi stochastic surfaces for the purpose of enhancing the biointegration of medical implants against current state-of-the-art.



SOME IMAGES FROM PAPER (Scale Bar = 50μm)

Kelly, S., Paterson, A. M., & Bibb, R. J. (2016). A review of wrist splint designs for Additive Manufacture. In A. E. Rennie (Ed.), Rapid Design Prototyping and Manufacture Conference (pp. 29-39). Design School, Loughborough University, 15-16 December 2016.

Abstract:

Currently, patients with wrist ailments may be prescribed wrist splints to aid in their treatment regime. The traditional fabrication process of custom-made splints is skill dependent, time-consuming and the splints themselves pose numerous problems with regards to patient compliance. To overcome this, the use of AM has been proposed in recent years and there has been an increase in public awareness and exploration. Many of these developments have been as a result of the Maker-movement, the Internet-of-Things and development of more accessible technologies and infrastructures to enable production of AM builds; hobbyists, industry and academia are exploring the use of AM for splints, all with strengths and weaknesses. This paper highlights and describes specific examples of AM wrist splints currently available in the public domain and summarises strengths, weaknesses, opportunities and threats for the future implementation into the healthcare sector.

Creativity@Home

Creativity@Home is a new initiative that has been developed by the Engineering and Physical Sciences Research Council (EPSRC) to generate and nurture creative thinking that might lead to potentially transformative research.

A two-day event was organised on 12th and 13th September 2016 which was attended by 38 PhD/CDT students from the AM CDT, 3D Printing Group and the Sustainable Chemistry CDT in The University of Nottingham.

Objectives of the event:

- Learning a range of creative problem-solving techniques
- Building a student community
- To promote and encourage student and staff interaction which may result in initiation of new research
- To apply learned skills in research

Day One
Monte Carlo or Bust

This activity involved teams designing and building life-sized concept cars to fit the briefs from team owners, sponsors and safety advisers... all before the time ran out!

With a huge range of building materials available, the teams had to plan effectively if they wanted to meet the specifications and deadline. Each team member had a role, so communication was key, and teamwork and imagination was essential. This was a highly creative challenge that developed from the initial brief to the final unveiling of the teams' innovative designs.

Day Two
Cryptic Challenge

This was a non-stop activity where teams completed as many of the 30-plus challenges as possible. These were specially selected to entertain the teams and test their brains and wit, rather than brawn and intellect. Many took place head to head and featured special bonus puzzles for those who finished first or are perhaps slightly less active!

"The Creativity@Home was a great way to get to know the other PhD students from our group as well as from other CDTs."

Yazid Lakhdar

"A collection of trials and challenges encouraged creative thinking, competitiveness and comradeship."

James Smith

"The Creativity@Home event was a highlight and very useful for teambuilding and bonding. I would definitely recommend it to be organised for future cohorts as I found it extremely beneficial."

Niloufar Hojatoleslami

"It was challenging to work with other people and adapt to everyone's way of working and thinking, which is part of a research group dynamic."

Priscila Melo

Nottingham in Parliament Day

Nottingham in Parliament Day was a one-day takeover of Westminster on the 25th October 2016. The day was an opportunity to showcase the businesses, institutions and people that make Nottingham great!

This was an exciting opportunity for the CDT to demonstrate the research that is being carried out by our students and also the opportunities that the Centre offers to potential postgraduate students.

CDT student Carlo Campanelli presenting a replica of the Big Ben and the Tower Bridge to MP Lilian Greenwood

Seminar Series

In February 2016, we launched the CDT/Postgraduate seminar series, which is held every four weeks. This involves five 15-minute individual presentations by the students. Additionally, the Centre hosts the Invited Speaker seminar series, held on a quarterly basis with distinguished academics in the field of AM and 3D printing.

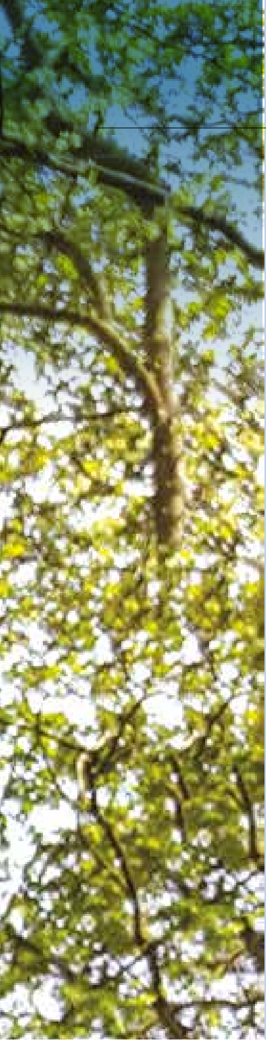
The purpose of the CDT/Postgraduate seminars is to provide an academic environment in which students and other members of the Centre for Additive Manufacturing can present their research, advancements, field results, findings and benefits from peer discussions. The seminars are also an excellent opportunity to improve presentation skills, get feedback from colleagues, strengthen the post graduate community and encourage cross CDT/PhD activities. All seminars are chaired and attended by academic colleagues and will continue in future academic years.

Future PG seminars schedule

Zou Zhiyi Zhengkai Xu You Li Irene Henning Adam Thompson	**02/11/2016**
Yaan Liu (Ann) Vicente Rivas Santos Thuy Trang Ngo Le Ma Sam Irving	**24/11/2016**
Sam Catchpole-Smith Yazid Lakhdar Deshani Gunasekera Peng Zhuo Paola Sanjuan Alberte	**26/01/2017**
Olusola Oyelola Obinna Okafor Nicholas Southon Marina-Erini Mitrousi Liesbeth Birchall	**23/02/2017**
Lewis Newton Sam Morris Lars Korner Yijia Zhou Hatim Cader	**30/03/2017**
Georgina Marsh Ge Zhao Elisabetta Prina Arthur Coveney Ellen Webster	**27/04/2017**
Duncan Hickman Dominic Hui Qifeng Thomas Nethercott-Garabet Ian Richards	**25/05/2017**
David Pervan Chung Han Chua Charlotte Blake Cassidy Silbernagel Fiona Salmon Carlo Campanelli	**29/06/2017**
Aylin Turgut Amanda Husler Alexander Gasper Richard Selo Isam Bitar	**27/07/2017**

"All the group team-building events, activities and meals alike, have proved extremely beneficial in bringing the group closer together. These events have been especially positive in allowing both CDT cohorts and the group's researchers from outside of the CDT to network with each other."

Michael Ward



Team-Building Events

Team-building events are an important part of our CDT and PhD community as they are not only important for the immediate experience of the activities, but also for the group's skills, communication and bonding.

Events such as Paintballing Day and Creativity@Home have been very well attended by both staff and postgraduate students, with positive feedback. We will continue to incorporate these events in our programme, as we believe they improve productivity and motivation within individuals, which will result in personal development and bring all members together for a common cause.

"These events have been great fun, and have helped everyone get to know each other better. This includes getting to know people outside of the CDT and people who you otherwise might not have had a reason to interact with."

Duncan Hickman

"The team-building events were enjoyable and gave researchers the opportunity to interact with others, as well as developing individual communication skills."

Hatim Cader

Industrial Partners

Since the start of the CDT, we have attracted more than 30 industrial sponsors across the Centre's academic partners. This is an invaluable addition to the Centre and student experience, and ensures that the PhD projects are relevant to industry and capable of having a significant impact on the way products are currently manufactured. While our sponsors benefit from university researchers for product innovations, the Centre gains increased external research funds which enhance student experience.

Our students will also benefit from completing a three-month internship with their project sponsor. This is a compulsory 10-credit module (MM4INT), which requires the students to submit a Personal Development and a Final Report. This will give them the opportunity to understand the industrial environment that their research will influence.

We are extremely proud to be working with some of the world's leading industry and look forward to explore further collaborative research opportunities.

Other sponsors include:

Oerlikon, QuantumDx, Exova, Arthritis Research UK, GSK, Alcyomics, Stryker, Siemens

Sponsor testimonials:

"The opportunity to exploit the capabilities and expertise at the AM facilities is of great benefit to AWE, and the value of the CDT projects allows us to influence innovation whilst sponsoring student's academic development. It is noticeable how quickly the outputs of the CDT projects are promoted and shared by holding regular meetings and on-site visits. Work carried out to date by the CDT students has demonstrated value for money and AWE is eager to see how these novel ideas will progress as the PhD matures."

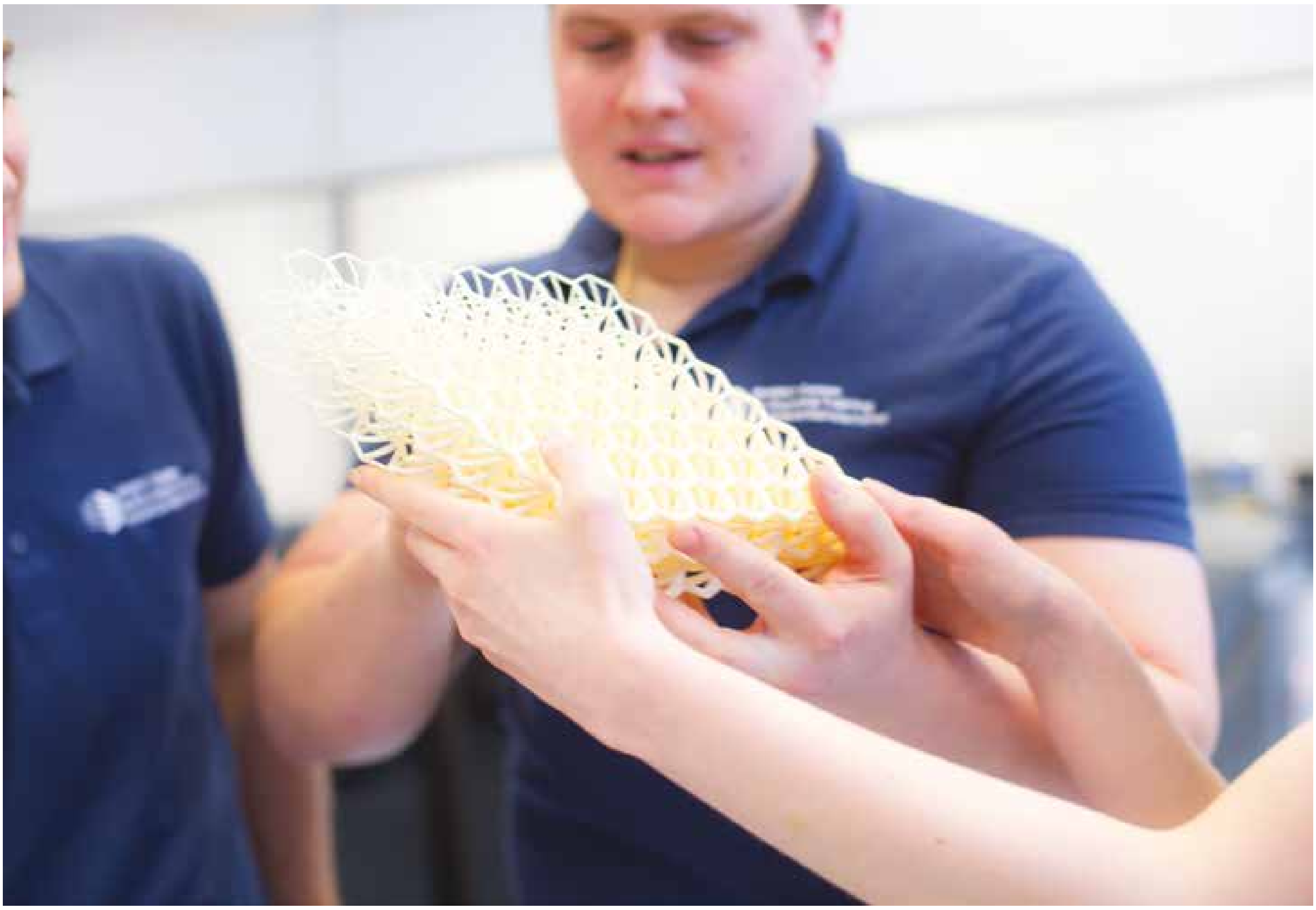
Anna Terry, AWE

"As a company, we are already benefiting from the different insights that Lars Korner is bringing to the table due to his different background. He is also acting as a bridge to the wider academic community in Nottingham, so we are noticing other areas that might be useful to us and may merit future CDT sponsorship. Overall, we are very happy both with the scheme and the current implementation with Professor Leach's team and with Lars working with us."

Dr David Bate, Nikon

"We see Lewis Newton as a key link between the Metrology & NDT group at MTC and the Manufacturing Metrology group, transferring fundamental research into industrial implementation, passing expertise and opening up conversations about further collaboration. The dialogue between MTC and Nottingham has already increased dramatically as a result of his studentship and we are keen for this to continue."

Evangelos Chatzivagiannis, MTC



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