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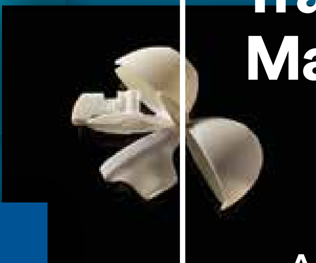
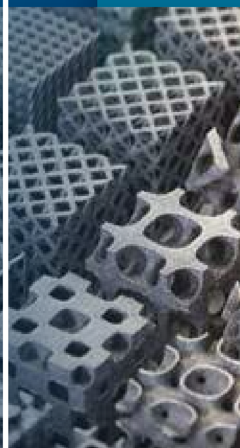
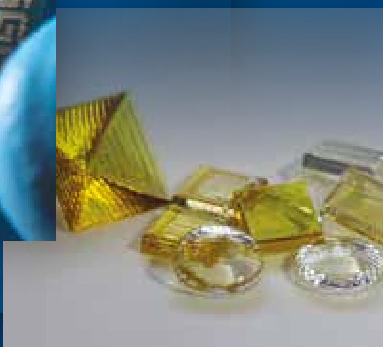
EPSRC
Engineering and Physical Sciences Research Council



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

Annual report
Academic year 2016-17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Newcastle University

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Update on the Centre's progress

"It hardly seems like yesterday since we received notification that our collaborative EPSRC Centre for Doctoral Training (CDT) in Additive Manufacturing and 3D Printing led from Nottingham in partnership with Liverpool, Newcastle and Loughborough Universities would be funded. We have now reached the mid-point of our funding and recruited half of our student intake. Reaching the halfway point of the CDT in Additive Manufacturing has given us the opportunity to reflect on our achievements and activities over the past three years. Welcoming another cohort of 8 students to the CDT in October 2016 kept the momentum building in terms of our numbers and additionally, has shown that the CDT is truly multidisciplinary in nature, exemplified by recruitment of students from diverse backgrounds including biological science, physics, chemistry and nanosciences was well as the more traditional engineering disciplines. This continuing trend is one that we're rightfully proud of, bringing diverse backgrounds together to further this disruptive technology. A further highlight for our year was centred on EPSRC's mid-term review of all CDTs, where thanks to the hard work of our CDT staff, academic contributors and industrial partners we received the top rating available. This rating and our relationships with industry were further exemplified by our first 'CDT Industry Day' which brought together all of our Industrial collaborators and partners for the day to learn about all of the PhD projects being researched and the advances being made by the students and to allow further cross-fertilisation of ideas as well as providing an invaluable networking event for the 81 delegates who attended from our 25 different sponsors and partners. The students have also been busy reaching out to other organisations and supporting the local community, providing an eye opening insight into their projects to local communities as well as overseas visitors interested in our CDT model. Needless to say with a further 30 students to recruit over the next two cohorts recruitment and industrial relationships are still top of our agenda, but on top of this 2018 will see our first cohort of students complete their studies and begin to graduate, realising our fundamental aim of producing talented young researchers to push Additive Manufacturing and 3D Printing ever further into the mainstream."

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

Cohort 3 introduction

2016 was another successful year for recruitment; eight high-calibre students joined the Centre, bringing the total number to 36. The academic backgrounds of the new cohort (see demographics below) reflect the Centre's policy of recruiting highly qualified, enthusiastic graduates from a broad range of related disciplines.

The Centre also aims to attract more female students as well as produce graduates who are employable both in industry and academia.

Student demographic (cohort 3)

8 Students

3 Female

5 Male

Background

4 Engineering
1 Biological Sciences
1 Chemistry
1 Nanoscience
1 Physics

6 UK Students
1 Overseas
1 EU

Cohort 3 project outlines

Ian Richards
University of Liverpool

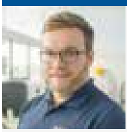
Investigating the mechanical and biological potential of porous structures for surgical applications

Porous, low density structures have been used in tissue engineering for some time. Recently, pores have been implemented into surgical devices to allow for tissue ingrowth and greater stability in situ; however, porosity has a marked effect on mechanical potential. We suspect that pore characteristics – such as shape, size, density and interconnectivity – are drivers of biological activity, but their level of control is not well understood.

Our research aims to determine the relationship between pore characteristics, biological activity and mechanical properties across a range of different tissue and material types using additive manufacturing. Data generated will be used to inform the design of new innovative surgical devices.

Arthur Coveney
Loughborough University

Selective Laser Robocasting

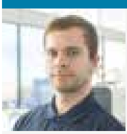


The purpose of this project is to determine the feasibility of combining elements from two additive manufacturing techniques: material extrusion and selective laser sintering. This new technique, known as selective laser robocasting, hopes to advance additively produced multi-material ceramic components.

We repurpose a micro assembly platform to consider the suitability of a ceramic slurry for selective deposition through direct ink writing, consolidated through selective laser sintering. By selectively dispensing and sintering the ceramic loaded slurry, we are able to process ceramics through additive manufacturing. There are issues to overcome – such as layer-layer slipping and shrinkage post sintering – but, through this new process, ceramic structures with higher complex geometries can be produced, and multiple material printing will be achieved with additional dispensing modules.

Isam Bitar
University of Nottingham

Generic methodology to determine quality assurance, validation processes and techniques to measure the internal dimensional properties of additive manufacturing parts



The emergent use of additive manufacturing and 3D printing technology for the manufacture of end use products requires the development of significant supporting methodologies and additional tools. Among these requirements is the provision of suitable metrology approaches underpinning testing, certification and quality assurance procedures. This is seen to be of particular relevance to additive manufacturing in safety critical applications; for example, in the aerospace industries.

The current approach to mechanical testing standards is to use existing methods with additional guidance for testing materials, but there is a clear need for specific guidelines on testing additive manufacturing materials.

Through additive manufacturing, the 3D item is created by placing ‘thin’ layers sequentially. The performance of the end product is dependent on the coherence obtained between these layers; new developments in testing are therefore likely to focus on assessing performance across the layers (i.e. layer to layer (or through-thickness), strength and toughness), and/or assessing anisotropy in the finished material.

The scope of this project is to develop input, process and test methods to assess the anisotropy of additive manufacturing parts, and to deliver a novel methodology that will allow Element, a group of independent materials testers, to be at the forefront of additive manufacturing testing. This will be the first step in additive manufacturing standardisation.

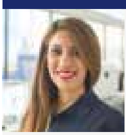
Fiona Salmon
University of Nottingham

Additive manufacturing of glass

Our project aims to investigate and develop glass as a material for additive manufacturing processes, particularly laser sintering and laser melting. A broad understanding of the material, background literature and engineering techniques will be developed and used to further the project. We also have a medical application in mind that aligns with my research interests: biologically active glass.

Marina-Eirini Mitrousi
University of Nottingham

An experimental study into processing biocompatible polymeric materials with laser sintering for pharmaceutical applications

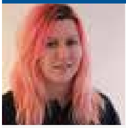


We are seeking to develop new methodologies and materials for pharmaceutical applications. For example, an effective setup of parameters in laser sintering is one of the main concerns of this research; the aim being to process biocompatible materials, such as PEO and cellulose, for drug delivery systems.

We are also investigating the effect of sintering on common polymer biomaterials, in order to transfer these materials into an effective laser sintering powder. Once a way of processing new materials has been found, we are one step closer to developing lattice structured pharmaceutical tablets with controlled dosage release.

Ellen Webster
Loughborough University

Comparative scanning techniques for application in the field of additive manufacturing

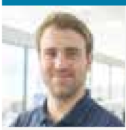


This research focuses on collaborative engagement projects that use a variety of different scanning techniques in their application of additive manufacturing. From museum conservation to art projects and scientific investigation, there is much scope for analysing varying approaches to 3D scanning. While many are context-based applications, we aim to build cases studies of collaborative work to offer a comparative insight into the area. Through the collection of observational and primary field research with companies such as Digital Life 3D, the project will place the theme of 3D scanning within a wider context, as well as showcase the micronarratives of the topic.

I am also carrying out a collaborative exercise with Digital Life 3D that aims to gain first-hand experience of their Beast Cam Technology, as well as provide key contributions insight into their additive manufacturing efforts. This will be displayed in the Boston Museum of Science, USA, in 2018.

Thomas Nethercott-Garabet
Loughborough University

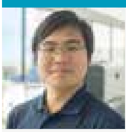
Design for hybrid additive manufacturing



Multi-axis hybrid manufacturing combines additive and subtractive operations within the same machine platform. It offers improved capabilities in terms of part feature resolution and surface finish, compared to additive manufacturing followed by CNC machining. The chronology of feature creation needs to be optimised, together with the decision on which features to create using which technology. The designer needs to have an input into these decisions as they will have a critical impact upon the cost, timing and functionality of parts that are produced. Research will focus on developing a design methodology, exploring the applications and benefits of using hybrid additive manufacture.

Chung Han Chua
University of Nottingham

Design optimisation for upper-limb prosthesis



There have been significant developments in the manufacturing of upper-limb prostheses, including in the materials and design, which should translate into effective products. However, in spite of advancements, electrical prostheses currently experience high rejection rates. There is a demand for lightweight prostheses that give users greater dexterity and better handling of everyday objects.

My research aims to develop a design optimisation methodology using a virtual environment. By using a kinematic simulator, it is possible to rapidly assess the performance of a hand prosthesis computationally. In this way, parametric based optimisation can be used to improve current designs, by employing the computational metrics as the objective functions.

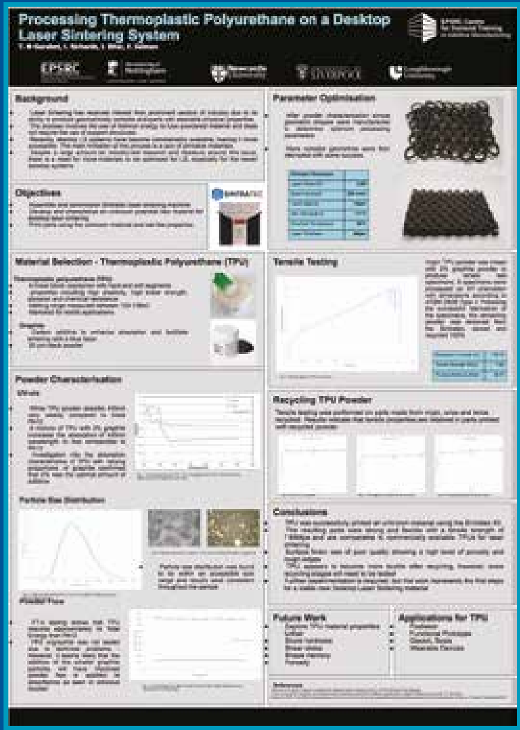
Cohort 3 group grand challenge

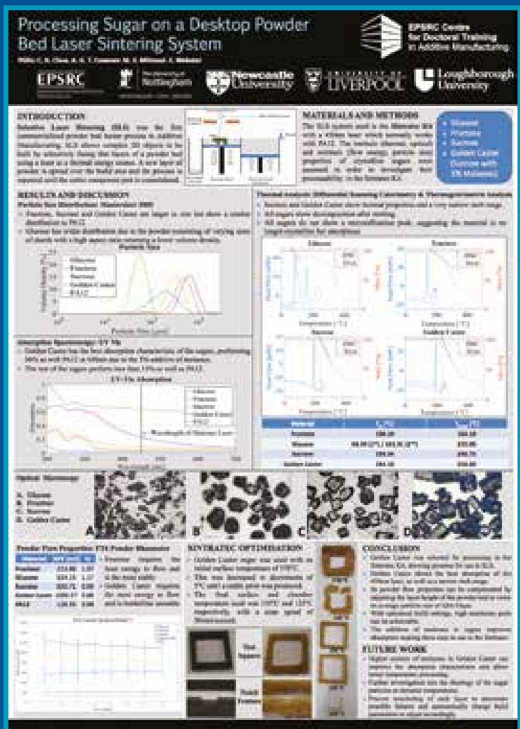
For this project, students were put into two groups with the aim of constructing and commissioning a desktop laser sintering system that will be used to investigate new materials for laser sintering.

The objectives of the project were to: build a laser sintering system from a kit; commission the system with a known material; determine how to process the material via a new system; evaluate the transferability of their findings to commercial laser sintering; and report their findings.

As well as preparing a poster for their group – presented at the Solid Free Form Symposium in Texas, USA – the students produced an initial and final report in order to pass the module.

The group poster on 'Optimising Thermoplastic Polyurethane for Desktop Laser Sintering' was accepted for a publication in the proceedings of the conference (see Publications, page 35).





Cohort 2 project updates

Sam Catchpole-Smith
University of Nottingham

Selective laser melting of lattice structures for combined thermal and mechanical applications

My research has resulted in three papers: one as first author, one as second author and one as third author. While some of the work has come solely from authors at the Centre for Additive Manufacturing (CfAM), there have been collaborations with the Advanced Component Engineering Laboratory (ACEL) and the Optics and Photonics group at the University of Nottingham.

In the latter half of the year, a number of lattice samples were designed and manufactured. A thermal conductivity test rig has also been designed, manufactured and commissioned in accordance with ASTM standards. All of the manufactured lattice samples have been tested for thermal conductivity, and the results of this experiment are currently being written up into a publication.

In addition, a convective heat transfer rig is in the design stage; a prototype has been tested for function and we are in the process of working on improvements. The new test rig will be ready for commissioning in the new year.

Xabier Garmendia
The University of Liverpool

Coated bulk metallic powders

The aim of this project is to develop coated bulk metallic powder feedstock for use in additive manufacturing. To create the powder coating, atomic layer deposition (ALD) processes are being investigated as a route to high-value metal powder feedstocks. The treated powder will enhance properties of parts such as crack growth resistance or yield strength.

A replica of an existing Renishaw's powder recirculation and sieving system have been built and tested at Renishaw Plc site. We have also designed a batch scale ALD reactor, which will be integrated and tested on the existing powder sieving and recirculation system. Several equipment design modifications were implemented along with the required programmable logic controller (PLC) modifications. Initially, copper thin-film coatings were added to AlSi10Mg powder, which has been characterised by means of scanning electron microscopy (SEM) and X-ray fluorescence (XRF) techniques. In the near future, we'll be comparing treated and non-treated powders, processed via selective laser melting (SLM) Potentially, further coatings will be tested, having considered the possibility of scandium.

Liesbeth Birchall
University of Nottingham

Quantum dot - silicone nanocomposites via Reactive Inkjet

This project develops reactive inks that can produce quantum dot/silicone composites in situ. Silicones are ideal matrices for quantum dots (semiconductor nanoparticles which fluoresce brightly under ultraviolet light). The fluorescent composites could then be used in applications such as lighting or security. In particular, the emission of quantum dots varies with temperature; this project specifically works towards a printable temperature sensor.

The silicone inks have been optimised to print at ambient temperature. Inks with suitable viscosity were formulated with two solvents: octyl acetate and toluene as a second option. We determined jettability using the Ohnesorge Equation. Our initial work used a single printhead, but single continuous layers could not be formed due to poor pinning. Therefore, we used a pinned grid strategy, where several layers of Ink A and Ink B were deposited before printing subsequent layers. A test print gave satisfactory resolution and accuracy, but the anchor points lead to rough surface texture where ink flowed around them.

We then optimised jetting for the dual printhead assembly, which jets inks simultaneously so that pinning was no longer an issue. In this case, a line-by-line printing method gave good edge definition, print accuracy and smooth surface texture.

Lastly, we loaded quantum dots into the ink. Fluorescent composites were successfully produced when mixing inks in glass vials, but jetting failed as the quantum dots were not sufficiently dispersed.

Our next steps are to improve dispersion, either by changing the quantum dot stabilising ligand or adding an appropriate dispersant. Fluorescent composites can then be printed into desired patterns.

Nathalie Sallstrom
Loughborough University

Directed neural cell growth in additive manufacturing systems for applications in next generation prosthetics

Current prosthetic sockets are uncomfortable, partially due to the socket not being compliant to changes in dimensions of the residual limb. This project focuses on developing a soft hydrogel, which can be used within prosthetic sockets. The hydrogel should also be able to guide neurons to achieve a neural connection between the prosthetic device and the user. A novel hydrogel using non-cytotoxic but neuronal cell repelling monomer (KSPMA) has been identified as a potential candidate material.

The plan is to use a coating material that allows cell attachment to guide neurons. Our initial work has indicated that the generation of a KSPMA-based hydrogel with the required mechanical properties presents some interesting challenges. A key part of the work ahead will be to overcome these whilst allowing the gels to be produced via additive manufacturing methods.

We used laponite clay particles as a crosslinker to improve the hydrogel strength and ductility. However, KSPMA is a salt and, when dissolved in water, potassium ions disassociated. This most likely caused adsorption onto the negatively charged parts of the laponite clay platelets, interfering with the hydrogel's formation.

Our work ahead will look at modifying the reaction conditions to remove the charging effects so that a cohesive hydrogel can form. Once we have developed a suitable hydrogel, the focus will be on making the material appropriate for additive manufacturing techniques, as well as coating with a cell adhesive material (such as BIBB) to allow neural guidance.

Yazid Lakhdar
University of Nottingham

Additive manufacturing of advanced ceramic materials

This project aims to combine colloidal processing and additive manufacturing technologies such as inkjet printing and binder jetting to develop routes to the additive manufacture of fully dense advanced ceramic parts. By firstly developing the processing routes and then exploiting the materials they yield, the purpose is to make advanced ceramic materials much more accessible in the additive manufacturing world, and further the understanding of their potential engineering applications.

Using alumina as the starting point, we will develop processing techniques, and explore the equipment and characterisation required to deliver material for testing. We will also investigate additive manufacturing of non-oxide ceramics, as the project develops a broader understanding of the processing techniques most applicable to each type of ceramic material.

Iliya Dimitrov
Loughborough University

Additive manufacturing for quantum systems

This project in experimental physics aims to deliver a cheap way of creating structures with micro and nanometer features, using additive manufacturing. Our main area of investigation focuses on electrohydrodynamic (EHD) jetting. Currently, we have developed two print head designs for addressable printing of multiple materials. The designed print head consists of three subsystems – electrical contact, main body and nozzle tip. The main body, printed by stereolithography (SLA), does not possess the fine resolution of the tip needed for quantum applications of EHD jetting, so we are currently investigating an alternative method for tip development.

Established EHD printers suffer from low throughput and require significant time when changing print materials. The print heads under development aim to address both issues, and we're seeking commercial value as an outcome. Resolving such key issues should gain interest from industry, reduce the overall cost of current EHD printers and increase their market share.

Developed under the framework of systems engineering, our aim is to identify potential failure modes and mitigate the consequences of their realisation. We are paying particular attention to the cause, frequency and severity of each failure, as well as estimating an overall coefficient to specify key failure modes. The application of the approach has been extended from lab practices into the PhD, in general; the objective being to estimate if applying systems engineering results in increased productivity for doctoral researchers.

Babis Tzivelekis
Newcastle University

Manufacturing of microfluidic cartridges for lab-on-chip applications

There are multiple benefits to operating with fluids at microscale, and being able to create highly accurate mock ups of large scale biological and/or chemical activities, as well as monitor them in real time, can lead to impressive biotechnology applications. Microfluidics is not entrenched in modern laboratories; and only a restricted number of high-cost, sophisticated devices are operated by specially trained personnel. Laborious and costly traditional manufacturing processes oblige designers to adopt a cautious approach in R&D. Particular focus on novelty rather than volume production scenarios further decelerates commercialisation of lab-on-chip technology and contributes to the ill-suited state of microfluidic technology. Additive manufacturing could bridge the gap between proof-of-concept results and commercial microfluidic technology.

In this project, we are investigating polymer additive manufacturing processes and characterising their performance in batch manufacturing of microfluidic devices compared to traditional processes. Stereolithography was selected as a candidate processing method for on-chip nucleic acid amplification devices, and a collaboration with QuantuMDx Ltd assay and engineering team resulted in the development of a prototype design for 2-step endpoint on-chip polymerase chain reaction (PCR).

We addressed several concerns through individual experiments: manufacturing, post-processing and integration protocols development; a process performance and repeatability study; material compatibility with biological samples; and suitability for PCR. Currently, devices are being manufactured in the lab for real-time PCR testing and results will be indicative of further modifications in the processing and/or post-processing protocols. We are also performing micromachining experiments with traditional polymers; the aim being to conventionally manufacture a PCR chip for comparison purposes.

Joseph Dudman
Newcastle University

Bioprinting of osteoarthritic joint co-cultures

My project is focused on bioprinting for regenerative joint repair. Through funding from the EPSRC and Arthritis Research UK, I am exploring various material jetting technologies in order to print biological tissues that are able to closely mimic articular cartilage. The project will look at printing osteoblasts, mesenchymal stromal cells, chondrocytes and fibroblasts – alongside a range of biocompatible materials – to generate tissue scaffolds.

Further investigations will look into the development of tissue scaffolds and bioprinting techniques that are able to improve current surgical practices such as autologous chondrocyte implantation for articular cartilage repair. Such modifications to current surgical practices would improve treatment efficacy and reduce the associated recovery period required following injury.

In addition to this, I am exploring additive manufacturing technologies for generating tissue models, which can be used to study the pathology of osteoarthritis as well as screen potential new treatments.

I am also researching how different polymers might electrostatically stabilise cells held within a suspension liquid for ink jetting applications. In development are a number of varying waveforms and printing configurations to optimise the material jetting process and improve its reliability for use within tissue engineering applications.

Samuel Morris
University of Nottingham

Process parameter and heat treatment effects on texture and microstructure of inconel 718 manufactured by selective laser melting

We have established a processing window to produce defect free parts for Inconel 718, along with initial computational work modelling the solidification of Inconel 718. Computational modelling allows us to investigate the solidification path of materials, along with the effects of alloy composition and solidification rate on element segregation and precipitation of secondary phases in Inconel 718.

Moreover, we are studying the effects of hatch spacing, scan strategy and part geometry on grain size and orientation and secondary phase precipitation in 'as-built' Inconel 718. This research will be supplemented by computational modelling that accounts for diffusion of elements in the solid state, giving a more accurate element segregation profile. We will model the effect of temperature and duration of heat treatments on homogenisation and secondary phase nucleation and growth. By comparing this model to experimental results, we will have a detailed understanding of the process effects on Inconel 718, enabling us to establish the validity of using computational modelling to determine optimum heat treatments.

Kegan McColgan-Bannon
Newcastle University

Hybrid natural/synthetic polymers to mimic the musculoskeletal environment

The aim of this project is to synthesise and develop hybrid natural-synthetic biomaterials. The purpose is to mimic the properties of damaged musculoskeletal tissue, such as in osteochondral defects, where tissue damage can affect the cartilage layer or trabecular bone structure.

By taking advantage of the novel properties of these biomaterials in the construction of tissue engineering scaffolds, it may be possible to induce tissue regeneration in vivo, leading to potential treatments for common musculoskeletal conditions.

Our project encompasses many aspects of medical device development, from base material production, scaffold design and fabrication, then later to the incorporation of cell laden hydrogels in the construction of composite medical devices. While there is potential for the incorporation of a range polymers, both natural and synthetic, much of our work to date focuses on the development of scaffolds from poly-ε-caprolactone (PCL) and poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) hybridised with type I collagen.

We have synthesised and characterised hybridised PCL-collagen for physicochemical, mechanical and biological properties, with a view to use in the regeneration of cartilage defects, characteristic in the onset of osteoarthritis. We are also characterising collagen functionalised nanofiber webs of PHBV in the same manner for application in non-load-bearing osseous tissues.

Priscila Melo

Newcastle University

Processing of porous implants for bone regeneration using binder jetting and fused filament fabrication

I have performed a number of experiments, including the study of the behaviour of two different batches of apatite-wollastonite (AW) under binder jetting and sintering processes. It was concluded that the raw material production route directly affects the sintering behaviour of AW, as well as the particle size and size distribution within the blend.

In order to compare the effectiveness of additive manufacturing with traditional manufacturing techniques for porous structures, we processed the powders using unidirectional pressing. To do this, we needed a smaller printer capable of testing tiny amounts of powders and new powder blends. This led to the design and manufacture of a specific desktop binder jetting printer. By testing smaller amounts, we were able to save on cost and production time, as well as make wiser choices relating to the blend properties – all of which has facilitated the future scale up of the process.

We spent the second part of the year developing a bioactive composite filament containing commercial poly-lactic and AW powders. This preliminary test demonstrated the composites' bioactive behaviour in improving its osteoconductive capabilities. We printed scaffolds using fused deposition modelling and performed physicochemical characterisation, which demonstrated enhanced distribution and homogeneity of the ceramic within a polymer matrix. Not only that, but a carbonated apatite layer was formed when immersed in simulated body fluids. Degradation studies did not reveal a significant loss in mass over an eight-week period.

Currently, we are investigating medical grade poly-L-lactide (PLLA)/AW powder and fibres. And, in a separate project, we have created, in partnership with the Dental School at Newcastle University, a PLLA/phosphate glass fibre composite for maxillofacial fixation devices using compression moulding. This is an ongoing study, and an abstract has been submitted and approved for the 42nd International Conference and Expo on Advanced Ceramics and Composites in Orlando, Florida. Upon presentation, the work will be submitted to the Journal of European Ceramics Society.

Michael Ward

University of Liverpool

Additive manufactured ultra-realistic facial prosthetics

My second year has focused on obtaining substantial knowledge on all aspects of facial prosthetic manufacturing techniques, hyperelastic models, functionally graded lattice structures, surgical methods and polyjet printing materials.

The primary body of my work revolves around an ABAQUS model and MatLab script. The script takes the X,Y,Z dimensions of a cuboidal test sample and outputs the coordinates of both the nodes and elements as an input file for ABAQUS. The finite element model (FEM) consists of the said cuboidal structure, which is split into three layers to represent the epidermis, dermis and subcutaneous layers. This will be further developed to incorporate fibre structures to achieve anisotropic properties.

I have also investigated the tensile properties of porcine cheek samples. Uniform strips of multiple samples were tested in a uniaxial manner, whilst submerged in room temperature phosphate-buffered saline. In addition, I used a three camera 3dMD system to make preliminary scans of subjects' faces, the colours of which will be categorised using a SpectraMatch scanning tool.

In the near future, I will be seeking approval for an MRI scan of a person's entire head. The aim is to produce dual material models of noses and ears; carry out tensile testing on Objet materials (Tango Plus and Agilus); and carry out tensile and compressive testing on human tissue samples.

Lars Korner
University of Nottingham

Sampling conditions in X-ray computed tomography for surface metrology

Due to the large design freedom offered by additive manufacture, conventional metrology systems are being challenged. X-ray computed tomography (XCT) has been identified as a potential metrological system, which enables the measurement of a part's geometrical conformity, and analysis of some material properties such as porosity and inclusions.

Performing surface metrology on XCT data is an evolving application of XCT. However, the large set of variables affecting XCT measurements challenges any statements of confidence intervals or even uncertainty and traceability statements. This project, which is sponsored by Nikon Metrology UK LTD., intends to systematically explore the effects of sampling conditions of XCT, such as number of projections, onto the measurement of AM surfaces via XCT.

Lewis Newton
University of Nottingham

Development of methods for measuring the surface topography of additive manufactured surfaces

Post processing is a common part of the wider additive manufacturing supply chain. By assessing surfaces before and after operations are applied, it is possible to gain an understanding of these processes, their mechanisms and their effect on the 'as-built' surface.

In order to assess the topography, however, measurement and the acquisition of information from these measurement instruments is required. To do this, the process of topography acquisition needs to be investigated; this includes determining the reliability of the measurement process and evaluating measurement errors.

Currently, methods of acquiring surface texture by the measurement instrument – in this case, focus variation microscopy – are being investigated for their response to the surfaces of various additive manufacturing processes and materials. The resultant data is then analysed to find the most common approach to computer surface texture parameters. However, these parameters may be inadequate in capturing the signature features of various processes. In response to this, there are alternative methodologies that can be applied to various additive manufacturing surfaces before and after post processing, such as feature based assessments and the use of fiducial markers for mapping surface topography.

In the case of feature based evaluation, I am investigating the electron beam melting process in terms of the effect of surface tilt on surface topography. By breaking the surface down into various features – such as weld track and particles on an additive manufacturing surface, or tool marks and pits from a finished additive manufacturing surface – it is possible to gain information on the function of the surface or the process of its production. In relation to EBM, I'm also studying the effect of surface tilt on surface topography, focusing on particle size and coverage on the surface.

Using fiducial markers, registration of regions of the same surface can be applied through stages of post process. Through alignment, it is possible to monitor the mechanism of the various finishing operations, as well as track the feature of the original surface, to give information that is both qualitative and quantitative. Through work with the Manufacturing Technology Centre, I will be researching processes such as shot peening, laser polishing, grinding/ linishing and mass finishing approaches.

Vicente Rivas-Santos
University of Nottingham

Design for metrology in additive manufacturing

This project explored an analysed potential features to be included in designs of AM parts to improve the measurements such as fiducial markers, used to help the data fusion in imaging applications; datum references, used for stablish a frame for the measurement process; and couplings and fixtures to facilitate the part fixing to the measurement device. I concluded a review of the available design methodologies for additive manufacturing and noted where there was a lack of consideration for metrology concepts, systems and processes.

From this information, I was able to draft the basic ideas for the 'design for metrology' methodology. I found that no considerations were made for how artefacts might be measured, which meant process characterization was more difficult and took longer. As a case study for testing the viability of design for metrology, two test artefacts for the new additive manufacturing process developed by Xaar, high-speed sintering, were created. The two artefacts are: a calibration artefact, used to assess the accuracy of the system; and a benchmarking artefact, use to test the behaviour of the system creating basic geometric features. Both artefacts were designed following the limitation and standard procedures of two measurement systems: a contact CMM and a photogrammetry setup to provide fast and reliable measurements.

Niloufar Hojatoleslami
Newcastle University

Processing and characterisation of osteochondral organoids for osteoarthritis modelling

Around 10 million people in the UK have osteoarthritis (OA), a musculoskeletal condition that affects the smooth cartilage lining of the joint. The aim of this project is to develop methods to create a bone cartilage interface in vitro, which models the progression of OA.

We will exploit several innovative manufacturing techniques throughout the project to determine the best method of producing the required scaffolds, incorporating biomaterials and cells for our osteochondral model.

Our base scaffold material will be developed using thermally induced phase separation (TIPS) of apatite-wollastonite to mimic bone, and bio-printing (using the n-Scrypt) will be exploited to produce the cartilage. Finally, we will assess the interfacial regulation between the ceramic and hydrogel layer, biocompatibility, rate of degradation and permeability of the materials used to develop the bone-cartilage constructs to determine the quality and usefulness of the models.

Greg Murray
Loughborough University

Additive manufacturing for custom orthoses

An orthosis is an externally applied device used to modify the structural and functional characteristics of the neuromuscular and skeletal system. It has long been recognised that abnormal foot morphology or structure, such as high arches or flat feet, causes tissue stress and increases the risk of injury. If left untreated, lower limbs such as ankles, knees and hips are also more likely to suffer injury.

This project considers the use of additive manufacturing to produce customised products – consistent with patients' profiles and medical diagnoses – that fit perfectly, and offer support and pressure relief.

Early stages of our research cover conventional manufacturing methods for foot orthotics, as well as more recent ventures into the use of additive manufacturing. We have also explored methods of patient data capture and processing.

Moving forward, the project will cover the use of lattice based structures to alter the properties and performance of foot orthoses, including the potential integration of embedded sensors to aid the diagnosis stage.

Mahid Ahmed
Newcastle University

Bioprinting skin equivalents for toxicity testing

Bioprinting throws up many challenges, one of which is the flocculation of cells within bio-inks during the printing process due to cell-cell adhesion. To try and prevent cell-cell adhesion, we investigated poly-l-lysine (PLL) with primary dermal fibroblasts and epidermal keratinocytes. Speckle coating cells with PLL cell-cell adhesion is largely restricted until the polymer is endocytosed. We observed that the cells typically endocytose the polymer within 24 hours; though, of course, this varies with each donor. PLL appears to reduce the metabolism of both cell types, which is perhaps a result of cytotoxicity.

Primary fibroblasts and keratinocytes are routinely isolated from donor biopsies for the development of full-thickness autologous 3D skin models. Maintaining the phenotype of freshly isolated keratinocytes is problematic as keratinocytes are prone to terminal differentiation and so the quality of cells is very much donor dependant. The keratinocytes are typically used at passage 3, whereas fibroblasts may be used up to passage 7. Because the models are in early development, it may be necessary to optimise the development process before bioprinting models using a Microfab Jetlab 4. Histological analysis suggests that seeding densities – and supplements in particular – may need to be modified before bioprinting.

We are currently optimising the jetting process to increase droplet volume, decrease print times and accommodate bio-inks with high cell densities. If the time taken to print cells can be reduced then the risk of flocculation is limited.

James Smith
Loughborough University

Fabrication of novel biopolymers blends for the additive manufacture of functionally graded prosthetics

The growing medical device and implant industry is reliant upon a small number of biomaterials to make products. Furthermore, these materials don't often fit the needs of the body and lead to issues such as stress shielding, implant failure and injury. My proposal is to create novel polymer blends tailored for additive manufacture.

Over the past academic year, I have fabricated a range of new polymer composites, which have been characterised through scanning electron microscopy, particle size analysis, fourier-transform infrared spectroscopy and differential scanning calorimetry. And, in doing so, I have gained an understanding of the composites' properties. In addition, all specimens underwent mechanical testing (tensile and compression), and the datasets that were generated were analysed to obtain mechanical information i.e. ultimate tensile strength, elastic modulus and percentage elongation.

Now, I'm working on manipulating the polymer composite formulations to match bone and flesh more closely, before starting on further biocompatibility studies and printing using additive manufacturing technologies.

Alex Gasper
University of Nottingham

Spatter and quality issues caused bypowder in laser powder bed fusion

This project investigates the role of powder in the laser powder bed process. Through greater understanding, potential quality issues can be better controlled. A factor of the dynamic behaviour of the powder during processing is the generation of spatter. This spatter constitutes a secondary powder system within the process and can influence the production of parts and recycling of the powder. We chose to investigate nickel based superalloys as an exemplar material.

3D Masterpiece, built by CDT students

Cohort 1 project updates

Sarah Kelly
Loughborough University

Design rules for additively manufactured wearable devices

The growing medical device and implant industry is reliant upon a small number of biomaterials to make products. Furthermore, these materials don't often fit the needs of the body and lead to issues such as stress shielding, implant failure and injury. My proposal is to create novel polymer blends tailored for additive manufacture.

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Nicholas Southon
University of Nottingham

Process monitoring in laser sintering

In this project, we have completed in-process measurements of an industrial laser sintering system using fringe projection – and detailed analysis of the data is ongoing, ready for publication. These measurements are given context by detailed process mapping.

We have also produced an integrated in-process fringe projection measurement system; procurement is still in progress but the optical design is now complete. Further to this, fringe image analysis and 3D surface analysis code have been developed, which will transfer well to the integrated system.

Hatim Cader
University of Nottingham

Inkjetting of Solid Oral Dosage Forms

This investigation involves the manufacture of solid oral dosage forms (more commonly referred to as tablets) through inkjetting. The project takes advantage of inkjetting's numerous advantages, including the creation of precise geometries and the ability to print multiple inks for a single tablet.

For the pharmaceutical industry, this translates into highly precise drug loadings and customisable tablets with controlled drug release, paving the way for personalised medicines and therapies. My overall aim is to successfully inkjet a reservoir device dosage form, where a polymer-drug matrix is surrounded by a release controlling membrane.

Using the Fujifilm Dimatix printer, we have inkjetted three components of the tablet: a drug polymer core, the release controlling membrane and the impermeable shell. We have successfully manufactured tablets that can extend the drug release duration from approximately seven minutes to over seven hours.

We are currently looking at how to achieve different release profiles, initially done by investigating different printing parameters and ink compositions to see what impact they have on the overall drug release profile of the tablet. Using this data, we will be able to create more complex release profiles, such as introducing a delay or changing the rate of drug release.

Duncan Hickman
University of Nottingham

Selective laser melting of functionally graded lattice structures with variable unit cell size

I have developed the idea of using topology optimisation to influence the distribution of unit cell sizes within lattice structures, through the use of an error diffusion based method. This is a continuation of my previous research that focused primarily on creating three-dimensional structures and the practicalities of using this lattice design algorithm. This earlier work highlighted areas of strengths and weaknesses in the design strategy, and, over the course of the year, I have investigated these more thoroughly.

Specifically, I have looked into how well the optimised density distribution from the topology optimisation is reflected in the final lattice design, and how this can be improved. This involved breaking down the methodology and investigating each step to find out what key factors alter the lattices that have been created. In doing this, various computational experiments had to be configured and tested to ensure they produced reliable results. Future work will continue to improve the lattice structures so that they more closely match the intended optimised design. This includes the use of finite element analysis (FEA), which I have already started to use to give preliminary results and to experiment with setup.

I have also contributed to a jointly authored paper that is currently awaiting final publication in the journal Additive Manufacturing. The paper discusses various design strategies employed to create unit cell based lattice structures based on topology optimisation, and gives an overview on how each strategy is implemented, as well as an insight into their effectiveness.

William Rowlands
Loughborough University

Effect of additive manufacture extrusion on la doped barium titanate ptcr materials, as part of additive manufacturing of advanced ceramics

A wide range of experimental parameters affect additive manufacturing processes and final manufactured components. This is also true for micro-extrusion of high solids loading pastes, which we chose 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.

We found that the extruded ceramic layers blended 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, we found micropores and occasional larger voids; however, of the provided alumina paste, 98% density was achieved, comparable to the >99% from conventional manufacture – a good trait for taking things further.

The additive manufacturing process can fabricate composite ceramics as the extrusion does not significantly affect the mixing of the material components. In the future, we'll be investigating further improvements on green forming and sintering processes.

In addition, we prepared barium titanate and lanthanum doped barium titanate PTCR materials for additive manufacture via extrusion and parameters optimised to fabricate coherent samples for dielectrical measurements, and honeycomb lattices; and investigated the rheology of the different solids loading content with dispersant concentration. The sintered density of the parts was not affected by the extrusion process with highly dense undoped barium titanate (99 %TD) parts fabricated, although the density reduced by La dopants remains low compared to conventional processing. We identified an optimum yield strength of >400 Pa as a key rheological characteristic for fabrication via extrusion.

Rebecca Garrard
University of Liverpool

Process monitoring in electron beam melting

My research project is focused on implementing in-process monitoring of chemical composition to electron beam melting (EBM). In order to characterise material in the melt area, we are detecting and analysing X-rays released when material is irradiated by electron beam. So far, we have selected a detector with sensitivity in the soft X-ray range, and electronics for the detector are in development.

Previous tests using an X-ray source failed to show a readable response from the detector and amplifier; therefore, we're investigating the amplifier further. I'm also developing a UV source to test the X-ray detector, as it is more controllable than the X-ray source; the detector is sensitive to UV radiation.

Carlo Campanelli
University of Nottingham

Processing of high performance fluoropolymers by additive manufacturing

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

This PhD focuses 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.

We have tested several fluoropolymers for laser sintering and inkjet applications. The high melting temperature, high viscosity, high molecular weight, and chemical inertness make the processing of these polymers quite challenging but progress has been made since the start of the project, which allowed the production of small parts with limited curling.

Adam Thompson
University of Nottingham

Surface texture measurement of metal additively manufactured parts by X-ray computed tomography

I have produced a number of publications during my PhD, initially producing a 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 (XCT) with additive manufacture. From this, two review papers have been produced, published in Measurement Science and Technology and the International Journal of Metrology and Quality Engineering, respectively.

Following the review stage, I undertook initial experiments examining metal additive manufacturing surfaces. Two publications were produced as a result of this research, comparing measurements made using different measurement technologies. In this work, 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 XCT.

We also used stylus profilometry to measure the surface. Results showed that no single technology provides a completely trustworthy measurement, and that agreements between technologies offer a useful starting point towards an understanding of surface features. Disagreements provide hints as to why measurement technologies react differently to topographic features.

Following this, I worked on developing the use of XCT measurement of internal and hard-to-access surfaces; a novel application of this technology. The first stage of this research is currently under review in Additive Manufacturing. My initial investigations revealed that an examination of the sensitivity of XCT instruments was required, so I performed a study into the effects of changing geometric magnification and sampling in the reconstruction volume on XCT surface measurements.

I'm currently preparing a paper based on this work for submission to Nature Communications, while concurrently performing measurements to apply the techniques developed during my PhD to an industrial case study.

Alex Gasper
University of Nottingham

Spatter and quality issues caused by powder in laser powder bed fusion

This project investigates the role of powder in the laser powder bed process. Through greater understanding, potential quality issues can be better controlled. A factor of the dynamic behaviour of the powder during processing is the generation of spatter. This spatter constitutes a secondary powder system within the process and can influence the production of parts and recycling of the powder. We chose to investigate nickel-based superalloys as an exemplar material.

CDT Industry Visit Day
6 April 2017, University of Nottingham

The Industry Visit Day was held in Jubilee Campus Conference Centre and was attended by 81 delegates, including CDT students, representatives from industry – who are currently sponsoring a student – and new industry links.

The day started with a presentation by Professor Chris Tuck, CDT Director, who provided an overview of the Centre and its progress over the past three years, both in research and industry collaboration. This was followed by presentations

from CDT students on their projects, highlighting how they have benefited from having an industrial sponsor and the skills they have developed through their industrial internship programme. There were also networking and poster sessions during the day, which offered the opportunity for further interaction to all delegates.

Since the launch of the Centre in 2014, the CDT has attracted over 25 of industrial sponsors and its industry portfolio is still growing.

Sponsor portfolio

Student testimonials on the benefits on having a sponsor

“Not only does it allow for a unique perspective that may not have been possible within an academic setting, it also allows for the project to be more in keeping with industry.”
Sarah Kelly

“Having spent some time with GSK, I learned about the different research protocols that are used by a major pharmaceutical company and how they differ from research in academia.”
Hatim Cader

“The specific, long-term objectives of my industrial sponsor have helped me better define the aims of my research project.”
Yazid Lakhdar

“Close collaboration with an industrial sponsor allows access to a huge knowledge base and research needs are more easily identified.” **Babis Tzivelekis**

“In addition to funding research projects into the treatment of osteoarthritis, ARUK TEC has organised numerous training events, such as ‘Patient Participation and Involvement’, and workshops run by research groups located in connected universities. The Centre holds an annual symposium located in the RJAH Orthopaedic Hospital in Oswestry, which brings researchers together to present developments in different areas of the field of cartilage tissue engineering.”
Kegan McColgan-Bannon

Sponsors' testimonials on the benefits of working with CDT students

"Michael Ward has added considerable insight and academic rigour to many of our projects and is a valued member of our team. We are delighted to have him with us for the next two years of the programme and, we hope, a full time role thereafter."
Henry Pinchbeck, 3D LifePrints

"The CDT student Greg Murray is a key contributor to the development of smart materials via additive manufacturing for next generation functional footwear. The CDT engagement allows access to high calibre graduates to work on projects of industrial relevance; access to university capabilities; access to subject specialists; and the development of strategic links with the higher education sector."
Simon Bradshaw, Texon

"We have the direct benefit of working with the student on a topic of interest, which enhances our understanding. Thanks to this relationship, we also have connections to the group he is working in and this enhances our understanding of a large number of areas. I am impressed by the amount of progress made on a difficult topic and can see practical applications becoming available soon."
David Bate, Nikon

"We see Lewis Newton as a key link between the Metrology & NDT group at the MTC and the Manufacturing Metrology group at the University of Nottingham, transferring fundamental research into industrial implementation, passing on expertise and opening up conversations about further collaboration. The MTC and Nottingham have developed an exciting collaboration as a result of his studentship and we are keen for this to continue."
Evangelos Chatzivagiannis, MTC

Other sponsors include Texon, Stryker and Alcyomics.

Outreach

Open Source Prosthetics and Assistive Devices Group

10 October 2016

The event was an introductory presentation and an exercise in the use and development of 3D-printed prosthetics. A working group has been set up to design and produce customised assistive, adaptive and rehabilitation devices, in collaboration with Nottingham University Hospitals, Royal National Orthopaedic Hospital and the charity Remap.

Academic Support Family Learning Session

11 October 2017

This outreach session was designed for young children and their families to introduce them to 3D printing, additive manufacturing and the opportunities they afford. PhD students took a desktop FDM 3D printer and a number of 3D-printed objects with them to the session, explaining to pupils how the machine works, why it's special and what the PhD students do (as well as keeping an eye on the machine!). The students prepared a Tennis Ball Towers design challenge, with the successful team winning a 3D-printed robot.

Visit from the National Defense University, USA

25 April 2017

The group visit consisted of US navy officers and guards (class of 2017) from the Eisenhower School for National Security and Resource Strategy, and international officers. The day involved an introduction by NDU followed by a presentation by Professor Ian Ashcroft, who

provided an overview of the CDT, ongoing research and interaction with industry as well as a lab tour by students and staff. After the visit, we received a letter from NDU explaining how the event contributed to their students successfully finalising their deliverables to senior US government and industry leaders. With this in mind, we would like to continue this relationship, arranging future visits for both institutions that will lead to increased knowledge exchange and student benefits.

Pint of Science
14-16 May 2017

This outreach event is one of the world's largest public science festivals and its aim is to make science accessible to the public.

CDT students ran a stall at the event, which included live demonstrations as well as 3D printed objects. The stall attracted a lot of visitors, including the sheriff of Nottingham.

Christ the King College visit
16 May 2017

Having already been involved in some 3D printing projects, students from Christ the King College were given a more advanced overview of additive manufacturing and 3D printing. The purpose of the visit was to encourage college students to engage in science, technology, engineering and mathematics (STEM) subjects and, more specifically, engineering as a career.

Family Learning Graduation Day

11-12 July 2017

The Family Learning Graduation Day was an opportunity to introduce additive manufacturing and 3D printing to primary school children. There was lots of interest in the material extrusion demonstration and many of the children engaged with the stand.

Shirebrook Academy Industry Day

14 July 2017

CDT students Lewis and Vicente visited a high school to deliver sessions on additive manufacturing and the importance of metrology work. These sessions were delivered in form of 10-15-minute activities, effectively engaging Shirebrook Academy pupils.

Starworks: Innovations in Prosthetics for Young People

28 September 2017

A sandpit event was run by the Starworks Innovation Project to bring different sectors of prosthetic development together; this included industry, academics, clinicians, patients and charities. The focus of this sandpit was ‘Upper Limb Personalisation and Adaption’ for young people. The differing perspectives from each sector highlighted the challenges young people face and sparked interesting debates. The main takeaway from this experience was the importance of communication between the sectors in order to make an effective product.

Student blogs and interviews

Priscila Melo
3DMedNet

7 September 2017
Binder jetting: processing parameters and application in orthopaedics

Using computer-aided-design (CAD), additive manufactured parts are produced layer by layer. The design is converted into an STL file, which is a specific format used by additive manufacturing machines. The design information can come from either a CT or MRI scanner, depending on the application, or a combination of both. The material, whether liquid or a solid state, dictates the technique applied to produce the device in question; for example, thermoplastic polymers are molten to a viscous state; resins are cured using light; solid bulks are deformed using mechanical energy; and powders are shaped using binders or lasers (Gibson, Rosen, & Stucker, 2010).

To read the full blog, please visit **https://goo.gl/KbKS5f**.

Alex Gasper
Essentra Components

4 May 2017
Additive manufacturing goes under the microscope

Q: “Describe a typical day in the laboratory?”

A: “There isn’t one.” Doctoral researcher Alex Gasper, an enthusiastic champion of STEM subjects and the whole engineering profession, says variety is the norm in his job.

Gasper is currently focusing on processing nickel superalloys for selective laser melting, an additive manufacturing process.

Powder feedstocks and 3D-printed parts
Gasper works in the CDT in additive manufacturing and 3D Printing based at Nottingham University. He is investigating powder feedstocks for the selective laser melting process with a focus on nickel superalloys, which are widely used in aerospace and other sectors. The CDT boasts a range of state-of-the-art equipment, including a set of selective laser melting machines. Gasper and his team are designing, building and processing additive manufacturing parts made from nickel superalloy powders.

“The additive manufacturing process generates spatter, which is subsequently analysed in the lab,” says Gasper, explaining that build times for a new component range from to two to 20 hours. “We’re trying to determine the best processing parameters for the nickel superalloy powder used to make the parts." The superalloy additive manufacturing parts are subsequently analysed and processed in a similar way as they would be in industry, with analysis via microscopy, and via the cutting and polishing of components.

The results of the analysis are correlated against the expectations of the researchers, and fed into the next set of experiments. Their research will ultimately contribute to the development of additive manufacturing superalloy parts in industries such as aerospace and power generation, and also more widely in terms of understanding of how metal powder behaves in the selective laser melting process – and its mechanical and material properties change.

Gasper says the research has the potential to impact many areas of additive manufacturing. The CDT is the only one of its type in the country, so it provides a special opportunity for a young engineer. "The facilities we have here for additive manufacturing and engineering are unique and there is an academic rigour which is very attractive to me. In terms of the direction I want to go in my career, it has proved to be an amazing opportunity."

Priscila Melo

Women in 3D Printing

20 September 2017

Q: Priscila, could you let us know about your background and what brought you into 3D printing in the CDT?

A: I am a biomedical engineer specialising in biomaterials and medical devices. I did both my Bachelor degree and Masters in Portugal. Ever since starting on my Bachelor degree, my goal has been to work with biomaterials, exploring new solutions and manufacturing processes. My interest in 3D printing, specifically as a manufacturing technique, emerged during my Masters when a friend of mine started his PhD on 3D printing of porcelain. I read up on it intensively and found that research on its application for medical devices was quite recent. Biofabrication, in particular, captured my imagination: the idea of being able to print an organ and give it to someone who needs it; the thought of a world without a transplant waiting list. It is easier said than done, of course. However, my interest didn't die there. Medical devices are a solution and have the potential to improve people's lives. Being able to create and develop personalised devices that can specifically meet a patient's needs was also interesting to me.

So, this became my goal: to embark on a PhD 3D printing of medical devices. The research is incredibly specific, which limited my choices, but I never discarded the use of other techniques. I was lucky and I'm

now exploring two additive manufacturing routes to processing bone implants.

Q: Could you explain the subject of your PhD?

A: This project is sponsored by the EPSRC and Glass Technology Services (GTS), an independent glass laboratory and consultancy company, focused on glass research and development. I have been working with GTS since September of 2015 on an R&D project. My aim is to develop a bone implant that incorporates a bioactive ceramic, apatite-wollastonite (AW), developed by Kokubo in 1982, and now produced at GTS as part of this R&D project. To do so, I'm looking to optimise the manufacturing process and make the material commercially viable for medical applications.

Q: Which technologies and materials are you working with?

A: I'm using two techniques: binder jetting and fused filament fabrication (FDM). With binder jetting, I'm producing porous AW implants for load bearing applications. This is the main part of my project, which seeks to optimise this process and commercialise the material for orthopaedics. With FFF, I'm manufacturing a polymer/ceramic filament that can be printed and work as a bone scaffold (cell growth platform). The objective is to ensure that the polymer is able to attract and guide bone cells once implanted, since it can't do this inherently. The AW ceramic is bioactive and so will enable the polymer to do this. Bioactive materials have the capacity to induce the formation of an apatite layer between the implant and the tissue. This layer has an identical composition to the human bone mineral phase.

Q: In terms of 3D printing technologies, what are the challenges for the medical field?

A: The medical field is full of solutions; however, none of them are perfect, and

> I was most excited about the printing of cardiac cells and the fact that you could actually see them pulsing, just like myocardium cells. It was like seeing a small scale beating heart
>
> **Priscila Melo**

all have weaknesses. The main goal of a researcher is to plug these gaps. 3D printing technologies are important because they offer personalised solutions, but they're not cheap. In my case, the established device won't be cheaper than commercially available ones, but it will be mechanically stronger and serve a wider range of applications.

Being able to offer tailored solutions is a big step. And all cases are different; some conditions are easier to treat and benefit from mainstream therapies, while other conditions need a more personalised approach. These are the conditions we target with 3D printing – at least for now. In the future, once the technology is well understood and available, then 3D machines could be installed in health units all over the world and be able to 'print' organs in situ. But that future far ahead. For now, improving existing therapies is the main focus.

Q: What is the most impressive or impactful use of 3D printing you've seen so far?

A: I have witnessed some amazing progress in 3D printing, but I think the one I was most excited about was the printing of cardiac cells and the fact that you could actually see them pulsing, just like myocardium cells. It was like seeing a small scale beating heart. This study is taking place at Sydney's Heart Research Institute and brings us one step closer to organ printing, but it's a long road, and a hard one. That said, this type of breakthrough is what makes 3D printing fascinating to me as a postgraduate.

Q: What makes the 3D printing industry particularly interesting for you, first as a postgraduate, and second as a woman?

A: I consider myself new to this world of 3D printing and, so far, all I want is to understand things and use my knowledge to improve people's lives. As a PhD student in my first year, I haven't make any amazing discoveries, but some of the results I've obtained look promising and will be reported in scientific publications.

As a woman, 3D printing opens up a whole new world of possibilities. Women in this area usually come from other subjects, but they're mainly situated in the medical sector. This is due to the fact that 3D printing is a relatively new technology and is highly associated with engineering; none of these factors contribute to increasing the number of women in the area.

Q: In your opinion, how could we encourage more women to become involved with 3D Printing?

A: Getting female professionals to promote the technology in schools and universities is a great first step to seed the idea. Girls never expect to see women in these types of roles, but once they know what you do and how it works they become interested and are curious about it.

Training and development

As well as the CDT's taught programme, additional training and development opportunities are offered to the students throughout the year. A few examples are:

Nature Publication Masterclass

This training programme was a two-day event designed to teach researchers how to write high-quality scientific manuscripts and optimise their chances of being published in high-impact journals. To achieve these objectives, Nature Masterclasses used a combination of short lectures, open discussions and practical exercises. To ensure that all cohorts benefit from this training, the masterclass will be repeated annually for the next two years.

Following a feedback report for the training, 88% of the students felt more confident about writing and submitting manuscripts, with 82% rating the quality of the training as 'excellent'.

"A really thorough, well explained and presented workshop. The editors were approachable as well as knowledgeable. Worth the investment as it was engaging throughout." James Smith, CDT student, Loughborough University

Postgraduate seminars

To encourage student interaction and cross-fertilisation of ideas, these seminars are held on a monthly basis with five students presenting a talk on their project. Each seminar is chaired by an academic colleague and is followed by a discussion/debate session.

Invited speaker seminars

Experts from the field of additive manufacturing, both in academia and industry, are invited to present a talk about their sphere of expertise. This not only enhances students' educational experience but also creates links and new opportunities. Previous speakers were Professor Peter Krüger, University of Sussex; Professor Iain Todd, University of Sheffield; Professor Russell Harris, University of Leeds; Dr Victor San Sangorrin, University of Nottingham; Dr Johannes Gumpinger, European Space Agency, and Dr Simon Locke from Dyson.

Creativity@Home

3D Design Masterpiece

7 April 2017

The overall challenge of this event was for individual teams to separately design, draw and paint giant pieces of canvas, which had to come together to reveal the final 'masterpiece'.

Collaboration and communication was key, as the teams with adjacent canvases had to match up their scaling, edges and colours.

Student feedback on Creativity@Home:

"The Creativity@Home event has been a useful way of getting to know CDT students from the Chemistry Department and further improve working relationships between our CDT cohorts."
Carlo Campanelli

"Creativity@Home provides an opportunity for CDT students to work together and create something interesting."
Chung Han

"Creativity@Home is a fantastic informal opportunity to network with fellow colleagues."
Michael Ward

"These workshops are a refreshing experience away from direct research, and allow us to work on our interpersonal skills with one another. The latest team building activity involved a fun painting challenge that relied on separate group efforts coming together for a larger group goal."
Lewis Newton

The Engineering and Science for Sustainable Future (ESSF) Student-led conference

26-27 June 2017, University of Nottingham

The ESSF conference was a joint conference organised by students from Additive Manufacturing, Sustainable Chemistry and BBSRC CDTs. The event was aimed at postgraduate students from across the universities in the UK, with the purpose of bringing together early-stage postgraduate students and academics from different backgrounds and expertise to address the challenges of a sustainable future through a multidisciplinary network of collaborations. Moreover, it was intended to enable students to organise a research event and develop skills they may not otherwise achieve by working in the lab.

As well as talks by postgraduate students, poster sessions and opportunities for networking, the conference included talks by three experts: Professor Lee Cronin from the University of Glasgow, who introduced his revolutionary ideas about recreating the origin of life in the laboratory as a kit to design artificial biology; Professor Paul Genever from the University of York on applying genetically modified stem cells to treat age-related diseases that affect the human skeleton; and Professor Maria Reis from Nova University, who spoke about the development of novel and more sustainable processes to produce biodegradable polymers from waste.

Four students, Yazid Lakhdar (AM CDT student), Mariana Gameiro, Thomas Clarke and Eleanor Bellows, did a fantastic job in planning, organising and delivering the conference, which took several months to prepare. They also secured the presence of Sir Fraser Stoddart, Nobel Laureate in Chemistry 2016, as keynote speaker of the event, who presented a talk on 'Serendipity and Scientific Careers'.

Publications

Analysis and comparison of wrist splint designs using the finite element method: multi-material three-dimensional printing compared to typical existing practice with thermoplastics. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 231 (9), pp. 881-897. July 2017. Cazon, A; Kelly, S; Paterson, A; Bibb, R J.; Campbell, R.I.

Rheumatoid arthritis (RA) is a chronic disease affecting the joints. Treatment can include immobilisation of the affected joint with a custom-fitting splint, which are typically fabricated by hand from low temperature thermoplastic (LTT), but the approach poses several limitations. This study focused on the evaluation, by finite element analysis (FEA), of additive manufacturing (AM) techniques for wrist splints in order to improve upon the typical splinting approach. An AM splint, specifically designed to be built using Objet Connex multi-material technology and a virtual model of a typical splint, digitised from a real patient-specific splint using 3D scanning, was modelled in Computer-Aided Design software. Forty FEA simulations were performed in Flexion-Extension and Radial-Ulnar wrist movements to compare the displacements and the stresses. Simulations have shown that for low severity loads, the AM splint has 25%, 76% and 27% less displacement in the main loading direction than the typical splint in Flexion, Extension and Radial respectively, while Ulnar values were 75% lower in the traditional splint. For higher severity loads, the Flexion and Extension movements resulted in deflections that were 24% and 60% respectively lower in the AM splint. However, for higher severity loading the Radial defection values were very similar in both splints and Ulnar movement deflection was higher in the AM splint. A physical prototype of the AM splint was also manufactured and was tested under normal conditions to validate the FEA data. Results from static tests showed maximum displacements of 3.46mm, 0.97mm, 3.53mm, and 2.51mm Flexion, Extension, Radial and Ulnar directions respectively. According to these results, the present research argues that, from a technical point of view, the AM splint design stands at the same or even better level of performance in displacements and stress values in comparison to the typical LTT approach and is therefore a feasible approach to splint design and manufacture.

Topography of selectively laser melted surfaces: a comparison of different measurement methods CIRP Annals – Manufacturing Technolology 66 543–546. April 2017. Thompson, A; Senin, N; Giusca, C; Leach, R.K.

Selective laser melting (SLM) of metals produces surface topographies that are challenging to measure. Multiple areal surface topography measurement technologies are available, which allow reconstruction of information rich, three-dimensional digital surface models. However, the capability of such technologies to capture intricate topographic details of SLM parts has not yet been investigated. This work explores the topography of a SLM Ti6Al4V part, as reconstructed from measurements by various optical and non-optical technologies. Discrepancies in the reconstruction of local topographic features are investigated through alignment and quantitative assessment of local differences. ISO 25178-2 areal texture parameters are computed as further comparison indicators.

Characterisation of the topography of metal additive surface features with different measurement technologies Measurement Science and Technology 28 095003. August 2017. Senin, N; Thompson, A; Leach, R.K.

The challenges of measuring the surface topography of metallic surfaces produced by additive manufacturing are investigated. The differences between measurements made using various optical and non-optical technologies, including confocal and focus-variation microscopy, coherence scanning interferometry and X-ray computed tomography, are examined. As opposed to concentrating on differences, which may arise through computing surface texture parameters from measured topography datasets, a comparative analysis is performed focusing on investigation of the quality of the topographic reconstruction of a series of surface features. The investigation is carried out by considering the typical surface features of a metal powder bed fusion process: weld tracks, weld ripples, attached particles and surface recesses. Results show that no single measurement technology provides a completely reliable rendition of the topographic features that characterise the metal powder-bed fusion process. However, through analysis of measurement discrepancies, light can be shed on where instruments are more susceptible to error, and why differences between measurements occur. The results presented in this work increase the understanding of the behaviour and performance of areal topography measurement, and thus promote the development of improved surface characterisation pipelines.

Fractal scan strategies for selective laser melting of 'unweldable' nickel superalloys. May 2017. Catchpole-Smith, S; Aboulkhair, N; Parry, L; Tuck, C; Ashcroft, I.A.; Clare, A.T.

In this paper, novel fractal scanning strategies based upon mathematical fill curves, namely the Hilbert and Peano-Gosper curve, are explored in which the use of short vector length scans, in the order of 100 μm, is used as a method of reducing residual stresses. The effect on cracking observed in CM247LC superalloy samples was analysed using image processing, comparing the novel fractal scan strategies to more conventional 'island' scans. Scanning electron microscopy and energy dispersive X-ray spectroscopy was utilised to determine the cracking mechanisms. Results show that cracking occurs via two mechanisms, solidification and liquation, with a strong dependence on the laser scan vectors. Through the use of fractal scan strategies, bulk density can be increased by 2 ± 0.7% when compared to the 'island' scanning, demonstrating the potential of fractal scan strategies in the manufacture of typically 'unweldable' nickel superalloys.

Meso-scale defect evaluation of selective laser melting using spatially resolved acoustic spectroscopy. September 2017. Proceedings of The Royal Society. A. Hirsch, M; Catchpole-Smith, S; Patel, R; Marrow, P; Wenqi Li, Tuck, C; Sharples, S.D.; Clare, A.T.

In this study, a combination of optical microscopy and spatially resolved acoustic spectroscopy imaging (SRAS) was used to identify and classify the surface defects present in selective laser melting (SLM)-produced parts. By analysing the datasets and scan trajectories, it is possible to correlate morphological information with process parameters. Image processing was used to quantify porosity and cracking for bulk density measurement. Analysis of surface acoustic wave data showed that an error in manufacture in the form of an overscan occurred. Comparing areas affected by overscan with a bulk material, a change in defect density from 1.17% in the bulk material to 5.32% in the overscan regions was observed, highlighting the need to reduce overscan areas in manufacture.

Biosynthetic PCL-graft-Collagen Bulk Material for Tissue Engineering Applications. Materials 2017, 10(7), 693; doi:10.3390/ma10070693. June 2017. McColgan-Bannon, K; Gianone, N.C.; Sefat, F; Dalgarno, K; Ferreira; A.M.

Biosynthetic materials have emerged as one of the most exciting and productive fields in polymer chemistry due to their widespread adoption and potential applications in tissue engineering (TE) research. In this work, we report the synthesis of a poly(ε-caprolactone)-graft-collagen (PCL-g-Coll) copolymer. We combine its good mechanical and biodegradable PCL properties with the great biological properties of type I collagen as a functional material for TE. PCL, previously dissolved in dimethylformamide/dichloromethane mixture, and reacted with collagen using carbodiimide coupling chemistry. The synthesised material was characterised physically, chemically and biologically, using pure PCL and PCL/Coll blend samples as a control. Infrared spectroscopy evidenced the presence of amide I and II peaks for the conjugated material. Similarly, XPS evidenced the presence of C–N and N–C=O bonds (8.96 ± 2.02% and 8.52 ± 0.63%; respectively) for PCL-g-Coll. Static contact angles showed a slight decrease in the conjugated sample. However, good biocompatibility and metabolic activity was obtained on PCL-g-Coll films compared to PCL and blend controls. After three days of culture, fibroblasts exhibited a spindle-like morphology, spreading homogeneously along the PCL-g-Coll film surface. We have engineered a functional biosynthetic polymer that can be processed by electrospinning.

Measurement of the internal surface texture of additively manufactured parts by X-ray computed tomography In: 7th Conf. Industrial Computed Tomography Leuven, Belgium (iCT 2017). Thompson, A; Körner, L; Senin, N; Lawes, S; Maskery, I; Leach, R.K.

Recent advances in X-ray computed tomography (XCT) have allowed for measurement resolutions approaching the point where XCT can be used for measuring surface topography. These advances make XCT appealing for measuring hard-to-reach or internal surfaces, such as those often present in additively manufactured parts. To demonstrate the feasibility and potential of XCT for topography measurement, topography datasets obtained using two XCT systems are compared to those from more conventional non-contact optical surface measurement instruments. A hollow Ti6Al4V part produced by direct metal laser sintering is used as a measurement artefact. The artefact comprises two component halves that can be separated to expose the internal surfaces. Measured surface datasets are compared by various qualitative and quantitative means, including the computation of ISO 25178-2 areal surface texture parameters. Preliminary results show that XCT can provide surface information comparable with more conventional surface measurement technologies, thus representing a viable alternative to more conventional measurement, particularly appealing for hard-to-reach and internal surfaces.

Two-side processing method for producing high-aspect ratio micro holes ASME J. Micro Nano. Manufac.5, 041006-14. Nasrollahi, V; Penchev, P; Dimov, S; Körner, L; Leach, R.K.; Kynghan, K. 2017.

Laser microprocessing is a very attractive option for a growing number of industrial applications due to its intrinsic characteristics, such as high flexibility and process control and also capabilities for noncontact processing of a wide range of materials. However, there are some constrains that limit the applications of this technology, i.e., taper angles on sidewalls, edge quality, geometrical accuracy, and achievable aspect ratios of produced structures. To address these process limitations, a new method for two-side laser processing is proposed in this research. The method is described with a special focus on key enabling technologies for achieving high accuracy and repeatability in two-side laser drilling. The pilot implementation of the proposed processing configuration and technologies is discussed together with an in situ, on-machine inspection procedure to verify the achievable positional and geometrical accuracy. It is demonstrated that alignment accuracy better than 10 µm is achievable using this pilot two-side laser processing platform. In addition, the morphology of holes with circular and square cross sections produced with one-side laser drilling and the proposed method was compared in regard to achievable aspect ratios and holes' dimensional and geometrical accuracy; and thus to make conclusions about its capabilities.

Optimising Thermoplastic Polyurethane for Desktop Laser Sintering. Proceedings of Solid Freeform Conference Teas. August 2017. Richards, I.P.F. *1†; Garabet, T.M.N. 2; Bitar, I.S. 3,4; Salmon, F.M. 3

Laser Sintering (LS) is an industrially relevant additive manufacturing process that has become more accessible since the introduction of commercially available desktop-LS systems. However, useable materials are currently limited to several grades of nylon, and so the aim of this study was to optimise an unknown, novel material for use in desktop-LS. A grade of thermoplastic polyurethane (UNEXTPU) was analysed to determine thermal properties, particle characteristics and bulk powder flow efficiency. To facilitate laser absorption at 445nm, a carbon additive (graphite) was added to UNEXTPU; the addition of graphite also significantly improved flow efficiency. UNEXTPU was successfully processed on a desktop-LS system, and mechanical testing found that it possesses properties comparable to industrial grade thermoplastic polyurethanes (Elongation at Break: 139%, Tensile Modulus: 48.7Mpa, Ultimate Tensile Strength: 7.9Mpa, Shore Hardness: 75). Bulk powder flow efficiency and mechanical properties were retained in twice recycled powder. This research has established a new viable elastomeric material for use in desktop-LS.

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