EXETER TECHNOLOGIES GROUP

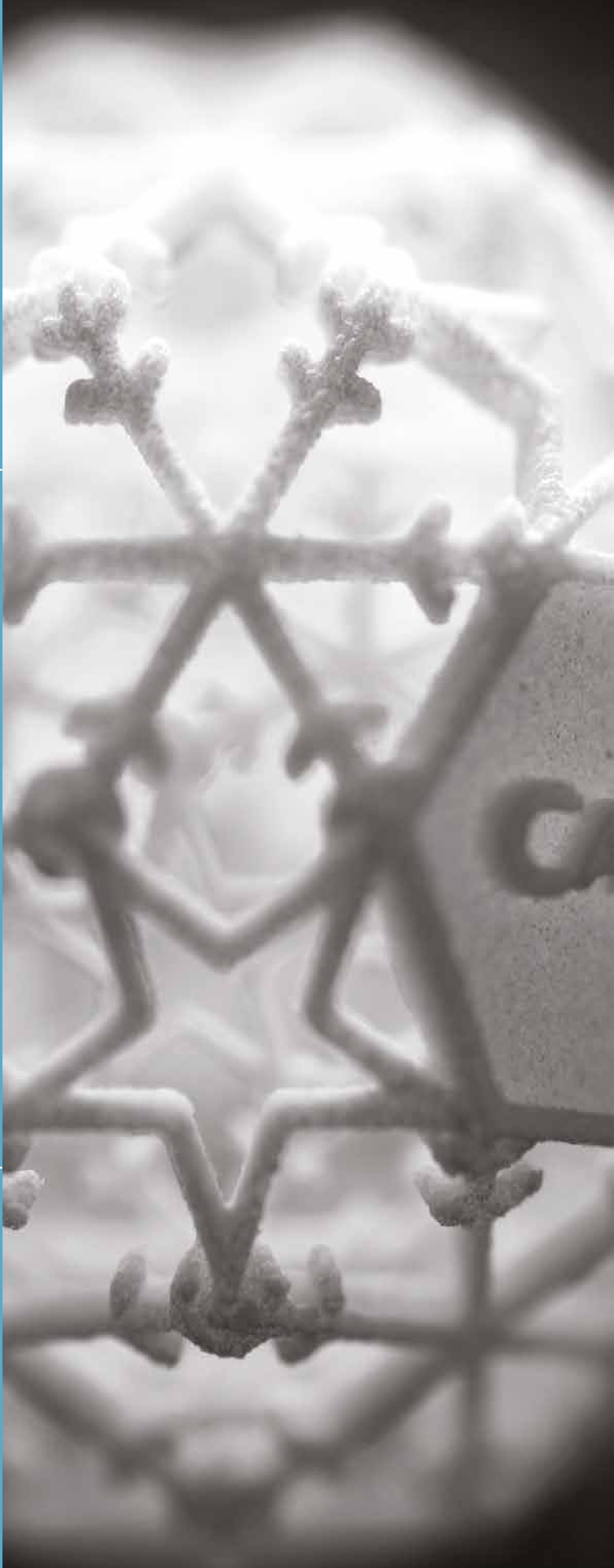
Centre for Additive Layer Manufacturing

RESEARCH AND DEVELOPMENT

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

UNIVERSITY OF EXETER

contents



CALM is the centre of expertise 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 (e.g. EPSRC), government organisations (e.g. 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.

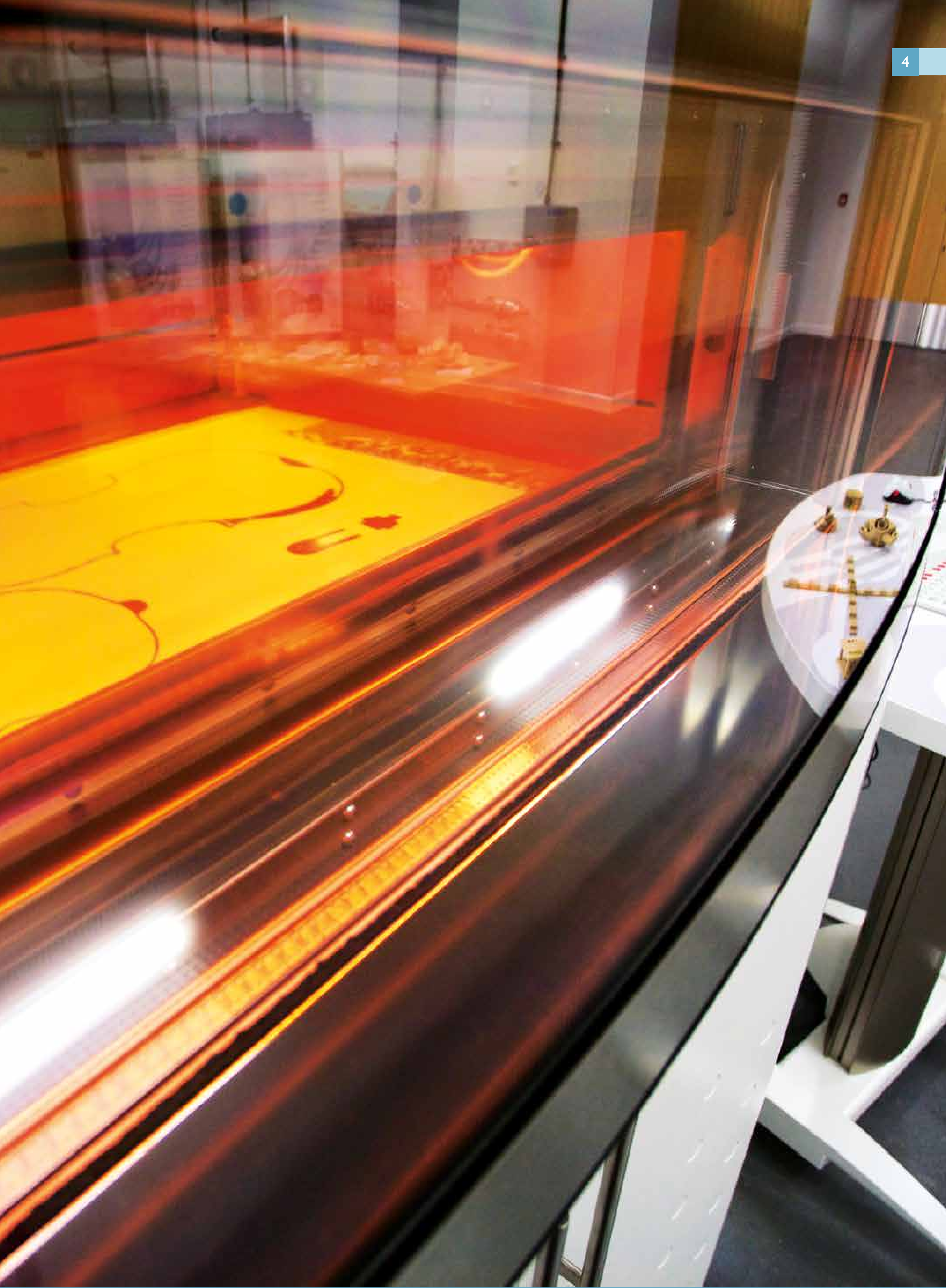
We have an extensive research programme on materials for ALM and offer contract research on all aspects of the technology, working in partnership with companies, other universities and government agencies.

Understanding the relationship between microstructure, processing and parts performance is at the heart of materials and process development. Particularly focussed 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 improving existing materials and processes and also developing new ALM polymeric materials and composites. 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) and ceramic particles (WS_2).

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



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

ALM challenges

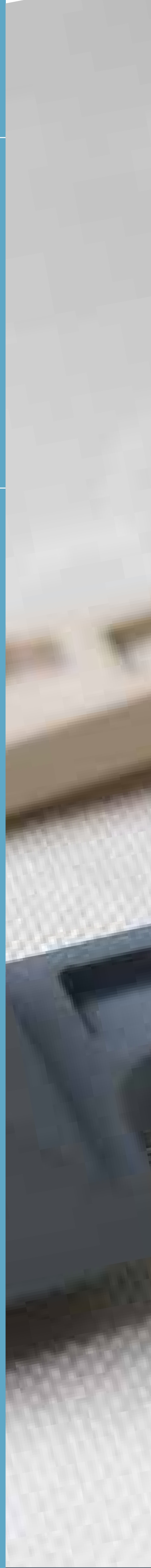
ALM is an enabling manufacturing technology and a catalyst for opening up new markets in customised products (for example surgical implants, or bespoke production equipment and tooling).

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.



CNT/PEEK bracket for improved light weighting and performance.

PAEK complex ducting for aerospace/defence.

Increasing the range of cost-effective powder grades

A wider range of more cost-effective powder grades are required for ALM.

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, combining its expertise in particle morphology and materials science with its processing knowledge of laser sintering and extrusion deposition, to deliver new materials to the market.

In addition, CALM is supporting the development of composite materials, providing new opportunities for the manufacture of lightweight and functional components. Composite materials made by traditional techniques have been proven to offer great benefits in a wide range of applications, but production can be labour-intensive and requires lengthy machining or expensive tooling.

These new developments within ALM, remove the need and cost associated with mould tools, whilst continuing to offer products with enhanced material properties.

By creating and developing bespoke grades of powders for laser sintering, we are extending the range of polymeric materials for ALM.

Lower cost materials are needed for High Temperature – Laser Sintering. We work to reduce the cost of high performance polymeric ALM materials by developing cheaper alternatives and understanding the effect recycling the powder has on the final material properties. Our work has shown that PEK can be recycled at a refresh rate of 30% before significant loss of tensile strength is observed.

Expanding knowledge of ALM materials

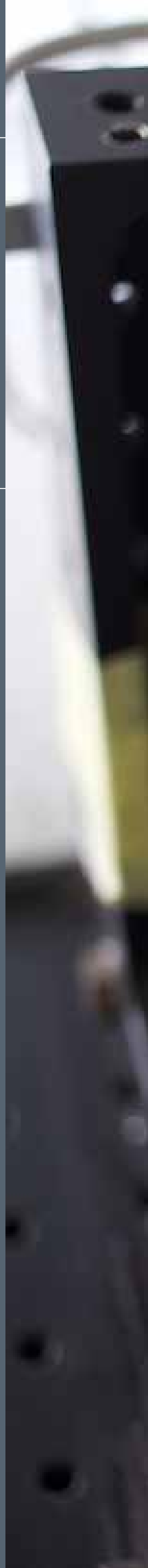
As ALM moves from development into full-scale production, material understanding remains essential.

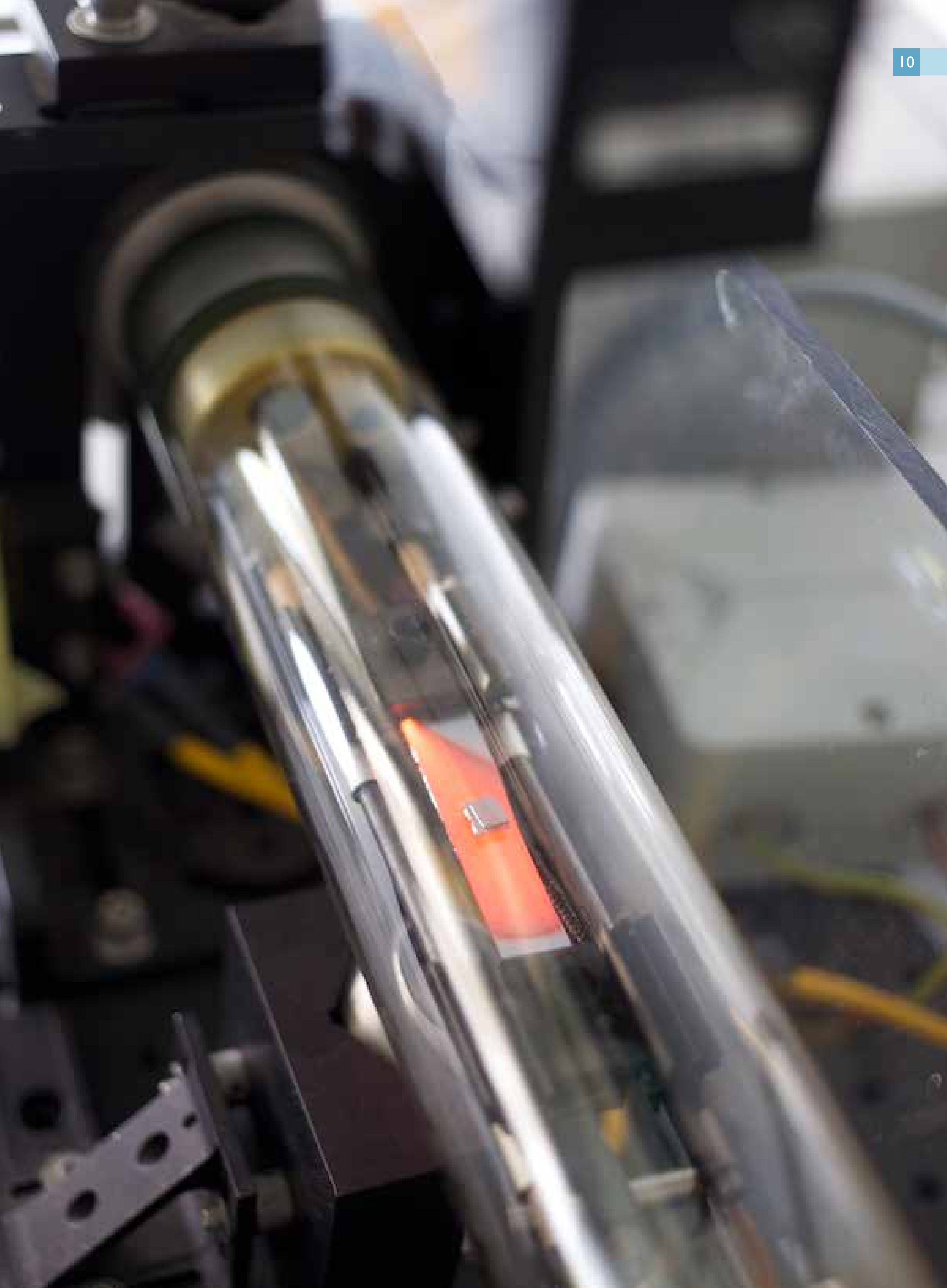
CALM is a global leader in materials research for High Temperature – Laser Sintering (HT-LS), publishing data that is independent from powder suppliers and machine manufacturers. For recent publications see pages 21/22.

Using in-house designed methodologies and tests we investigate how the size, shape and morphology of particles 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 such as tungsten sulfide.

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





Growth of aligned carbon nanotubes at high temperature using Chemical Vapour Deposition system.

Manifold manufactured with PEEK and 30% Carbon Fibre.

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 with unique mathematical models and high performance computing, 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 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.

Expanding knowledge of ALM components

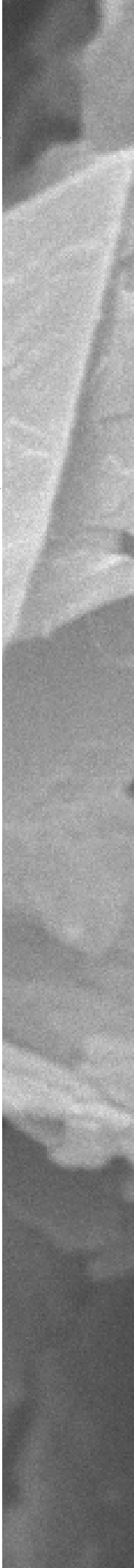
Quantifying key bulk properties using standard techniques is just the beginning of our investigations.

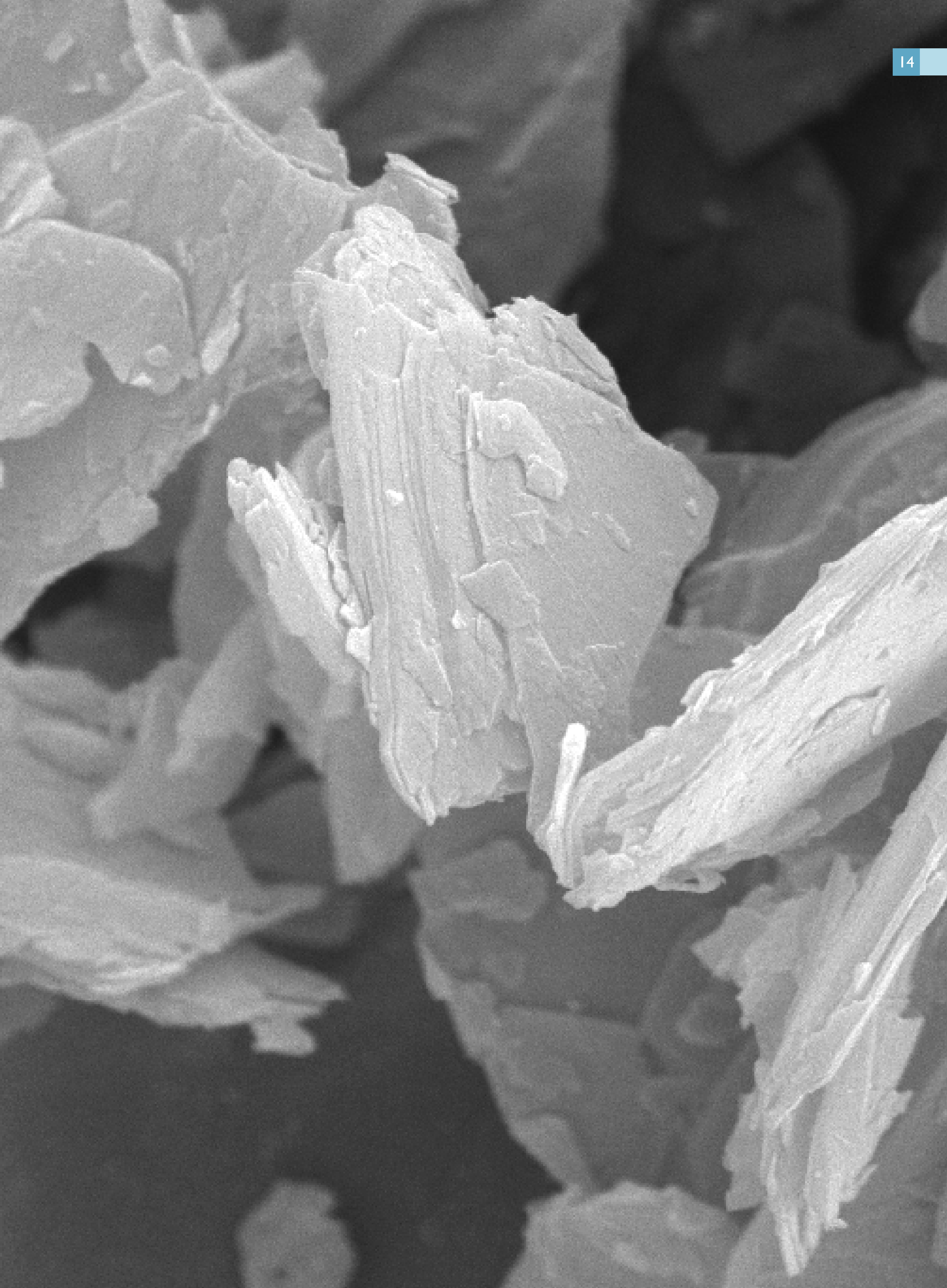
With an array of specialised tests, ranging from thermal and optical imaging techniques through to rheology and mechanical, we thoroughly investigate and scrutinise components. This helps us define component microstructure.

We identify how microstructure affects important macroscopic properties, helping us to predict how ALM components will behave when in use. This type of material characterisation can also be used to select important manufacturing parameters that will lead to optimised component properties.

In addition, we investigate a wide range of new and existing ALM materials, always looking for evidence-based answers to several important questions:

- What is the detailed microstructure between and across the layers of an ALM component?
- How do variable process parameters (e.g. laser power) change the microstructure?
- How can we optimise the microstructure to improve desirable macroscopic properties?
- How can we add further functionality for components through material developments?
- How can we match and exceed existing traditional manufacturing material properties?





Scanning Electron Microscopy image of Carbon Black (CB) powder.

Working in Partnership

CALM is an independent research centre with no restrictions on who we work with and in what area of ALM. We aim to achieve maximum impact from our work and therefore collaborate with a range of partners to achieve common goals.

We have successful collaborative partnerships with a wide range of innovative businesses and are developing new technology concepts for long term benefit to aerospace, defence and other industries in the UK.

Together we are developing novel advanced high performance ALM materials which will have superior physical properties to any currently on the market.

We regularly deliver projects that have short and long term impact, working confidentially with companies requiring material analysis and ALM research and development, to help them secure valuable intellectual property.

Several companies who started their journey into ALM with us are now developing their products for mass production and more than one hundred of these businesses now incorporate ALM into their product development process.

As a thriving ALM knowledge transfer hub we can offer development courses for businesses wanting to explore the opportunities of ALM.

Ashwoods Group, an Exeter based company who successfully develop and supply hybrid automotive engines, had a requirement for a hard wearing plastic motor cover that could operate at temperatures in excess of 200 °C, for their bespoke test rig.

CALM manufactured a PEK prototype component quickly, more cheaply, and with more features, than could be achieved by machining PEK billet.

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+, don't burn, and can compete mechanically.

Additive Layer Manufacture (ALM) of PAEK polymers and composites is now possible. If this production route could be matured and perfected, ALM PAEK would be exploited far more extensively in future aircraft. Similarly to metals ALM, which is now an established and indispensable tool in airframe design and manufacture, the usage of PAEKs is expected to grow.

The University of Exeter is part of a consortium of 8 organisations, led by Victrex, 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 and post-processors, as well as end-users.

> “We are at the start of an exciting journey in the development of new VICTREX PAEK grades that can efficiently and cost-effectively exploit all the advantages of additive manufacturing”
>
> *David Hummel, Chief Executive of Victrex*

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. Victrex presented early-stage results on a new polymer with significant potential for additive manufacturing. The University of Exeter had already acquired experience and contacts in PEEK polymer-based additive manufacturing and was able to help bring the consortium into existence.

A key objective is the improvement of the recycle rate for powders used in laser sintering. This would significantly reduce polymer wastage in this type of additive manufacturing process and reduce costs. The project will also address unpredictability of inter-layer adhesion and parts surface finish in filament-based printing.

The aim is to solve the well identified technical barriers hindering ALM-PAEKs exploitation. This will make the process reliable, cost competitive and a common-place fabrication route, available throughout the aerostructures supply chain.

Funded by: Innovate UK (Aerospace Technology Institute)

Partners: Victrex Manufacturing Limited, University of Exeter, E3D-Online Ltd, Avon Valley Precision Engineering, South West Metal Finishing Limited, Airbus Group Limited, EOS, HiETA

Research projects

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.

The success of this 2 year project, has led to a further project extension.

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 (HT-LS)

With the limited range of materials available for HT-LS, this jointly funded PhD focussed 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.

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 HT-LS system, EOSINT P 800. The HT-LS processing parameters and their effect on the mechanical characteristics of the laser sintered units were investigated and optimised. New insights into the HT-LS 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 HT-LS 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
Supported by: 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

Research projects

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 part of a collaboration with the Kroto Research Institute at the University of Sheffield.

By demonstrating these two key requirements (partial wetting techniques 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.

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

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

Investigating the use of fibre optic sensors integrated into parts built using extrusion deposition. This has implications for replacement parts and repairs which could be performed in the field (and further applications e.g. UAVs). Sensing capabilities can be integrated into positions not normally possible, improving the quality of the parts and increasing measurement options. The project also allows in-process monitoring during manufacture, to better understand the thermal environment. 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 is 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. This aim of the network is 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 is also being carried out.

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

Publications

2016

Wang Y., Chen B., Evans K.E., Ghita O., (2016) Novel Fibre-like Crystals in Thin Films of Poly Ether Ether Ketone (PEEK) *Materials Letters*, DOI:10.1016/j.matlet.2016.08.024

Berretta S, Evans KE, Ghita O., (2016) Predicting processing parameters in High Temperature Laser Sintering (HT-LS) from powder properties, *Materials and Design*, volume 105, pages 301-314, article no. C 2016, DOI: 10.1016/j.matdes.2016.04.097

Berretta S, Wang Y, Davies R, Ghita O. (2016) Polymer viscosity, particle coalescence and mechanical performance in High Temperature – Laser Sintering, *Journal of Materials Science*, volume 51:4778–4794 DOI:10.1007/s10853-016-9761-6

2015

Beard J, Evans KE, Ghita OR. (2015) Fabrication of Three Dimensional Layered Vertically Aligned Carbon Nanotube Structures and their Potential Applications, *RSC Advances*, volume 5, pages 104458-104466, DOI:10.1039/c5ra18048a.

Beard JD, Evans KE, Ghita OR. (2015) Control and Modelling of Capillary Flow of Epoxy Resin in Aligned Carbon Nanotube Forests, *RSC Advances*, volume 5, pages 39433-39441 DOI: 10.039/C5RA03393D.

Berretta S, Evans KE, Ghita O. (2015) Processability of PEEK, a New Polymer for High Temperature Laser Sintering (HT-LS), *European Polymer Journal*, volume 68, Pages 243-266, DOI:10.1016/j.eurpolymj.2015.04.003.

Wang Y, Beard J, Evans KE, Ghita OR. (2015) Unusual crystalline morphology of Poly Aryl Ether Ketones (PAEKs), *RSC Advances*, 2015, vol 6, no 4. pp. 3198-3209, DOI:10.1039/C5RA17110E.

Wang Y, James E, Ghita OR. (2015) Glass bead filled Polyetherketone (PEK) composite by High Temperature Laser Sintering (HT-LS), *Materials and Design*, volume 83, pages 545-551, DOI:10.1016/j.matdes.2015.06.005.

Wang Y, Rouholamin D, Davies R, Ghita OR. (2015) Powder characteristics, microstructure and properties of graphite platelet reinforced Poly Ether Ether Ketone composites in High Temperature Laser Sintering (HT-LS), *Materials and Design*, volume 88, pages 1310-1320, article no. C, DOI:10.1016/j.matdes.2015.09.094.

S. Berretta, O. Ghita, PEEK Optima ® LT1 for High Temperature Laser Sintering (HT-LS), 2nd *International PEEK Meeting, Washington D.C., April 2015*

R. Davies, Yat-Tarng Shyng, Y. Wang, O.Ghita, Extrusion Deposition of Carbon Nanotubes (CNT)/Poly Ether Ether Ketone (PEEK), 20th *International Conference on Composite Materials – ICCM20, Copenhagen, July 2015*

Yuan Wang, Richard Davies, Oana Ghita, High Temperature Additive Manufacturing of Poly Aryl Ether Ketones (PAEK) composites, 20th *International Conference on Composite Materials – ICCM20, Copenhagen, July 2015*

2014

Berretta S, Ghita OR, Evans KE. (2014) Morphology of polymeric powders in Laser Sintering (LS): From Polyamide to new PEEK powders, *European Polymer Journal*, volume 59, Pages 218-22 DOI:10.1016/j.eurpolymj.2014.08.004

Ghita OR, James E, Davies R, Berreta S, Singh B, Flint S, Evans KE. (2014) High Temperature-Laser Sintering (HT-LS): An investigation into mechanical properties and shrinkage characteristics of Poly (Ether Ketone) (PEK) structures, *Materials and Design*, volume 61, September 2014, Pages 124–132, DOI:10.1016/j.matdes.2014.04.035

Berretta S, Ghita O, Evans KE, Anderson A, Newman C. (2014) Size, shape and flow of powders for use in Selective Laser Sintering (SLS), High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping *- Proceedings of the 6th International Conference on Advanced Research and Rapid Prototyping*, VR@P 2013, pages 49-54

Ghita OR, James E, Trimble R, Evans KE. (2014) Physico-chemical behaviour of Poly (Ether Ketone) (PEK) in High Temperature-Laser Sintering (HT-LS), *Journal of Materials Processing Technology*, volume 214, no. 4, pages 969-978, DOI:10.1016/j.jmatprotec.2013.11.007

Strano G, Hao L, Evans KE, Everson RM. Optimisation of quality and energy consumption for additive layer manufacturing processes, *5th International Conference on Responsive Manufacturing, Ningbo, China*

2013

Allen RJ, Ghita OR, Farmer B, Beard M, Evans KE. (2013) Mechanical testing and modelling of a vertically aligned carbon nanotube composite structure, *Composite Science and Technology*, volume 77, pages 1-7, DOI:10.1016/j.compscitech.2013.01.001

Strano G, Hao L, Everson RM, Evans KE. (2013) Surface roughness analysis, modelling and prediction in selective laser melting, *Journal of Materials Processing Technology*, volume 213, no. 4, pages 589-597, DOI:10.1016/j.jmatprotec.2012.11.011

Strano G, Hao L, Everson RM, Evans KE. (2013) A new approach to the design and optimisation of support structures in additive manufacturing, *International Journal of Advanced Manufacturing Technology*, volume 66, no. 9-12, pages 1247-1254, DOI 10.1007/s00170-012-4403-x

Berreta S., Ghita O., Evans K. E., Anderson A., Newman C., "Size, Shape and Flowability of powders for their use in selective Laser Sintering (LS)" – *The International Conference on Advanced Research in Virtual and Rapid Prototyping (VRAP), Proceedings, 2013, Portugal*

2012

Beard MA, Bradbury J, Ghita O, Flint S, Evans K. (2011) Material Characterisation of Additive Manufacturing Components Made From a High Temperature Thermoplastic Polymer, *The International Conference of Advanced Research in Virtual and Rapid Prototyping (VRAP)*, Leiria, Portugal, 28 Sep - 1 Oct 2011

2011

Beard MA, Ghita OR, Evans KE. (2011) Using Raman Spectroscopy to Monitor Surface Finish and Roughness of Components Manufactured by Selective Laser Sintering (SLS), *Journal of Raman Spectroscopy*, volume 42, pages 744-748, DOI:10.1002/jrs.2771

Beard MA, Ghita O, Evans K. (2011) Monitoring the Effects of Selective Laser Sintering (SLS) Build Parameters on Polyamide Using Near Infrared Spectroscopy, *Journal of Applied Polymer Science*, volume 121, pages 3153-3158, DOI:10.1002/app.33898

Jerrard PGE, Hao L, Dadbakhsh S, Evans KE. (2011) Consolidation behaviour and microstructural characteristics of Al and a mixture of Al-Cu alloy powders following selective laser melting processing, *Lasers in Engineering*, volume 22, no. 5-6, pages 371-381

Strano G, Hao L, Everson RM, Evans KE. (2011) Surface Roughness in Selective Laser Melting, *International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal*

2010

Beard MA, Ghita OR, Evans KE. (2010) Using Raman Spectroscopy to Monitor Surface Finish and Roughness of Components Manufactured by Selective Laser Sintering (SLS), *Journal of Raman Spectroscopy* volume 42, Issue 4, pages 744–748

2008

Hatwell GE, Hao L, Sewell NT, Evans KE. (2008) Simulation of energy absorption in nylon 12 powders during selective laser sintering

Jerrard, P., Hao, L., Sewell, N.T., Evans, K.E. and Felstead, M.,(2008) Consolidation of Austenitic and Martensitic powder mixtures via selective laser melting, *9th National Conference on Rapid Design, Prototyping & Manufacturing, Lancaster, United Kingdom, pp.*145-152

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