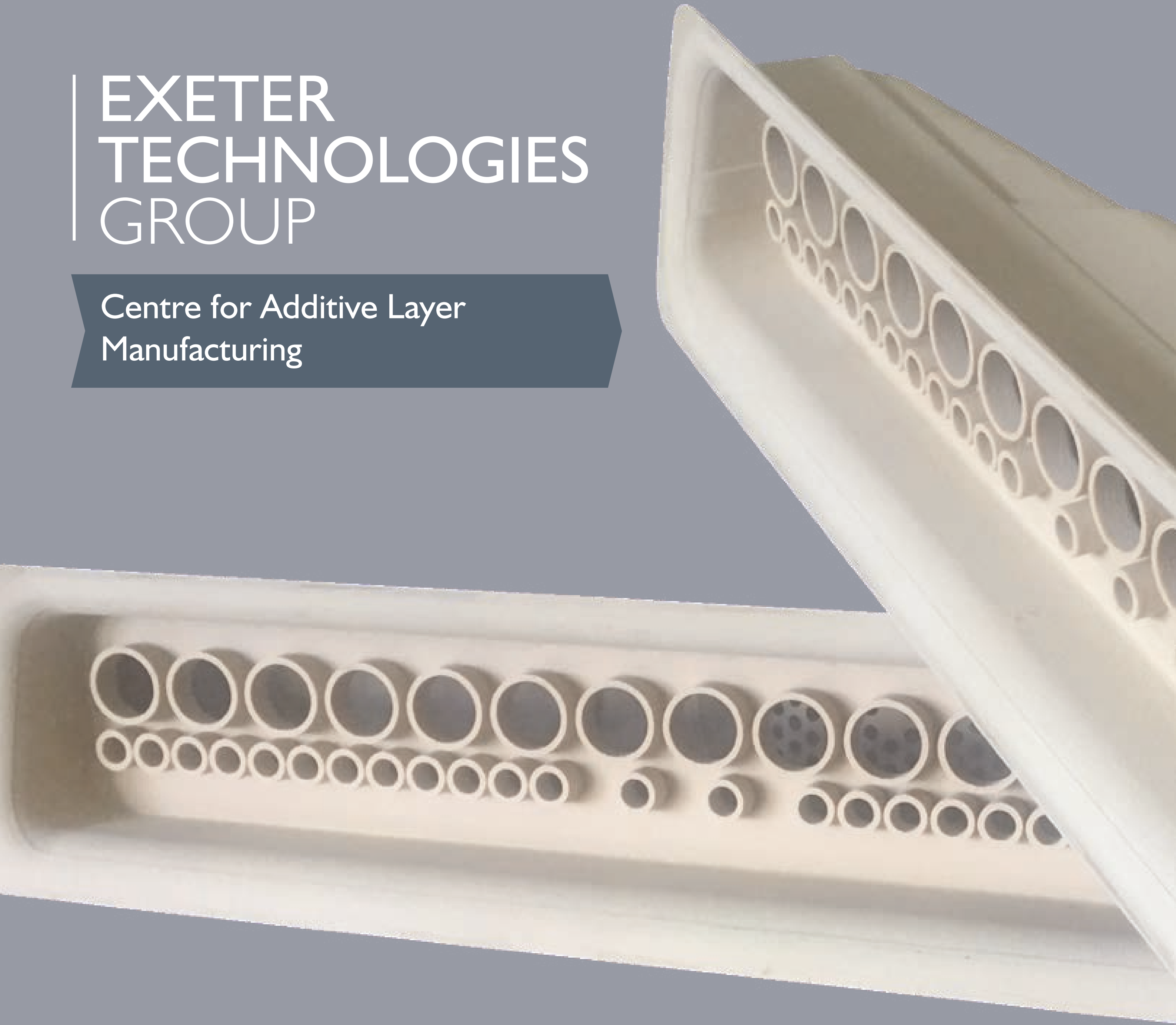
EXETER
TECHNOLOGIES
GROUP

Centre for Additive Layer Manufacturing



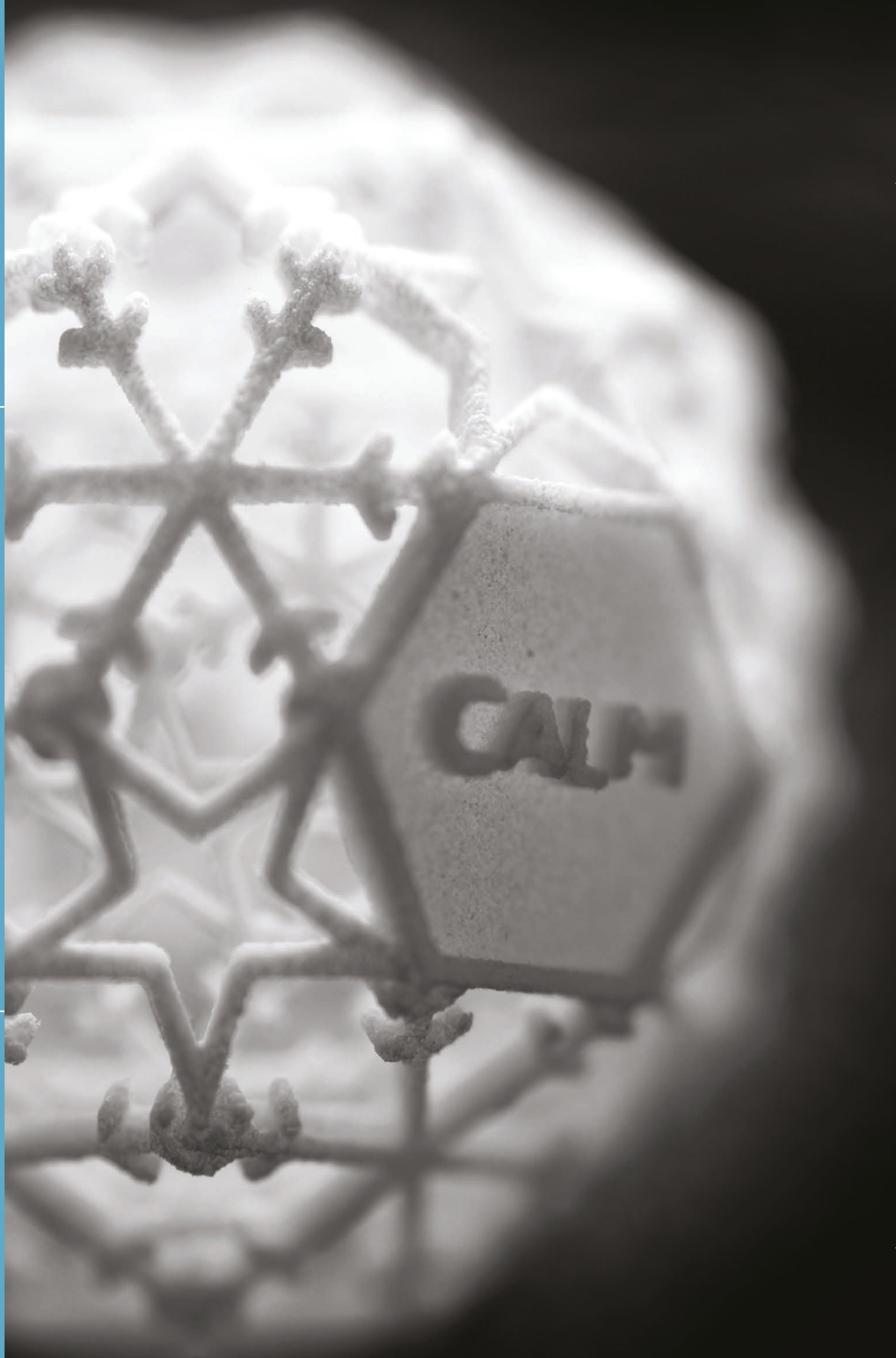
RESEARCH AND DEVELOPMENT

Research and Development at CALM
(Centre for Additive Layer Manufacturing)

UNIVERSITY OF EXETER

contents

Cover image: Laser sintered non-structural internal aircraft duct 500mm, made using Victrex PEEK developmental grade.



CALM is the centre of excellence in Additive Layer Manufacturing at the University of Exeter.

CALM is a leading research centre, working at multiple Technology Readiness Levels, on both fundamental and applied research. Our projects are funded through research councils (eg EPSRC), government organisations (eg Innovate UK and EU) or directly with industry partners through short and long term contract research. We aim to achieve maximum impact from our work and therefore collaborate with a wide range of organisations.

CALM offers independent research and technical support, working with both academia and industry worldwide, to develop the next generation of materials for engineering and high temperature polymers and composites.

With a background in material science and manufacturing, we are highly experienced in Additive Layer Manufacturing (ALM) materials research and development, from powder research, through to sintering and process investigation for part manufacture and analysis.

The Centre for Additive Layer Manufacturing (CALM)

Established in 2010, following significant investment from the EU, the University of Exeter and Airbus Group Innovations, CALM has supported hundreds of businesses in their quest to investigate and use ALM.

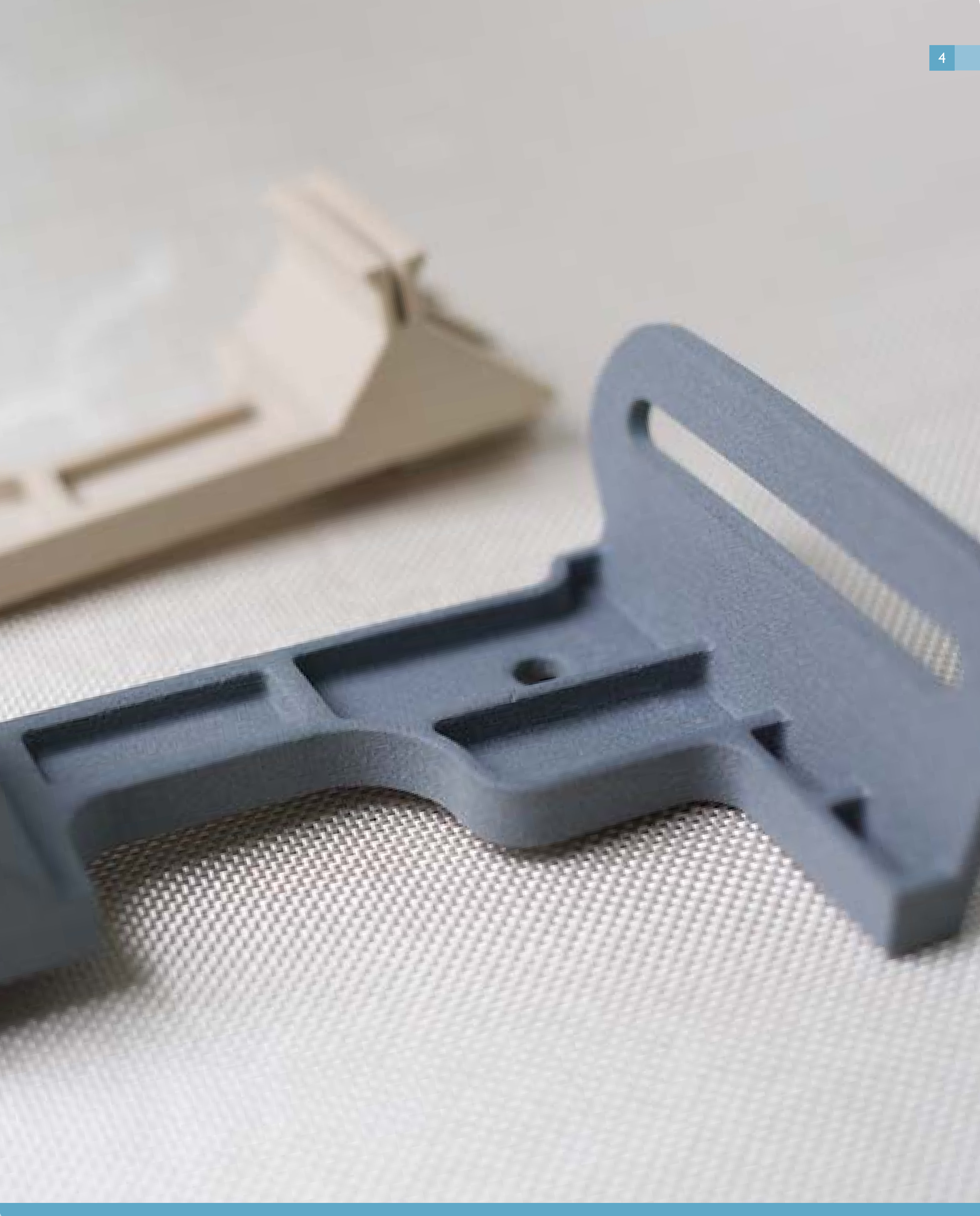
We have an extensive research programme on materials for ALM and offer contract research on all aspects of the technology, working in partnership with companies, other universities and government agencies.

Understanding the relationship between microstructure, processing and parts performance is at the heart of materials and process development. Particularly focused on solving material issues in ALM, we work together with our research partners at the cutting edge of current knowledge. We are working on projects that stretch and deepen our knowledge of ALM for high value and high impact industrial applications, creating more functional and sustainable products and processes.

We are the only independent centre worldwide researching laser sintering of high temperature and high performance engineering polymers and composites using the commercial high temperature laser sintering platform EOSINT P 800.

CALM is working with powder bed and free form fabrication (FFF) technologies tailoring existing materials and developing new ones. These include high temperature PAEK varieties and fluoropolymers, and high performance composites incorporating carbon fillers (graphite, carbon black), glass and carbon fibre reinforcement, carbon nanotubes (CNT), graphene, boron nitride and ceramic particles (WS_2).

We have the experience and capabilities required to run and compare new manufacturing technologies with established, conventional processes (eg extrusion, compression and injection moulding), and simulate manufacturing processes in thermal profiles and gas atmospheres.



CNT/PEEK bracket for improved light weighting and performance.

ALM challenges

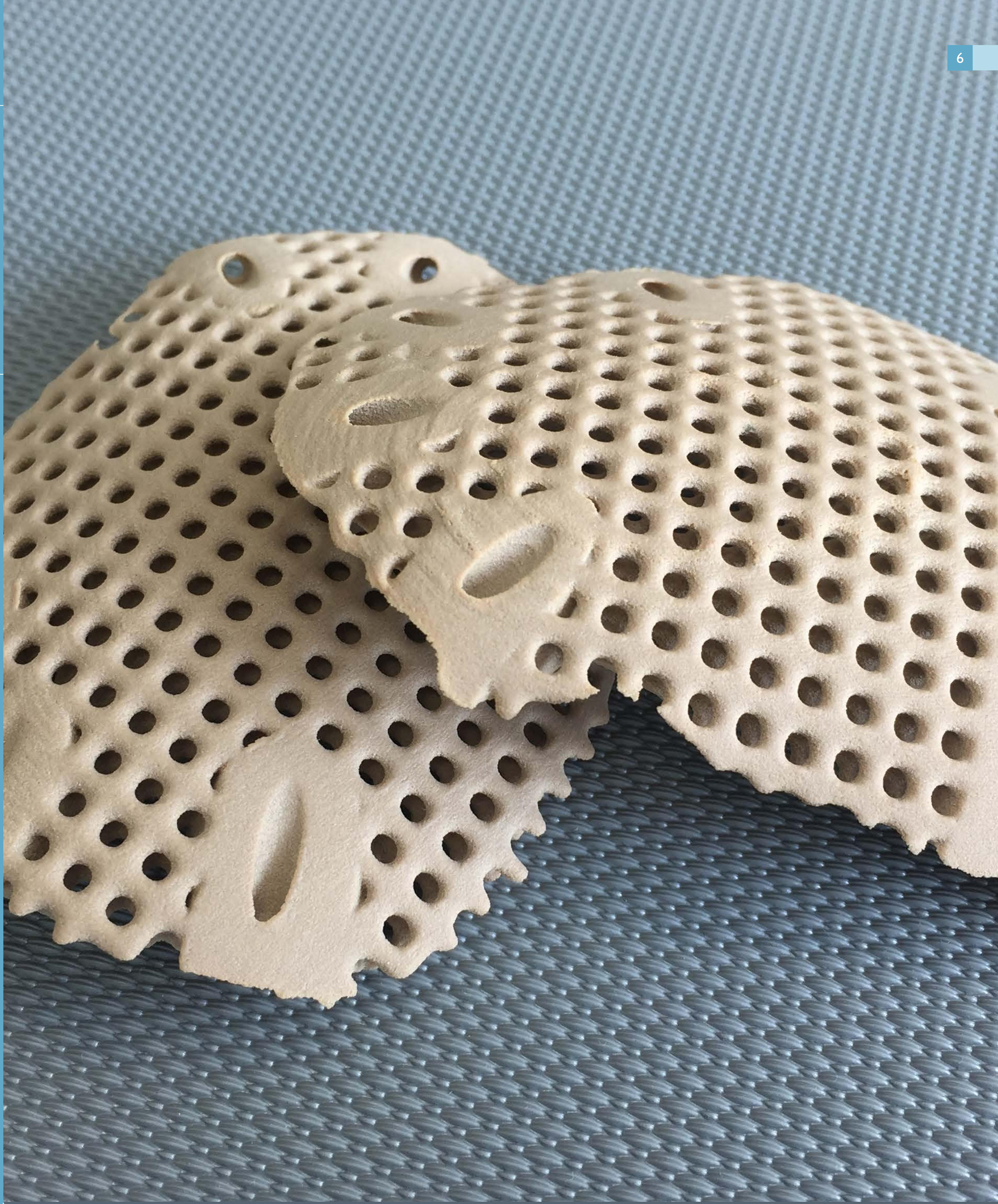
ALM is an enabling manufacturing technology and a catalyst for opening up new markets in customised products (for example patient specific surgical implants, or bespoke production equipment and tooling).

ALM offers tantalising prospects for better designed, more cost-effective and sustainable products, but there are inescapable challenges especially in the area of materials, such as:

- Limited range and high cost of powder materials for ALM
- The need for better control and monitoring of materials and systems in process
- The requirement for qualification of material properties across a range of production systems
- The need to understand how the microstructure of materials affects the performance of ALM components in use

Robust ALM manufacturing will only become widely adopted when material properties are known and understood at all levels – from molecular to macroscopic structures.

Our mission is to provide evidence-based solutions to the material challenges facing ALM.



Customised PEEK cranial implant geometries manufactured with laser sintering.

Expanding knowledge of ALM materials

As ALM moves from development into full-scale production, material understanding remains essential.

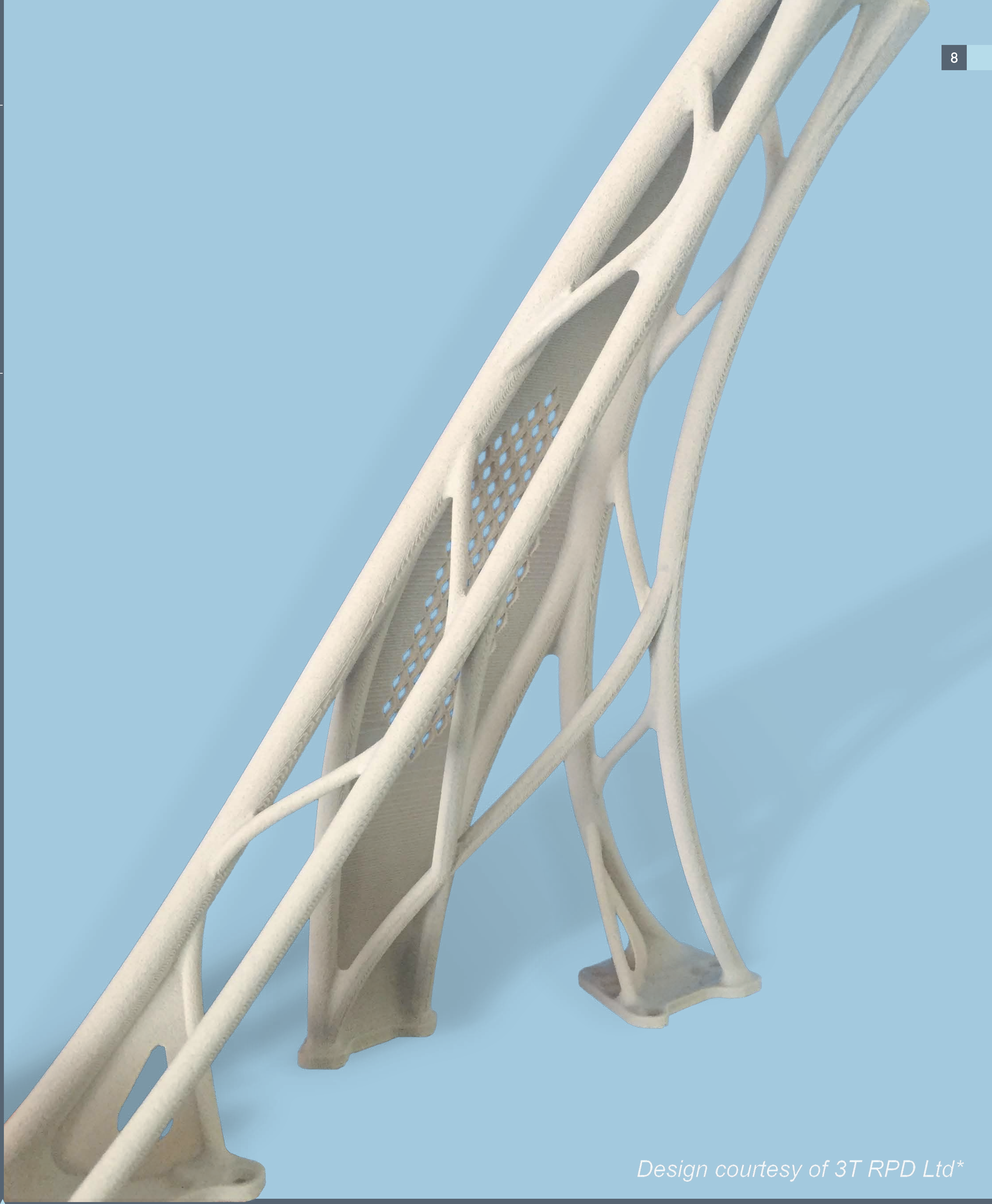
CALM is a global leader in materials research for high temperature laser sintering, publishing data that is independent from powder suppliers and machine manufacturers. For recent publications see page 23.

Despite laser sintering being one of the most cost-effective and robust ALM production methods, the range of commercially available materials that can be used in the process is still limited.

CALM is working with its partners to develop new high performance polymers. Using in-house designed methodologies and tests we investigate how the size, morphology of particles and subtle changes in chemical structures influence powder flow, spreadability and sintering. This is combined with statistical and mathematical methods to predict powder properties and performance.

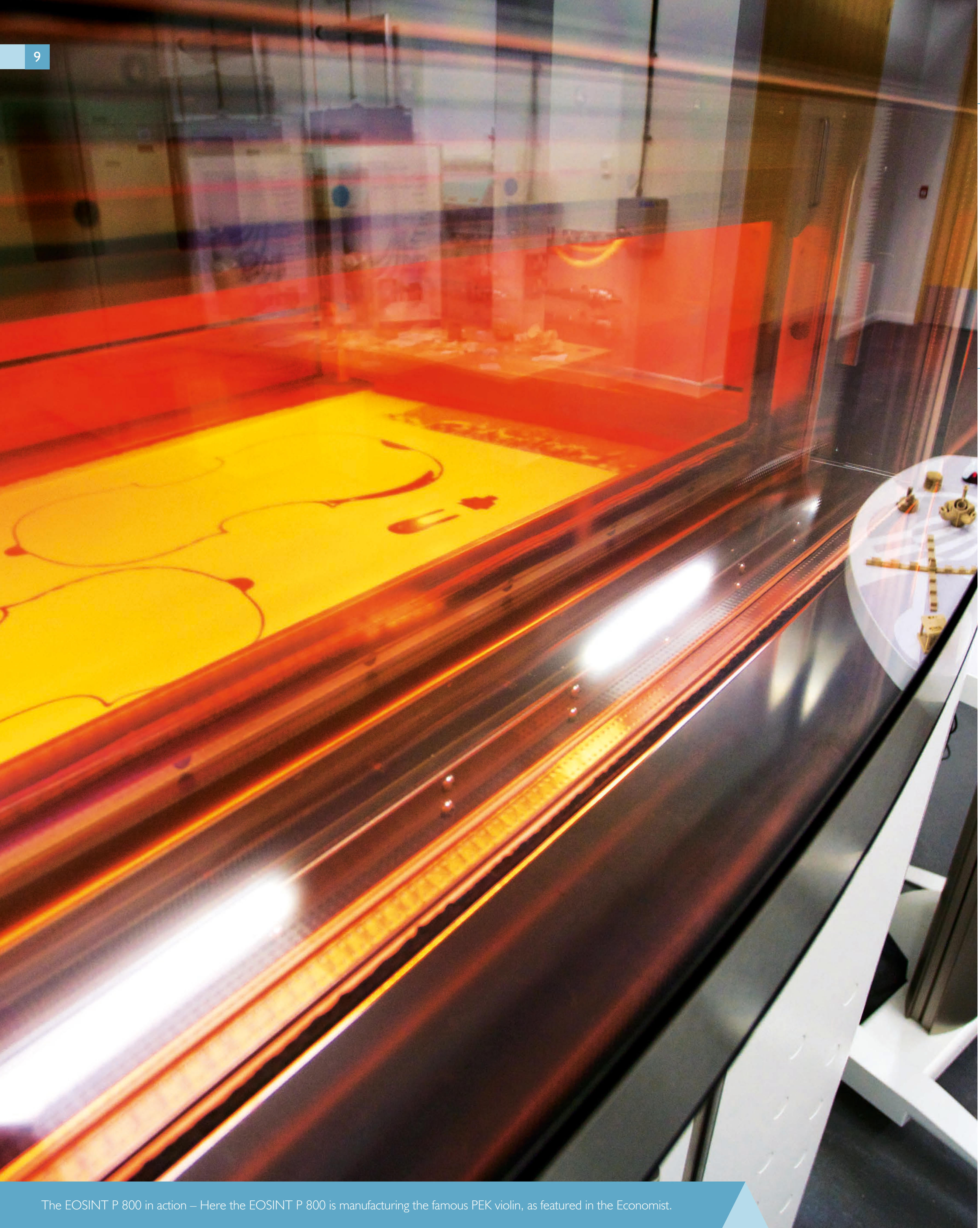
Through this work we are developing ways of improving key component properties and adding multi-functionality to parts, including introducing a range of glass, carbon fillers and nano-materials to create composite materials, providing new opportunities for the manufacture of lightweight and functional components.

Using in-house compounders, extruders and mixers, we manufacture and test novel ALM composite powders at low and medium batch sizes.



*Design courtesy of 3T RPD Ltd**

Topologically optimised demonstrator bracket made of experimental Victrex PAEK material. Design owned by 3T RPD Ltd., who reserves all rights to it.



The EOSINT P 800 in action – Here the EOSINT P 800 is manufacturing the famous PEK violin, as featured in the Economist.

New technologies and equipment assessment

As new technologies emerge the requirement for specific material knowledge becomes apparent.

CALM is supporting new equipment developments (powder bed or free form fabrication (FFF)), providing the material–process link. We optimise processes for specific materials, helping equipment manufacturers improve their systems.

We are engaging with new, exciting technologies with high potential to offer the robust manufacturing and high value parts sought after by industry. Through our work we can compare technologies and can define optimum processes for a specific material.

Combining the materials and equipment knowledge is essential to make the high performance parts of the future, where quality, consistency and performance are demanded. This requires a professional, thorough and collaborative approach, combining rigorous research approaches with the commercial and technical requirements of industry. CALM is partnering with the complete supply chain including selected equipment providers to help deliver the next generation of manufacturing technologies.

ASTM spinal cage geometries manufactured with laser sintered PAEK.

In process knowledge is vital in ALM

CALM is one of only a few organisations worldwide able to make high performing polymeric structures with the commercially available high temperature laser sintering platform – EOSINT P 800.

Using in-depth microstructure testing and analysis combined sometimes with modelling, we can predict and control the variability of components manufactured within the same build chamber, and also components manufactured on a range of different machine systems by different suppliers.

Process control based on in-depth material investigations is vital for ALM to become an accepted production tool.

Our work is rooted in realistic applications and production scenarios.

We use our knowledge to develop production-friendly ways of inspecting ALM components.

For example, we have designed a potentially non-destructive test, using Raman spectroscopy, which quickly determines the surface roughness of ALM components and relates it to laser sintering manufacturing parameters.

Investigating fully manufactured components only tells us half of the story. Using specific sensor technologies, we determine what happens to materials during manufacture. For example, the need for continuous in-line material monitoring led us to use optical fibre sensors for process improvement.

Improving knowledge and design of ALM components

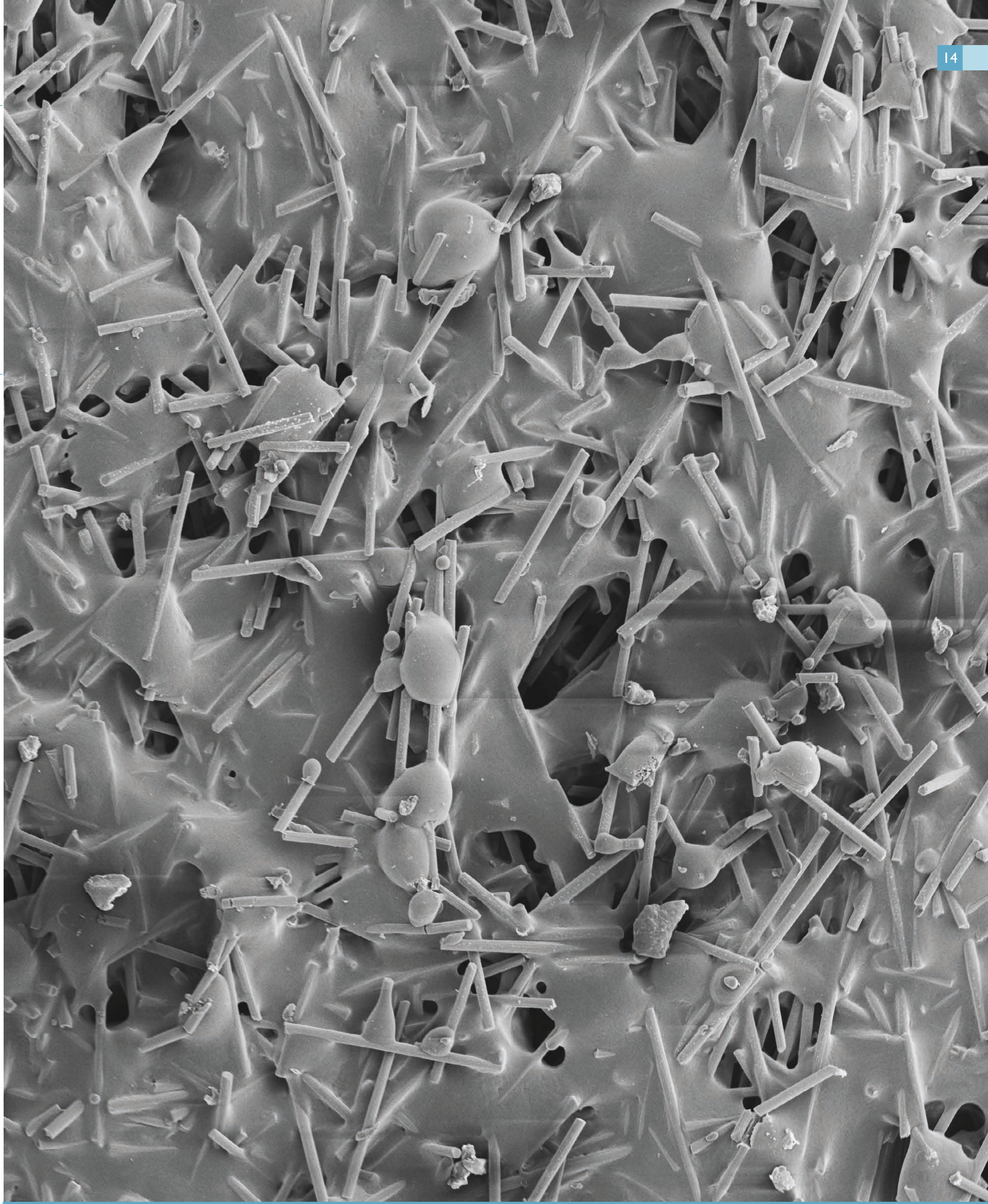
Quantifying key bulk properties using standard techniques is just the beginning of our investigations.

With an array of specialised tests, ranging from thermal and optical imaging techniques through to rheology and mechanical, we thoroughly investigate and scrutinise components. This helps us define component microstructure.

We identify how microstructure affects important macroscopic properties, helping us to predict how ALM components will behave when in use. Materials and parts characterisation allows us to define the material-process-properties relationship and define design guidelines as a function of material or equipment used. Different techniques offer different resolution and different levels of design freedom. We are able to advise and assess full parameters and equipment capabilities.

In addition, we are determined to understand and provide solutions to outstanding issues still concerning the AM processes including:

- Improving strength in the z-direction
- Developing new methods to fabricate composite materials to both reinforce components and add functionality
- Matching the performance of parts manufactured using conventional techniques
- Improving recycling rates



SEM image of carbon fibre reinforced PAEK (dry blend).

Research projects

Innovate UK 391 – Multifunctional PAEK nanocomposites for Additive Manufacturing (F4 PAEK)

Combining nano-particles with PAEK polymers, this project is looking to develop new bespoke lightweight multifunctional materials that can be 3D printed using powder bed fusion technology and FFF. PAEK polymers are temperature resistant, tough and corrosion resistant. They are increasingly being used as a metal replacement within aviation and military applications.

Boron nitride and graphene have been selected as the nano-materials most suited for the intended applications here. These new materials will offer multifunctional capabilities including lightweighting, thermal and electro-magnetic properties.

The project will study the surface chemistry of the nanoparticles for good interface bonding with PAEK; fabrication of the composite powder (encapsulation of the nanoparticles either on the surface or within the bulk of the PAEK particles) and laser sintering of these new powders. Powder properties (bulk density, compaction, shape – roundness and circularity, aspect ratio, viscosity, surface tension) are key parameters for a good sintering process.

Incorporation of nanomaterials with different particle sizes and shape, which will significantly affect powder flow, polymer viscosity and subsequently sintering mechanisms, are very important to the success of this project.

Funded by: Innovate UK

Partners: Qioptiq, Thales UK Ltd, Victrex Manufacturing Ltd, Hosokawa Micron Ltd, Airbus Operations Ltd, 2-DTech Ltd, Haydale Ltd

Innovate UK 102362 – High temperature affordable polymer composites for aerospace applications

High performance mouldable plastics like PEEK and others in the polyaryletherketone family (PAEK), and their engineered composites are materials of the future and of particular interest to airframe makers as a metal replacement, being 40-70% lighter than steel, titanium or aluminium. PAEK composites are also highly corrosion resistant, heat tolerant to 250°C+, possess outstanding flame, smoke, and toxicity performance, and can compete mechanically.

CALM is part of a consortium of eight organisations, led by Victrex, an innovative world leader in high-performance PAEK/PEEK polymer solutions headquartered in the UK, to develop PAEK for various 3D printing processes. This initiative brings together the entire materials and processing supply chain, including polymer makers/suppliers, through to parts manufacturers, post-processors and end users.

As a result of this large collaboration, Victrex is preparing newly developed materials for Additive Manufacturing (AM). The first of these is a high strength material for laser sintering (LS) which attains lower refresh rates, resulting in improved recycling for unsintered powder. The second is a filament with better Z-strength than existing PAEK materials and better printability for filament fusion (FF).

> “These next-generation VICTREX PAEK materials for Additive Manufacturing mark a decisive step forward, having potential to transform multiple applications, including Aerospace and Medical. The exciting progress is based on continued intense R&D at Victrex and excellent collaboration within the Victrex led consortium of companies and institutions pursuing innovation in Additive Manufacturing. Through this consortium we’re already seeing demonstrator parts that show how AM processes, coupled with high-performance materials, transform thinking to create truly innovative parts based on increased design possibilities.”
>
> *Jakob Sigurdsson, Victrex CEO*

The new VICTREX PAEK filament and powder tie in with technologies developed by other members of this Innovate UK project. EOS has recently released a new automation-ready manufacturing platform for laser sintering of plastic parts on an industrial scale (EOS P 500) with the capability to print high-performance polymers at high temperatures. Selected materials of the consortium are evaluated at EOS R&D facilities for processability on current EOS systems as well as for use with the EOS P 500 platforms. Victrex is planning to continue pre-commercial testing of a new PAEK Filament product in conjunction with consortium partner E3D, who has recently commercially released a new water-cooled filament extruder head especially optimised for this new PAEK filament.

In parallel with the material developments and process optimisation, South West Metal Finishing Ltd (SWMF), a specialist in surface treatment of aerospace components and part of the consortium, developed the first known surface treatment process, which enhances all surfaces of Additive Manufactured PAEK components by chemically dissolving the material to remove semi-sintered powder particles and large undulations, leading to smoothing of the surfaces.

CALM has also strengthened its methodologies and procedures of testing and analysis of PAEK HPP powders for AM, by creating rigorous protocols, ready to be used in new material developments.

This project was conceived and the team established following the first conference on European Strategy for Additive Manufacturing with High Temperature Polymers, held by the University of Exeter in 2014.

Funded by: Innovate UK (Aerospace Technology Institute)

Partners: Victrex Manufacturing Limited, University of Exeter, E3D-Online Ltd, South West Metal Finishing Limited, Airbus Group Limited, 3T-RPD Ltd, EOS, HiETA Technologies

Research projects

EPSRC EP/R004781/1 – TEAM-A: The tailored electromagnetic and acoustic materials accelerator

CALM is a partner in a five-year Prosperity Partnership programme with QinetiQ together with other research groups across the College of Engineering Mathematics and Physical Sciences.

The partnership is focused on developing advanced materials that can be used to control and manipulate the propagation of electromagnetic and acoustic energy in a highly tailored, bespoke fashion, and develop innovative techniques for their cost-effective manufacture.

Materials that have the ability to fully control and manipulate the flow of electromagnetic (eg radiated heat, light, radiowaves) and acoustic (eg sound, vibration, shock) energy have the potential to transform, and enable, a large and diverse range of technologies. Exeter and QinetiQ have long been at the forefront of the science and engineering of such materials, with recent examples being: the modification of wind turbines to reduce their interference with meteorological and aviation radar systems, where half of the viable wind-farm sites in the UK are currently blocked for this reason, and the development of new optoelectronic materials for the realisation of beyond ultra-high definition displays.

However, there are still significant challenges prohibiting the widespread take up of these new materials in applications. In particular, concepts developed in the laboratory are often incompatible with commercial manufacture, due to their complexity and the nature of the constituent parts. Instead, the basic science that describes the behaviour of these new materials needs to be combined with a detailed understanding of how such materials could be manufactured, so that new materials can be designed and engineered to tackle specific technological challenges using commercially viable approaches.

The full programme will develop advanced materials that can be used to control and manipulate the propagation of electromagnetic and acoustic energy in a highly tailored, bespoke fashion, and develop innovative techniques for their cost-effective manufacture.

Funded by: EPSRC
Partners: QinetiQ

Arkema & CALM PhD

Arkema and CALM are working together on optimising Poly Ether Ketone Ketones (PEKK) for the EOSINT P 800 powder bed process.

Arkema is a French chemical company leader in the field of high performance polymer materials, one of which is PEKK, invented in the 1960s as part of the Apollo space program.

PEKK Kepstan®, PEKK from Arkema, has a very high melting point (300°C to 360°C depending on the grade) and provides excellent mechanical properties, excellent resistance to chemicals and abrasion. Reinforced with carbon fibres, it is as rigid as some metals, but very much lighter and it is non-flammable without releasing any toxic fumes.

The PhD aims to gain a deep understanding of the material at the microstructure level in order to optimise it for the manufacturing process.

Funded by: University of Exeter and Arkema

Bond High Performance 3D & CALM PhD

CALM in partnership with Bond 3D are co-funding a PhD studentship seeking to investigate polymer behaviour and performance of Poly Ether Ether Ketone (PEEK) polymers. Bond 3D is a fast growing, young and entrepreneurial company based in the Netherlands who are developing a novel, ultra-performance Free Form Fabrication (FFF) printer for printing high performance polymers such as PEEK.

CALM is pleased to provide research support for the PhD programme which will focus on understanding the polymer behaviour from molecular scale to macro-scale performance throughout the new manufacturing process. Aspects such as crystal structure, size, amorphous and crystalline behaviour, layer-to-layer bonding, degradation effects, mechanical performance and design considerations will form part of the PhD study.

Funded by: University of Exeter and Bond High Performance 3D

EPSRC EP/N034627/1 – Novel high performance polymeric composite materials for additive manufacturing of multifunctional components

The aim of the project is to develop novel high performance, nanocomposite feedstock powder materials and filament for two processes: Laser Sintering and Fused Deposition Modelling (FDM). It will examine the potential use of inorganic fullerene-like tungsten disulfide (WS_2) as nanofillers for high value, PAEK (Poly Aryl Ether Ketone) based products.

The incorporation of these nanomaterials has been shown to improve thermal, mechanical and tribological properties of various thermoplastic polymers. It reduces wear and the coefficient of friction as well as offering processability benefits with dispersion characteristics that are superior to 1D and 2D nanoparticles. They are also the best shock absorbing cage structures known to mankind and importantly, they are non-toxic, and thermally stable.

Prof Yanqiu Zhu's group has carried out extensive research on WS_2 inorganic fullerenes and their applications in nanocomposites using conventional fabrication techniques and has recently invented a new rotary manufacturing technology for the continuous production of WS_2 inorganic fullerenes.

Funded by: EPSRC
Partners: University of Exeter and Ulster University Supported by: Victrex Polymer Solutions, Laser Prototype Europe Ltd – LPE, Bombardier Aerospace, Daido Metals Co. Ltd

EPSRC EP/L017318/1 – Particle shape and flow behaviour in Laser Sintering: from modelling to experimental validation

This project investigated the way the polymeric powders of different shapes and sizes flow, interact and sinter in the laser sintering process, through modelling and experimental validation. The spreading and compaction of the powder is an important part of the LS process. A non-uniform layer of powder leads to high porosity and weaker bonding between layers and therefore a structure with poor mechanical performance. Similarly, the size and shape of particles can change the sintering process. Larger contact areas between particles lead to a good sintering profile and ultimately to a high density part and good mechanical properties. Surface area of particles, polymer viscosity and surface tension were characteristics which were investigated when modelling the flow and sintering process.

It was a highly innovative project and its findings have the potential to help unlock the materials limitations for polymeric laser sintering. This allows rapid expansion into a wider range of higher value applications due to lower powders costs, wider choices and better understanding of their behaviour within the manufacturing process.

Funded by: EPSRC
Partners: University of Exeter and University of Edinburgh
Supported by: Victrex Manufacturing Limited and 3T RPD

Poly Ether Ether Ketone (PEEK) polymers for high temperature laser sintering (HTLS)

With the limited range of materials available for HTLS, this jointly funded PhD focused on the investigation of a new medical grade of PEEK. The study examined some of the key requirements needed for the successful development of new materials in LS processes at experimental and theoretical levels. This was the first study on a medical PEEK grade on a powder bed system.

Two medical grades of PEEK, 150PF and 450PF (OPTIMA LT3 and LT1), have been quantitatively investigated in parallel with well-established LS polymers in terms of particle size, particle morphology and flow behaviour. A calculation of the inter-particle interactions has been evaluated for all the materials proposed. These analyses, coupled with two strategies for the improvement of powder flowability, have formed a systematic and fundamental approach for studying powders in LS.

PEEK OPTIMA® LT1grade was selected for optimisation into the HTLS system, EOSINT P 800. The HTLS processing parameters and their effect on the mechanical characteristics of the laser sintered units were investigated and optimised. New insights into the HTLS mechanisms and functionalities of the EOSINT P 800 system were provided. The investigation also resulted in the proposal of a technique for the prediction of one of the HTLS processing temperatures from the powder properties as well as assessing a formula for linking material properties to processing parameters. Lastly, two case studies were performed with two long term medical implants manufactured utilising PEEK OPTIMA® LT1, and then tested.

Funded by: University of Exeter (PhD studentship) and Victrex (materials)
Partners: University of Exeter and Victrex

CDE 31809 – Development of CNT/PEEK structures using the additive manufacture for lightweight, high performance and multifunctional applications

Combining the unique properties of Carbon Nanotubes and the high temperature polymer-PEEK, with the exceptional capabilities offered by laser sintering, this feasability study's goal was to achieve lightweight parts with complex geometries and enhanced mechanical performance, such as strength and fracture toughness.

The research was a key enabler towards the development of highly complex multifunctional structures. The incorporation of the CNTs into polymeric powders for use in additive manufacturing demonstrated the potential for enhanced part strength in all directions (X, Y and especially Z direction).

Funded by: Defence Science and Technology Laboratory [DSTL]
Supported by: Airbus Group Innovations

UTOPIUM – Ultimate Toughness and Other Properties by Ultimate Materials

Carbon nanotubes (CNTs) are of great interest for the next generation of composite materials due to their exceptional mechanical and physical properties. They can be manufactured as vertically aligned "forests" at predetermined sites on a surface using a micro-patterned catalyst film to initiate growth by chemical vapour deposition. This allows them to be organised to form complex architectures, with the potential to act as aligned reinforcements in polymer composite films.

The project investigated the development of unique CNT polymer composite structures with a high potential for application in the aerospace industry. It successfully demonstrated some of the key requirements for the realisation of the UTOPIUM concept, of embedding patterned aligned CNTs within layers, bridging the interlayer boundaries and providing continuously aligned reinforcement.

In particular, the work showed that due to the strong capillary forces which occur at the nanoscale, careful control of the resin viscosity and gel time is necessary for the required partial wetting, as well as monitoring of the presence of resin via chromium-based marker dyes.

In addition, we were able to investigate and demonstrate rapid-patterning techniques which would be necessary to manufacture patterned nanotube forests during ALM. This was demonstrated by the use of inkjet-patterned nanoparticles as catalysts for nanotube growth, as the part of a collaboration with the Kroto Research Institute at the University of Sheffield.

By demonstrating these two key requirements (partial wetting and rapid patterning of carbon nanotubes) this project laid essential groundwork for the UTOPIUM concept. In future, the UTOPIUM idea could provide the reinforcement effectiveness of carbon nanotube composites in combination with the versatility of design offered by ALM techniques.

Funded by: Airbus Group Innovations (former EADS Innovation Works)

Research projects

CDE 36453 – High temperature additive manufacturing for rapid manufacture and adaption of bespoke military equipment

Acrylonitrile butadiene styrene (ABS) has been used extensively for extrusion deposition process. However, its low melting and glass transition temperatures make this material unsuitable for the high-end engineering applications.

This feasibility study proposed the modification of low cost extrusion deposition technology, commonly known as 3D Printing/FDM, to enable the freeform fabrication of high performance polymers, Poly Ether Ether Ketone (PEEK), reinforced with CNTs and carbon fibres (CF).

The project also aimed to apply the enhanced mechanical properties of the reinforced composite to define strategies for repairs of parts using the material deposition process. The success of this led to DSTL funding a further piece of work focussed on the adaption of the technology to be used for zinc alloy extrusion.

Funded by: Defence Science and Technology Laboratory [DSTL]
Supported by: Airbus Group Innovations

CDE100404 – High temperature additive manufacturing with embedded fibre optic sensors

Investigation of the use of fibre optic sensors integrated into parts built using extrusion deposition (also known as Fused Deposition Modelling – FDM). The benefits of this include gaining a better understanding of the extrusion process and its effect on the materials and parts. This includes real-time monitoring of the temperature of the material during the build process and monitoring the strains generated due to expansion and contraction of the material as it is heated and cooled. Furthermore the project has implications for in-life condition monitoring of parts (eg for UAVs) and for use in repairs that could be performed in the field with sensing capabilities integrated into positions not normally possible.

The project proved the viability of the approach for use in parts made of PEEK and proposed a method of measuring strain and temperature simultaneously. It builds on a previous CDE project (CDE36453) by Exeter University developing FDM technology for PEEK.

Funded by: Defence Science and Technology Laboratory [DSTL]
Partners: AV Optics

DSTL/AGR/00249/01 – Cost-benefit analysis (to the supply chain) of additive manufacturing

The aim of the project was to complete an independent cost-benefit analysis that supports or discredits the premise: "The adoption of Additive Manufacturing in Defence Logistics has the potential to deliver huge cost savings".

To test this hypothesis, the study considered the end to end logistics chain approach in order to identify, how, where and to what extent, additive manufacturing would differ in approach and costs when compared to the current spares and repair strategy.

Funded by: The Defence, Support and Logistics framework
Partners: Arke Ltd, Ricardo plc and Polaris Consulting Ltd

EPSRC EP/M01777X/1 – Re-Distributed Manufacturing and the Resilient, Sustainable City (ReDReSC)

The Re-Distributed Manufacturing for Resilient, Sustainable Cities (RDM|RSC) network was led by the Universities of Exeter, Bath, Cardiff and West of England, to develop a vision, roadmap and research agenda addressing the implications of Re-Distributed Manufacturing (RDM).

RDM represents technologies, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location and scale. The aim of the network was to explore how manufacturing will have to react in a future where the whole manufacturing supply chain will be increasingly affected by material scarcity and consequential increased prices, as well as, climate change, potential geo-political conflicts, and disruptive technologies.

The team at Exeter was tasked with understanding the underlying technical, economic, social and political developments, to identify where RDM would be most appropriately applied and whether additive manufacturing could be a viable tool. As part of this network we interviewed businesses and other manufacturing groups to assess their level of understanding and to ascertain the challenges associated with introducing this new concept.

Additive and hybrid manufacturing have been identified as potential promising technologies for implementing RDM, especially in the area of spares for replacement and repairs. A case study involving the manufacturing of a metal turbine wheel through additive and traditional manufacturing and repaired through hybrid manufacturing was also carried out.

Partners: University of Bristol, University of Cardiff, University of Exeter, University of Bath and University West of England

Publications

2018

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