The
University
Of
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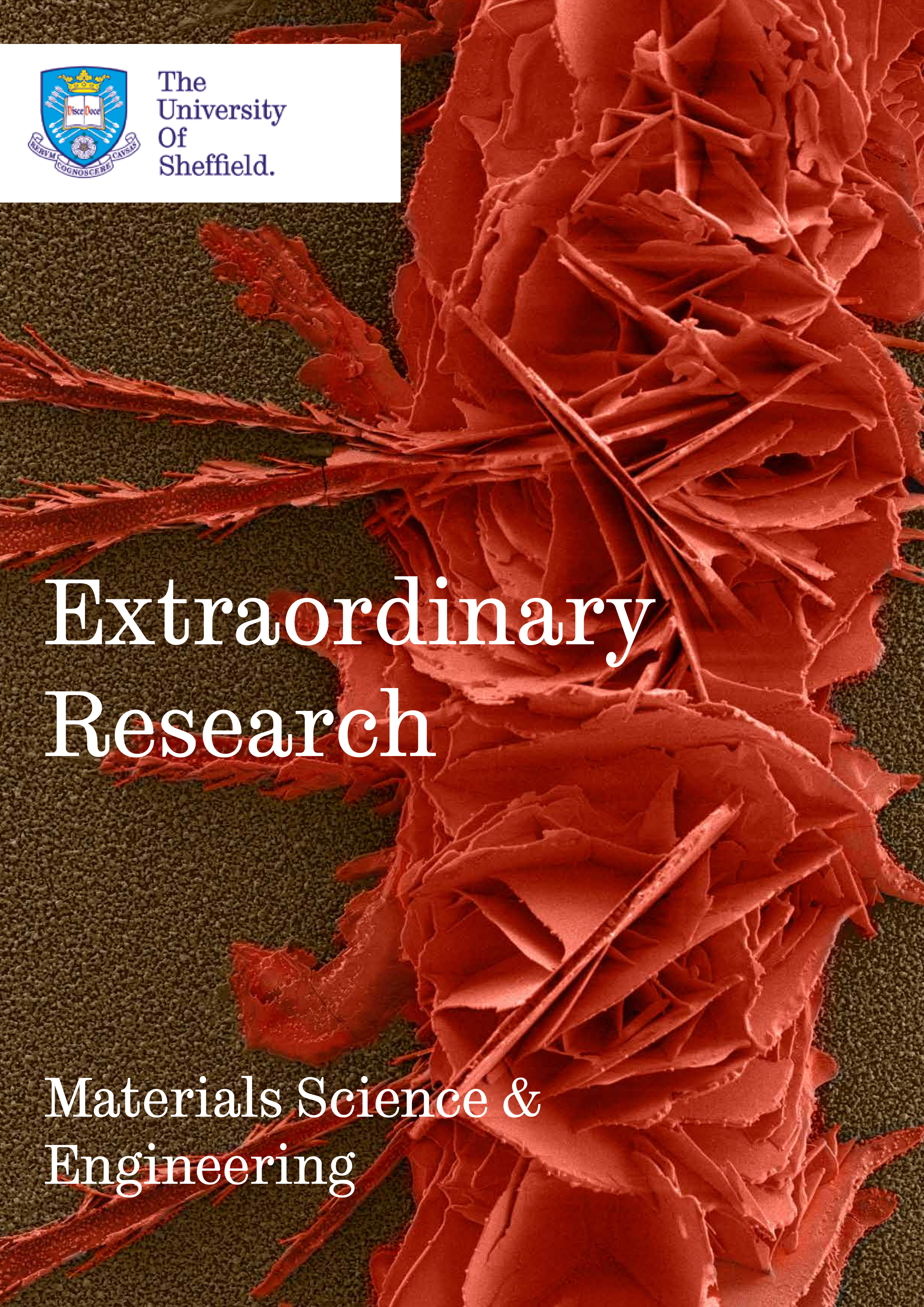


Extraordinary Research

Materials Science & Engineering

Contents

Cover image courtesy of Dr Giorgio Schileo

Extraordinary Research

Materials and Manufacturing research at The University of Sheffield spans a diverse range of disciplines with core activity in the Department of Materials Science & Engineering (MSE). With approximately 38 full time members of academic staff and an annual research income of ~£12M per year, MSE was ranked in the top 5 in the UK for research excellence and in the top ten for research output in materials science in the Research Excellence Framework 2014. MSE was also ranked 2nd position in Materials Technology in The Times Good University Guide (2017), and boasts 100% student satisfaction and 100% employability achievements in 2017 surveys.

The broad and interdisciplinary nature of our materials and manufacturing research is enriched by collaborations with science departments such as Chemistry and Physics & Astronomy delivering the highest quality fundamental research, whilst development at higher technology readiness levels includes the participation of the Advanced Manufacturing Research Centre with Boeing and the Nuclear Advanced Manufacturing Research Centre. Further translational research is underpinned by close collaborations between the Schools of Medicine and Dentistry and the more traditional engineering disciplines, allowing our researchers to exploit their understanding of underlying physical phenomena for the public good.

Long term investment and support by our sponsors, both private (e.g. Rolls Royce, Boeing, GKN, Seagate, Tata Steel, Johnson Matthey, Bentley) and public (RCUK, Innovate UK, EU), is devoted to creating a better understanding of the fundamentals of material science and to resolve challenges in a number of domains, especially the aerospace, automotive, healthcare, information technology and energy sectors.

We are also a major partner in the £235M Henry Royce Institute for Advanced Materials (www.royce.ac.uk). In Sheffield, we will host a £30M materials discovery centre in newly built facilities, and an £8M materials translational centre part funded by the European Regional Development Fund. These state of the art facilities will allow fundamental materials science to be translated to future materials manufacturing technologies, through collaboration with world leading scientists and driven by industry needs.

Royce Institute Discovery Centre

HENRY
ROYCE
INSTITUTE

The Henry Royce Institute is part of a £235m Government initiative to boost research and development in the area of advanced materials.

The purpose of the Royce Discovery Centre is to take materials and processing concepts, and develop them from basic principles through analytical and experimental processes with the aim of proving the concept in terms of feasibility and applicability for industrial use.

In order to achieve this, we draw on the expertise present within the Department of Materials Science and Engineering at the University of Sheffield, along with that of equipment and materials manufacturers. This allows us to understand the potential of what is possible, and investigate how this can be fully realised in an industrial setting.

Particular strengths of the Department are:
- Materials characterisation and testing
- Microstructural modelling
- Alloy development
- Additive manufactured part design and optimisation

Royce Institute Translational Centre

HENRY ROYCE INSTITUTE

The Sheffield Royce Translational Centre has received a £4million grant from the European Regional Development Fund to help manufacturing companies in the Sheffield city region to adopt next generation technology to produce and process metal powders. The UK is already a global leader in the development of new materials for use in engineering applications, and the field is growing rapidly.

The centre will work alongside the Henry Royce Institute Discovery Centre at the University's city campus, which will be focussed on early-stage research. The translational centre will then take these research discoveries and work with companies to help apply it to their manufacturing challenges.

It will house global-leading academics and engineers along with industrial-grade machines to bridge the gap between research into metal powders and applications for sectors such as aerospace, automotive, energy and medical high-value manufacturing.

Facilities will include
- gas atomisers
- post-production powder optimisation
- green part processing
- vacuum induction furnace
- powder densification and spheroidisation unit
- laser powder bed metal 3D printer
- hot isostatic press
- binder powder bed metal 3D printer
- metal injection moulder and metal injection furnace

Part funded by the

EUROPEAN UNION
European Regional Development Fund

Manufacture using Advanced Powder Processes

MAPP is the EPSRC Future Manufacturing Hub in Manufacture using Advanced Powder Processes - a £20 million research hub, led by the University of Sheffield. MAPP brings together leading research teams from the Universities of Sheffield, Leeds, Manchester and Oxford, and Imperial College London, together with a founding group of 17 industry partners and the UK's High Value Manufacturing Catapult.

MAPP's vision is to deliver on the promise of powder-based manufacturing to provide low energy, low cost, and low waste high value manufacturing routes and products to secure UK manufacturing productivity and growth. MAPP, together with their partners, have developed an ambitious research programme that spans the fundamentals of powder materials, advanced in-situ process monitoring and characterisation, and new approaches to modelling and control. Researchers are working with industry partners from key UK sectors, including aerospace and energy, and across the full powder processing supply chain.

MAPP's mission is to work with academic, commercial and innovation partners to drive the research needed to solve many of the fundamental challenges limiting the development and uptake of many powder-based processes. As a recent example, Team GB used the expertise of Sheffield researchers to help develop super lightweight, aerodynamic stem and handlebars for their bicycles, 3D printed at the University of Sheffield for the 2016 Rio Olympics.

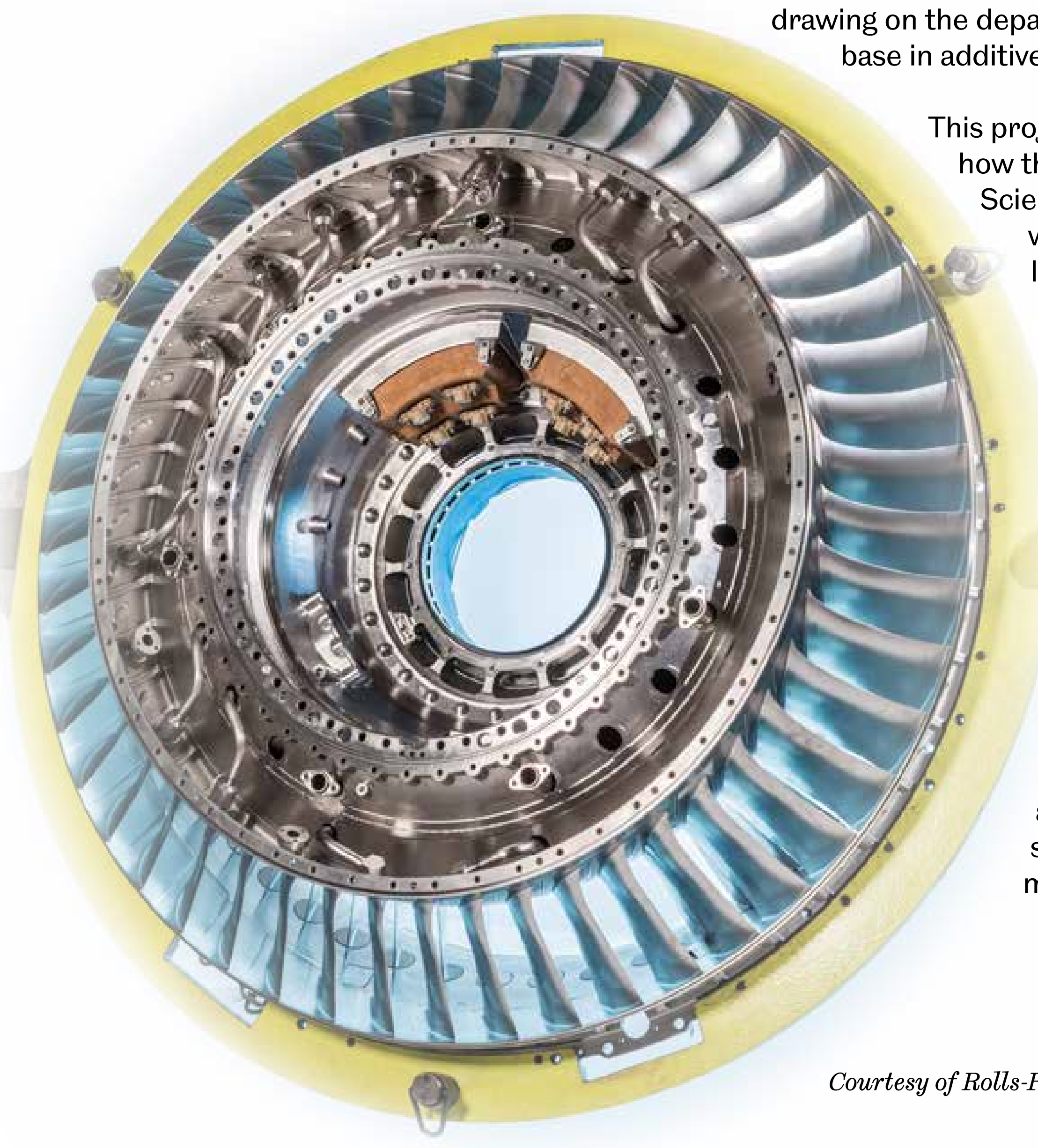
3D Printing of Critical Aircraft Structures

Rolls-Royce have used additive layer manufacturing (ALM) to construct a titanium front bearing housing (FBH) which is held inside a Rolls-Royce Trent XWB-97 engine. Additive layer manufacturing, also known as 3D printing, is a process by which a component is built up in discrete layers using a high energy source to melt or fuse metal powders.

The construction of the bearing marks the first time ALM has been used to produce such a significant load bearing component, rather than the conventional processes of casting or forging. The Department worked with Rolls-Royce to develop its ALM techniques through a programme of testing, research and quality assurance, building on Rolls-Royce's experience of innovation in high value manufacturing and drawing on the department's excellent research base in additive manufacturing.

This project is a great example of how the Department of Materials Science and Engineering can work with industrial partners like Rolls Royce and the HVM Catapult Centres to translate ground-breaking early stage research to industrial practice.

The fundamental research gives a strong underpinning to development activities that are closer to application providing insights into the process that increase confidence in its capabilities. This activity has facilitated a huge step forward in additive manufacture.



Courtesy of Rolls-Royce

FAST-*forge* for Low-Cost Titanium Parts

Researchers have developed a new concept in high value manufacturing which could lead to a more cost effective and sustainable production process in the aerospace and automotive industries.

Working with UK industry partners Metalysis, the UK's Defence Science and Technology Laboratory (DSTL), Advanced Forming Research Centre (AFRC) and Safran Landing Systems, the group of researchers were able to transform rutile sand to novel titanium alloy aerospace components using field-assisted sintering technology (FAST) and a one-step forging process.

This process, dubbed FAST-*forge*, is a hybrid manufacturing processing technology which consolidates titanium powder, including machined swarf, into a bulk material in two solid-state steps, as opposed to the conventional forty or so processing steps. This consolidation process exploits Metalysis' technology for the production of titanium powder directly from rutile, with traditional precision hot forging to give the benefit of being a near net shape process. The powder can be shaped close to the desired component without the need for numerous expensive and process-limiting thermomechanical steps.

The technology will provide engineers with more design flexibility, and potentially lead to improved buy-to-fly ratios: currently for some aerospace components, 90% of the forged titanium alloy is machined away to waste material. It may also increase the market share of titanium in other price-sensitive markets, widening the appeal of high-strength, low density titanium parts for sectors such as automotive, which needs to reduce the environmental impact and increase the fuel efficiency of its products.

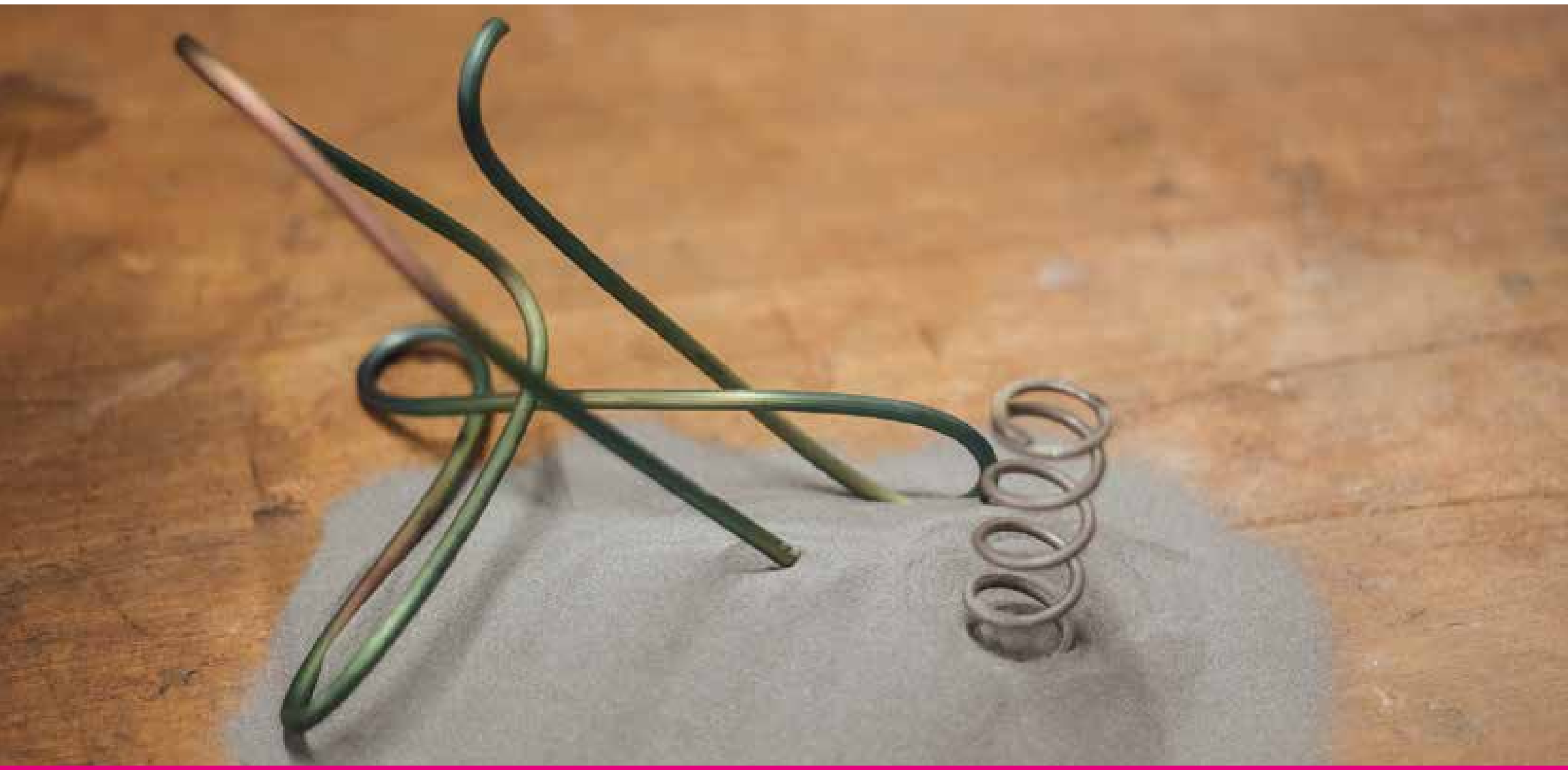
Continuous Rotary Extrusion of Titanium Wire From Powder

Continuous Rotary Extrusion (CRE) is a continuous extrusion process capable of producing a range of profile shapes and sizes from rod or powdered non-ferrous metal feedstocks. The CRE process has been in existence since the 1970s and was first invented as a way of recycling chopped copper cathode into new cables and producing special profiles for electrical conductors.

Aluminium and copper rod make up the majority of the commercial feedstocks used with CRE due to their extremely ductile nature. The real benefit of the process comes from the large number of process steps that it can replace, which reduces the overall cost of the final part.

Feedstock is continuously fed into the machine at room temperature. Through a combination of adiabatic heating and heat transfer from the extrusion tooling, the resultant severe plastic deformation completely reworks the microstructure of the feedstock and it emerges from the extrusion die in a fully annealed condition.

Stronger alloys have proven harder to extrude, but through a combination of EPSRC and InnovateUK funded projects, the Sheffield Titanium Alloy Research group have successfully processed titanium powders into both wire and strip profiles on CRE and Conform machines. This demonstrates the highly flexible nature of the process with both feedstock materials and machines. This process can use low cost titanium powder from a range of novel solid-state extraction processes to produce titanium wire that will be used, for example, as springs in automotive application, saving weight and increasing the fuel efficiency of vehicles. Other potential applications include processing specialty powders into wire for Wire Arc Additive Manufacturing (WAAM), which is rapidly becoming a more attractive way of 3D printing metals.

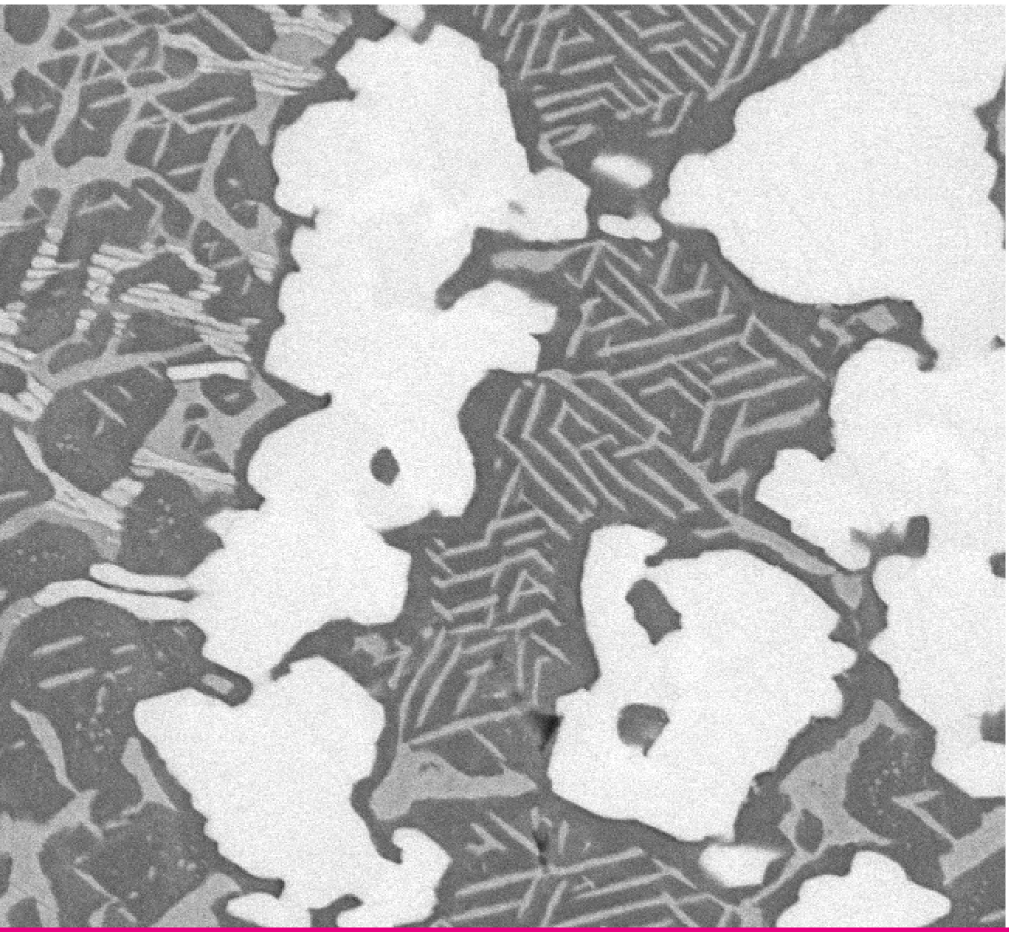


High Entropy Alloys for Light-Weighting Vehicle Components

High Entropy Alloys (HEAs) are a new type of near equiatomic multi-component alloy system that are typically composed of 5 or more alloying metals, which, contrary to expectations, can have simple phase structures. This offers the materials scientist exciting new opportunities to design alloys with new or superior properties to traditional alloys, for example possessing increased wear and corrosion resistance compared to traditional metals, whilst satisfying requirements for heat transfer and lower weight.

Researchers in Sheffield have investigated a number of new alloys for various applications. Amongst the suite of new alloys with properties that may be desirable for automotive applications, the CoCrFeNi-Al alloy family has shown comparable hardness and yield strengths to martensitic steel, which can be achieved by tuning the stoichiometry. Another advantage of HEAs is that the thermal stability of their main phase renders them relatively insensitive to production conditions, reducing production costs by allowing larger tolerances for cooling rate and heat treatments in production.

Fine tuning of alloys may allow for hitherto impossible combinations of high strength combined with good heat transfer properties and lower density. Such new alloys may find use in internal combustion engines, for example in the engine valve train, where new alloys may be able to combine both high strength and hardness and low density to help reduce the overall weight of the engine.



> *“High entropy alloys offer the materials scientist exciting new opportunities to design alloys with new or superior properties to traditional alloys”*

Feasibility of Vitrification of Simulant Level Nuclear Waste

The UK has been engaged in the development of civil nuclear power for more than 50 years and has a commitment to dispose of the historic legacy of waste generated over this time. Plutonium Contaminated Material (PCM) is a special type of intermediate level waste, associated with plutonium production, and includes filters, used personal protective equipment and decommissioning waste such as metals and masonry. It is a significant fraction of the UK's radioactive waste inventory and requires immobilisation prior to disposal.

The current treatment method for non-compactable plutonium contaminated wastes involves cement encapsulation, a process which typically increases the overall volume. The Immobilisation Science Research team firstly demonstrated the feasibility of the vitrification approach – turning the waste material into glass – by producing a suite of prototype demonstration materials. Of the prototype materials identified, blast furnace slag, a commonly available by- product from steel production, was preferred as it performed well against the agreed criteria such as the presence of residual waste material.

This project has successfully demonstrated the feasibility of immobilising simulant PCMs within a passively safe material – blast furnace slag – by a high temperature process prior to interim storage and disposal. This innovative use of blast furnace slag could potentially save storage space and costs due to the achieved volume reductions of between 65-95%.

UK Contribution for Recovery from Nuclear Accidents

Since the Great East Japan earthquake in 2011, and the subsequent accident at the TEPCO Fukushima Daiichi Nuclear Power Plant, Japan has been facing serious technical challenges due to the large amount of radioactive wastes arising from the decommissioning and clean-up activities. These wastes are unique to the accident and significantly differ from those coming from conventional plant operations, thus new technological solutions are required.

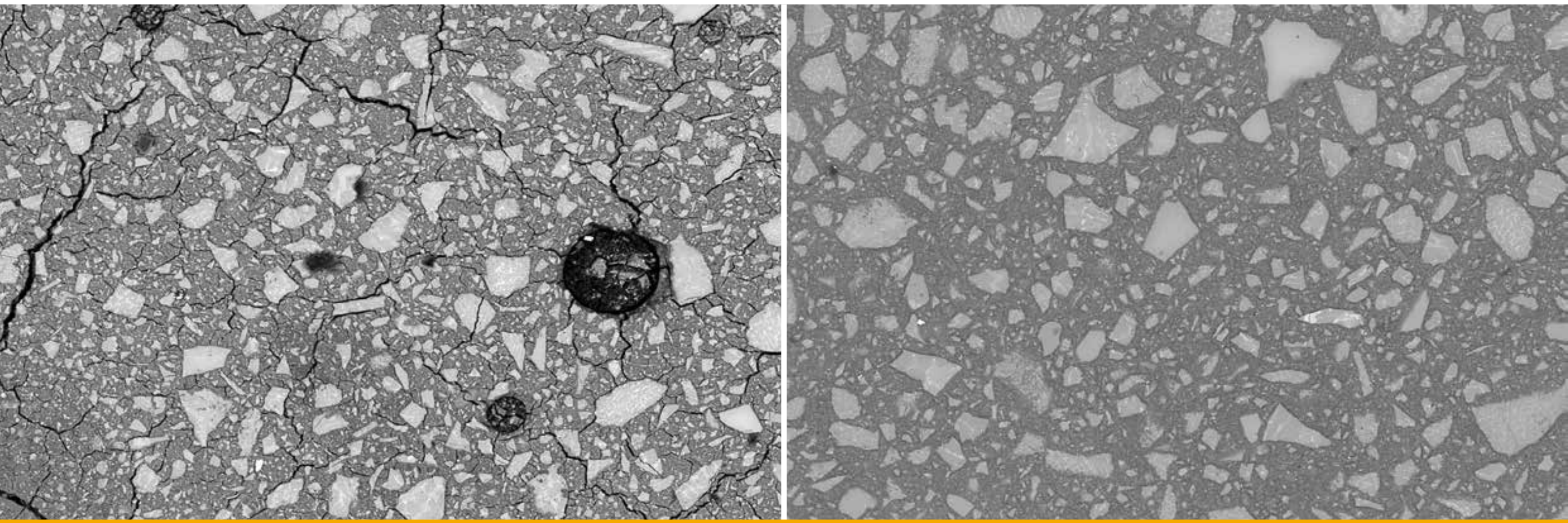
The Immobilisation Science Laboratory is currently one of the main contributors to the international research efforts for the decommissioning and clean-up of the waste arising from the Fukushima nuclear accident. Researchers are investigating novel hot isostatic pressing techniques to immobilise radioactively contaminated ion exchange material in a passively safe glass-ceramic product, while others are developing a solidification technique using phosphate-based cement systems to safely immobilise radioactive secondary wastes.

Also being investigated is the use of aluminosilicate geopolymer cements, the long-term performance of the cement disposal systems for radionuclide-loaded zeolite and titanate ion exchangers. Investigations of the corrosion behaviour and related properties of nuclear fuel debris is also necessary to help understand the behaviour of the fuel debris in the post-accident aqueous environment.

This research, in collaboration with UK and Japanese partners, will lead to the development of safe decommissioning and disposal technologies for recovery from nuclear accidents. The research outcomes can also support the long-term decommissioning strategies of UK legacy nuclear sites.

> *“This research will lead to the development of safe decommissioning and disposal technologies for recovery from nuclear accidents.”*

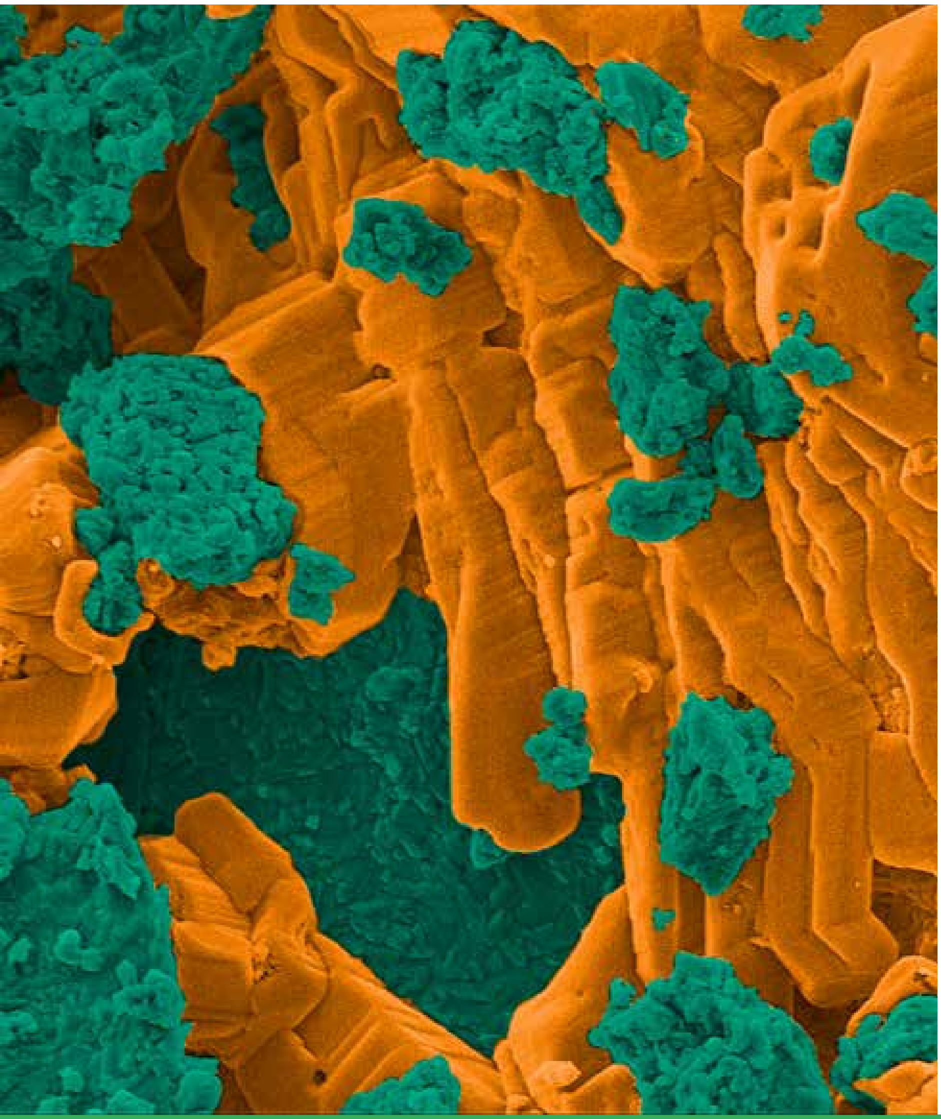
Microstructures of phosphate-based cement systems – problematic micro cracks (left) are successfully eliminated (right) by treating the system at an elevated temperature and reducing the amount of water in the system. The reduction of water is also advantageous to minimise the risk of hydrogen gas generation due to the radiolysis of water by radioactive waste components.

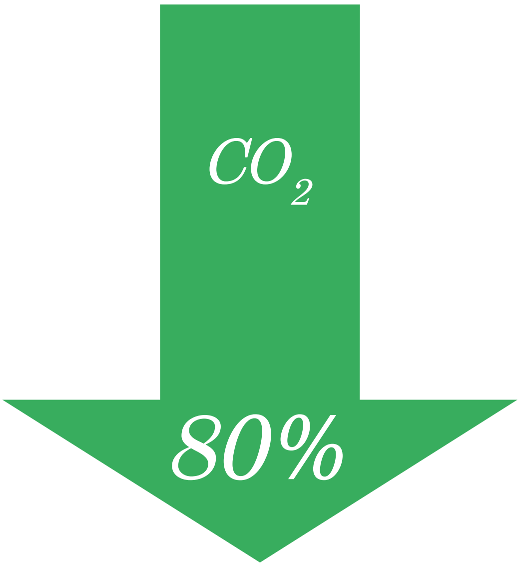


Geopolymer Cement

University of Sheffield researchers are leading the world in the development of new types of cement, to reduce the environmental damage which is currently caused by the construction industry. Cement production is currently responsible for as much as 8% of global human-derived CO_2 emissions, and so Sheffield researchers are analysing and optimising several types of alternative cement which could reduce this emissions footprint.

The most promising option in this area is ‘geopolymer’ cement, which is obtained by the reaction between a solid aluminosilicate material (including industrial by-products such as blast furnace slag or coal fly ash) and a source of alkalis. These materials can reduce CO_2 emissions by around 80% compared to a standard Portland cement, while offering excellent performance and durability. Sheffield is working in partnership with UK and international companies to accelerate the use of geopolymer technology on a large scale in construction and infrastructure, and using cutting edge science to provide reliable predictions of the long-term durability of these new materials.





Unravelling the Secrets of Silk

Materials are a cornerstone of our society, global economy and a major challenge facing us in the 21st century. Materials manufacture and processing results in over 20% of the world's carbon emissions, with many structural materials sourced from non-sustainable supplies. Here nature can contribute much to the discussion, as its materials tend to be supremely energy efficient as well as recyclable.

Biopolymers, specifically silks, offer inspiration and solutions to challenges facing the synthetic polymer industry; provided we understand how to process them correctly. The Natural Materials Group is currently investigating how silks are spun into fibres that possess properties as yet unmatched by their industrial counterparts. Taking lessons from the spider and silkworm, this group is developing a range of biomimetic spinning devices capable of processing naturally sourced feedstocks into products with predictable properties.

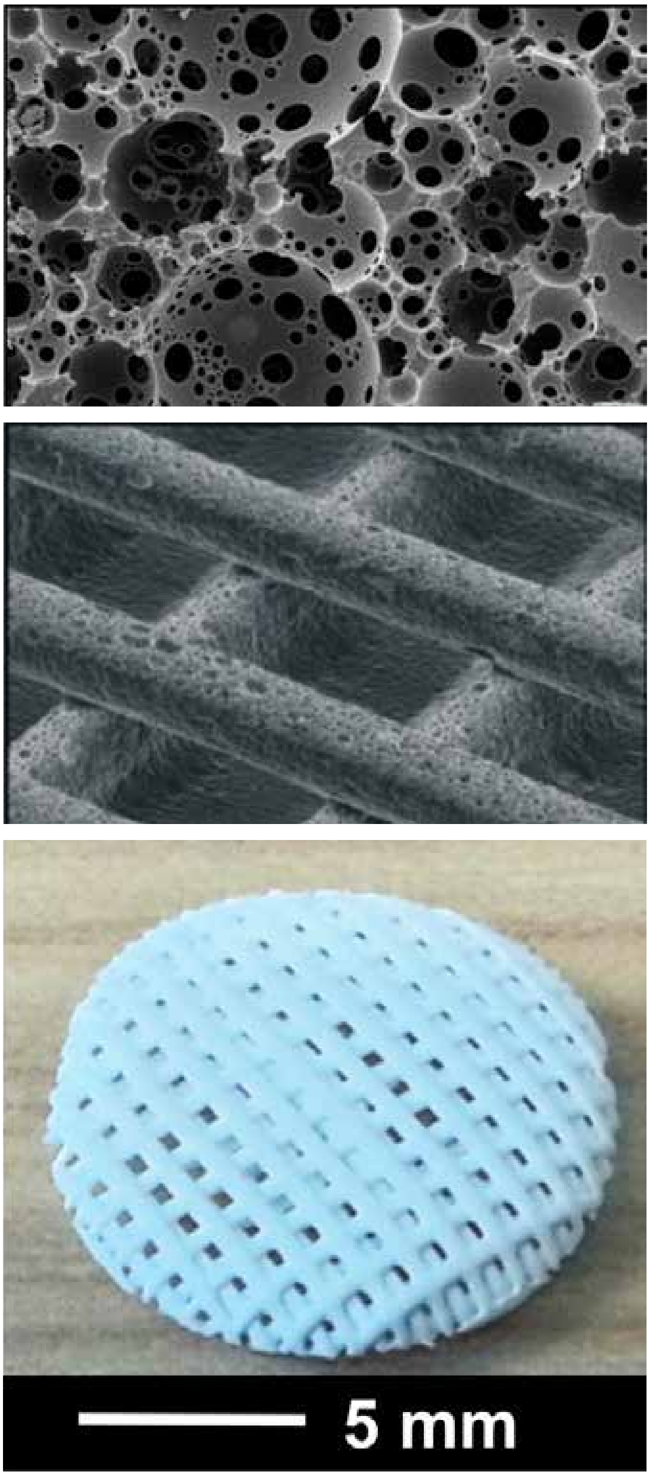
This industrially new, yet evolutionarily ancient, way of manufacturing materials in a sustainable and environmentally benign manner has the potential to change the way in which we process our own materials. It is most likely to find applications ranging from high performance fibres to biomedical implants, sensors and optical devices.

Porous Materials to Support Tissue Growth

Sheffield researchers are developing porous matrices to support 3D cell culture to mimic natural tissue structure. Natural tissues and organs are typically structured in a hierarchical fashion, in which the Extra-Cellular Matrix (ECM) provides a microporosity to optimally support cell growth while larger scale structures (e.g. vasculature and boundary layers) are incorporated to support the function and structure of the tissue and organ.

Researchers aim to reproduce this multiscale structuring in synthetic biomaterials via a combination of additive manufacturing with self-assembly. In this structuring technique the internal porosity is governed by self-assembly and the macroscopic structure is constructed by additive manufacturing. Emulsion templating is used as self-assembly technique to produce materials with a high microscale porosity. These emulsions can subsequently be used as photocurable resins for stereolithography, producing user-defined macroscale structures with a tissue-like microporosity. The mechanical properties of these materials can be varied via changing the monomer ratio within the resin.

These hierarchical structures can be produced in 3D structured materials such as woodpile-style scaffolds, microspheres with controllable diameter and as 3D microenvironments that can be integrated in standard poly-dimethylsiloxane (PDMS) based microfluidics. These scaffolds are being investigated as a platform for tissue-on-a-chip based devices and bone tissue engineering.



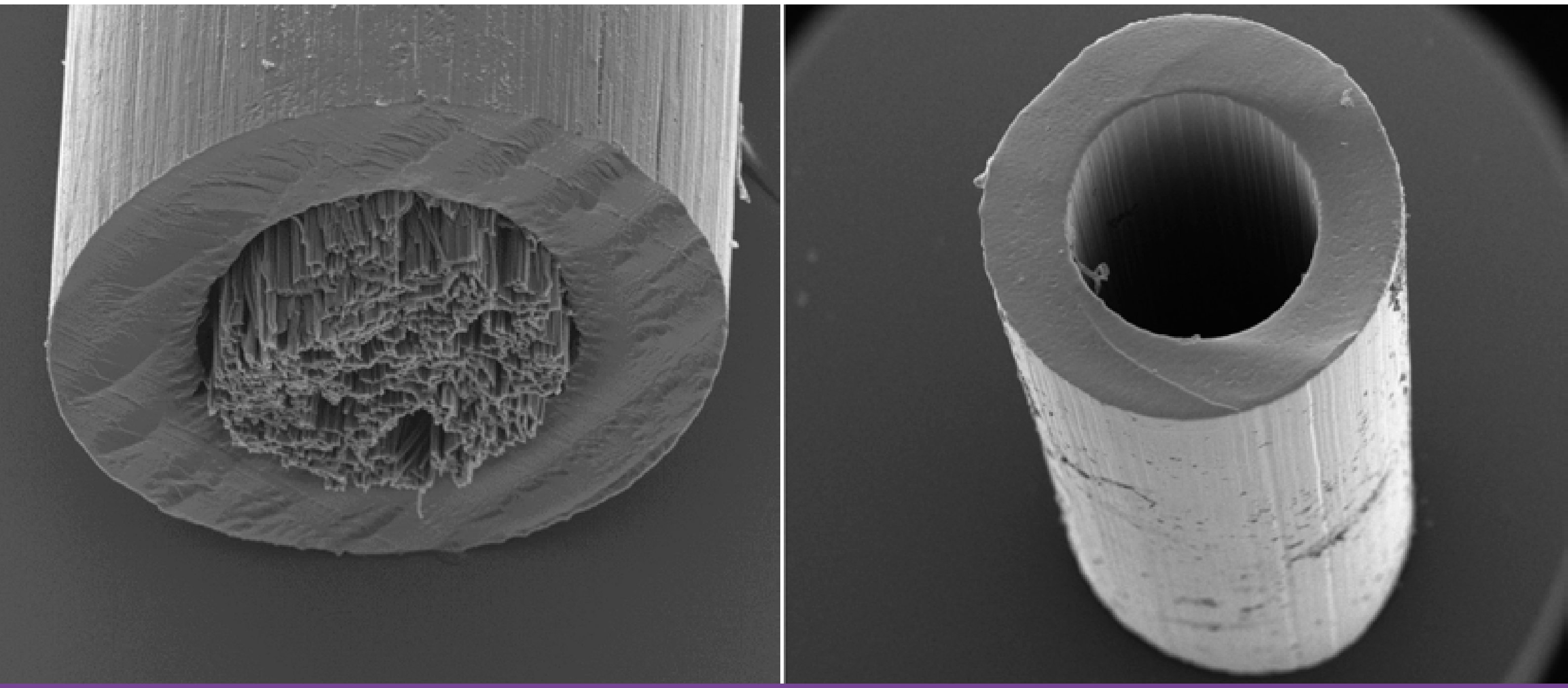
Biomaterials for Nerve Reconstruction

Researchers from the biomaterials group in Materials Science & Engineering are helping address issues related to damaged nerves by collaborating with the Dental School at The University of Sheffield on the design of advanced nerve guide devices. This work sees the manufacturing of nerve guides with improved bulk biomaterials properties, physical design and surface chemistry. They use 3D structuring via laser stereolithography and electrospinning for fabrication of structures that mimic the native tissue.

> *“Promising results reveal that reinnervation can be achieved comparable to that of a gold standard graft repair for short-gap injuries.”*

They have synthesised photocurable caprolactone, polylactide and polyethylene glycol pre-polymers which can be structured using microSL. This set-up can be used to rapidly produce structures with a resolution of 50µm. The effectiveness of prototype nerve guides is investigated by in vitro analysis using neuronal cells, Schwann cells and explanted dorsal root ganglion. If devices show promise, tests progress to *in vivo* analysis using a common fibular nerve injury model.

Promising results reveal that reinnervation can be achieved comparable to that of a gold standard graft repair for short-gap injuries. This positions future work well for phase 1 clinical trial studies, while parallel work is investigating medium and long gap injuries.

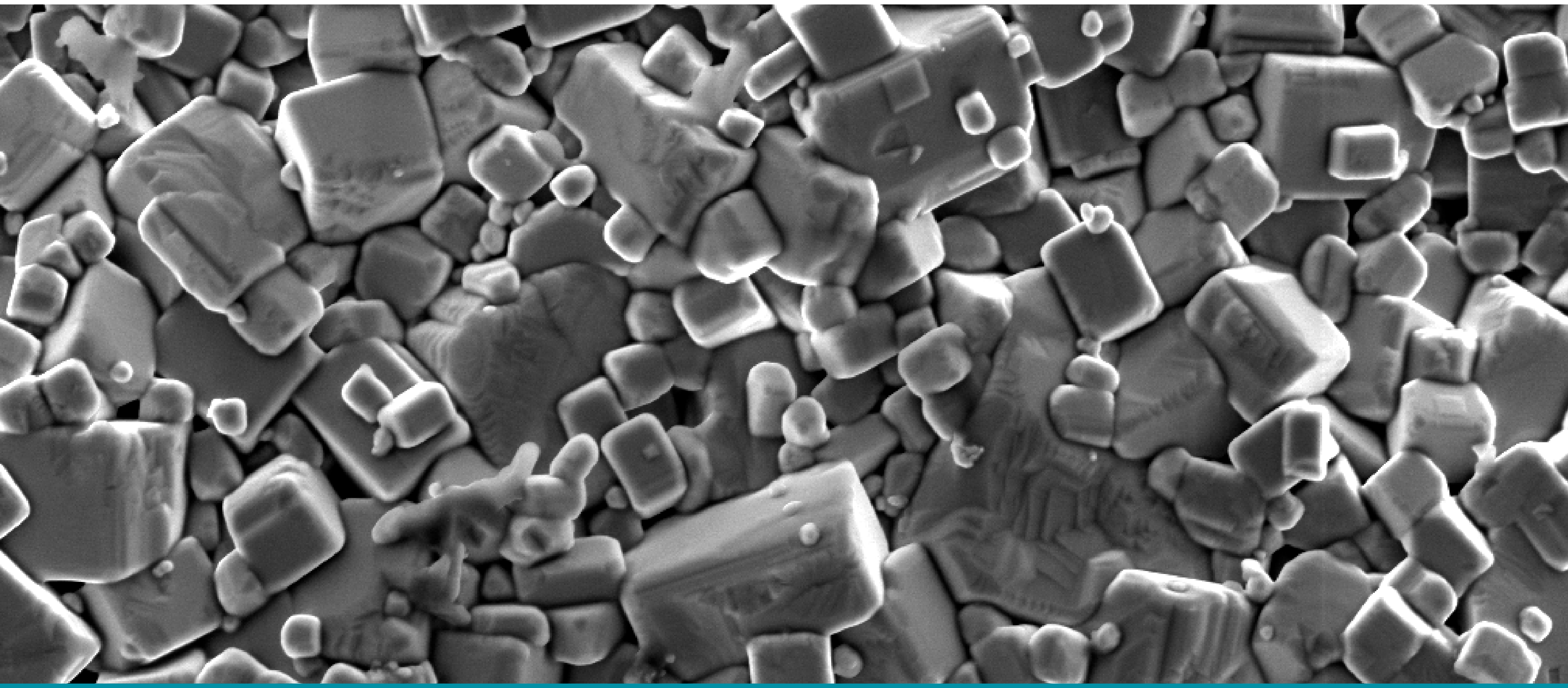


Life Cycle Assessment of Functional Ceramics

To fully achieve a sustainable economy in a given industrial sector, all aspects of the materials development, implementation and production must be taken account. For large research projects in sustainability to be successful (i.e. reduce the environmental footprint), a holistic, multi/interdisciplinary approach must be used.

At Sheffield, Life Cycle Assessment (LCA) has become an integral part of our approach to establish the true 'green credentials' of functional materials and devices. In collaboration with the Management school, materials researchers have applied the Supply Chain Environmental Analysis Tool (SCEnAT) to the comparative LCA of several electroceramic systems and devices.

One key aim of research at Sheffield on a recent large EPSRC Grant was to develop a lead free, environmentally friendly alternative to lead based piezoelectrics. A starting choice of ceramic was based on Potassium Sodium Niobate (KNN) which has promising properties comparable in some respects to Lead Zirconate Titanate, the leading lead based piezoelectric. Based on 1 kg production of powder by standard synthesis routes, a range of environmental impacts were assessed for PZT vs. KNN. The findings of this study were quite remarkable. KNN is on-average 16x worse for the environment then PZT. The main culprit for its disastrous environmental footprint is the mining and refining of Nb which is poorly controlled and releases a range of toxic elements into the local water supply and food chain.



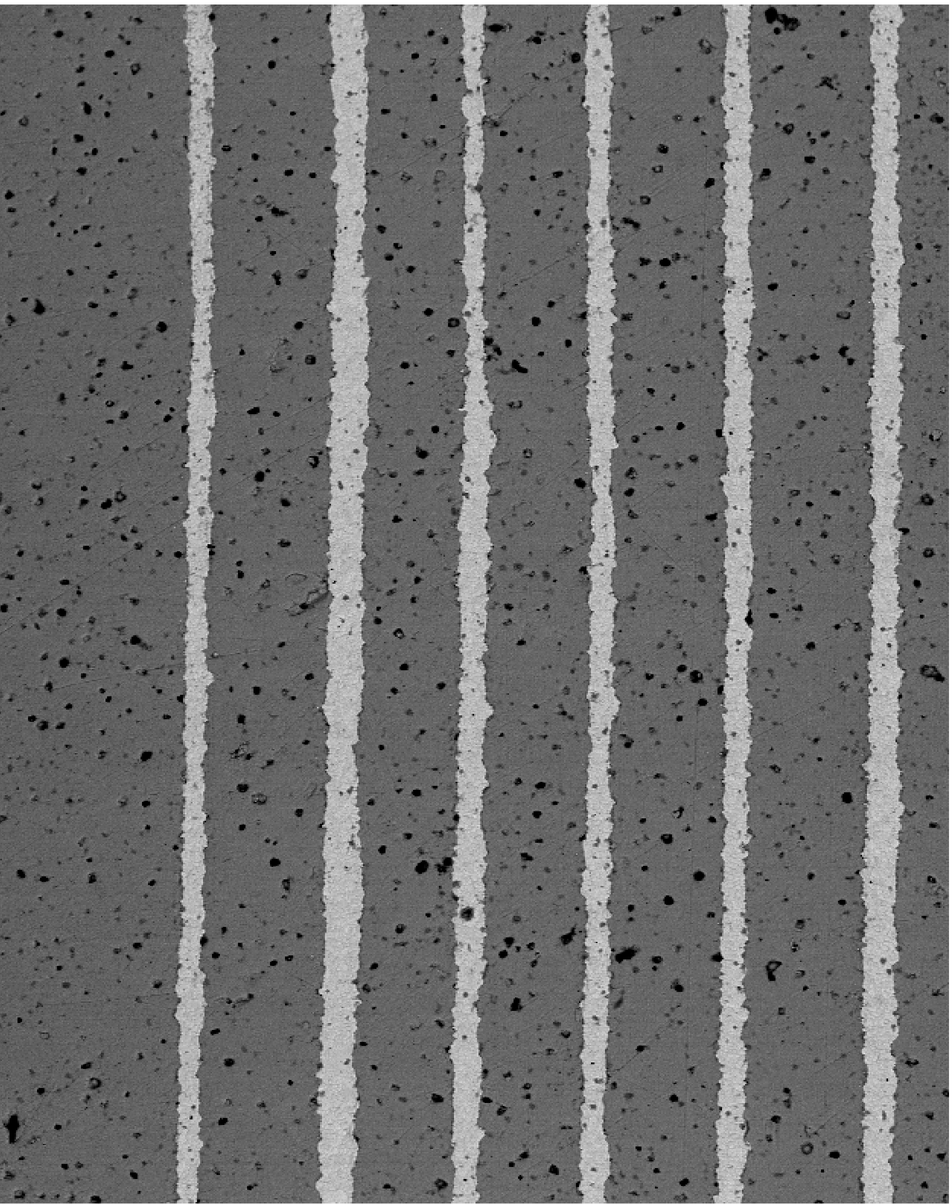
Sustainable Ceramic Processing

Researchers in the Dept. of Materials Science & Engineering have recently developed 'cold-sintering' of ceramics in collaboration with academic partners at North Carolina and Pennsylvania State Universities.

Cold sintering is a new and disruptive technology which relies on the use of aqueous ions and pressure to densify ceramics at <200°C as opposed to >1000°C for conventional sintering.

Preliminary estimates indicate that cold sintering of 1Kg of ZnO, for example, consumes 45kWh, resulting in a carbon footprint of 23.6 kgCO_2-eq, whereas the equivalent mass using conventional sintering consumes 81kWh, yielding a climate change impact of 42.5 kg CO_2-eq.

An ever increasing number of ceramics have been found which, with the right aqueous additives, undergo the cold sinter process. Applications are sought initially in the fabrication of RF substrates in MW technology where compatibility with FR4 polymer substrates and precise control of lateral dimensions facilitated by cold sintering offer great potential to develop new materials for higher frequency, 5G mobile networks scheduled for the early 2020s.



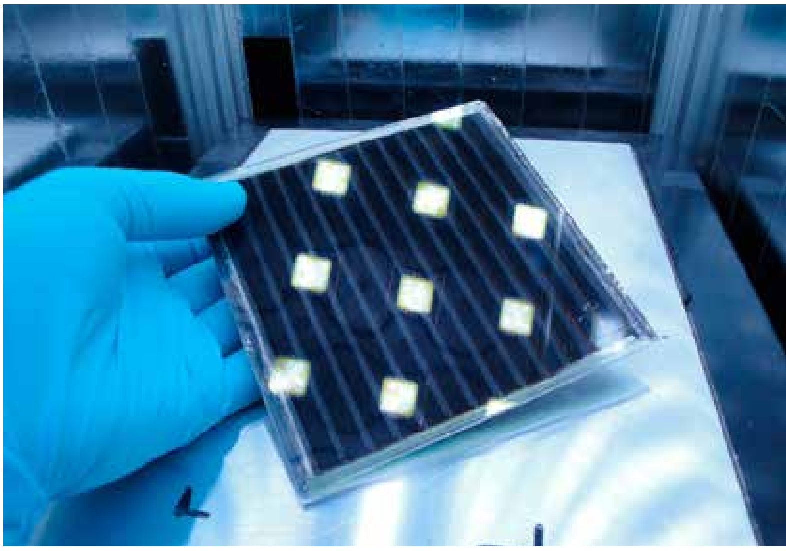
> *"Cold sintering is a new and disruptive technology which relies on the use of aqueous ions and pressure to densify ceramics at <200°C as opposed to >1000°C for conventional sintering."*

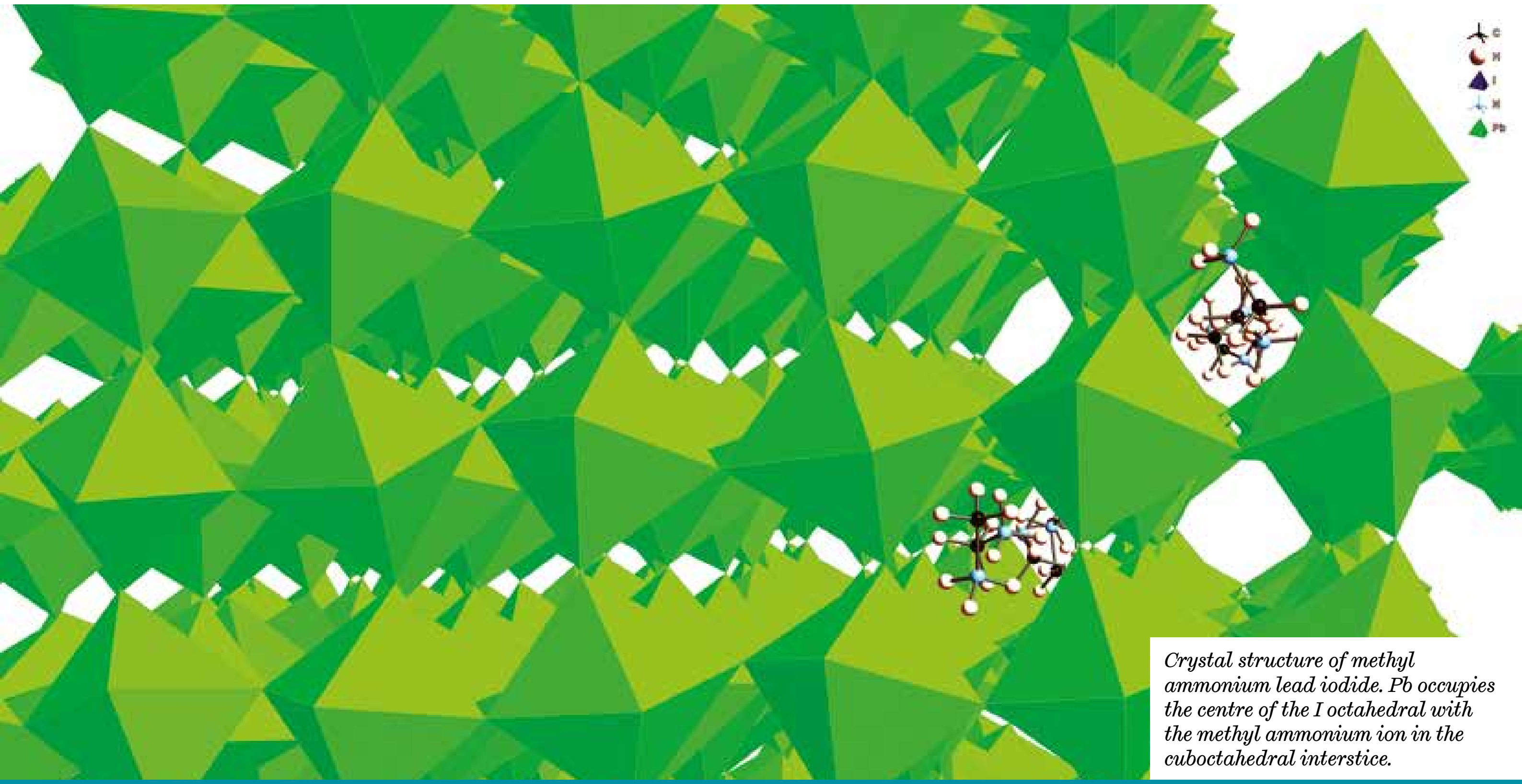
Perovskite Structured Solar Cells

The University of Sheffield is working with Greatcell Solar ltd to develop the next generation of perovskite solar cells which are based on a new, perovskite structure, photovoltaic (PV) compound, known as methyl ammonium lead iodide.

The cells offer efficiencies close to those of conventional Si based PV cells but at a much reduced cost. There many types of structure for the cell but commonly a TiO_2 nano-porous layer is used as the electron conductor which is grown on the surface of a fluorine doped Sn oxide transparent conducting layer on a glass substrate. A hole conductor is then deposited on the surface followed by the top electrode (Ag or Cu). The energy payback period has been calculated by life cycle assessment to be as low as 0.75 years, which means that users would see an energy payback on its investment of this technology in less than 1 yr provided that long term stability issues can be overcome.

At Sheffield we have been using advanced SEM techniques to study the distribution of dopants in the perovskite structured photovoltaic layers, and modelling its structure.





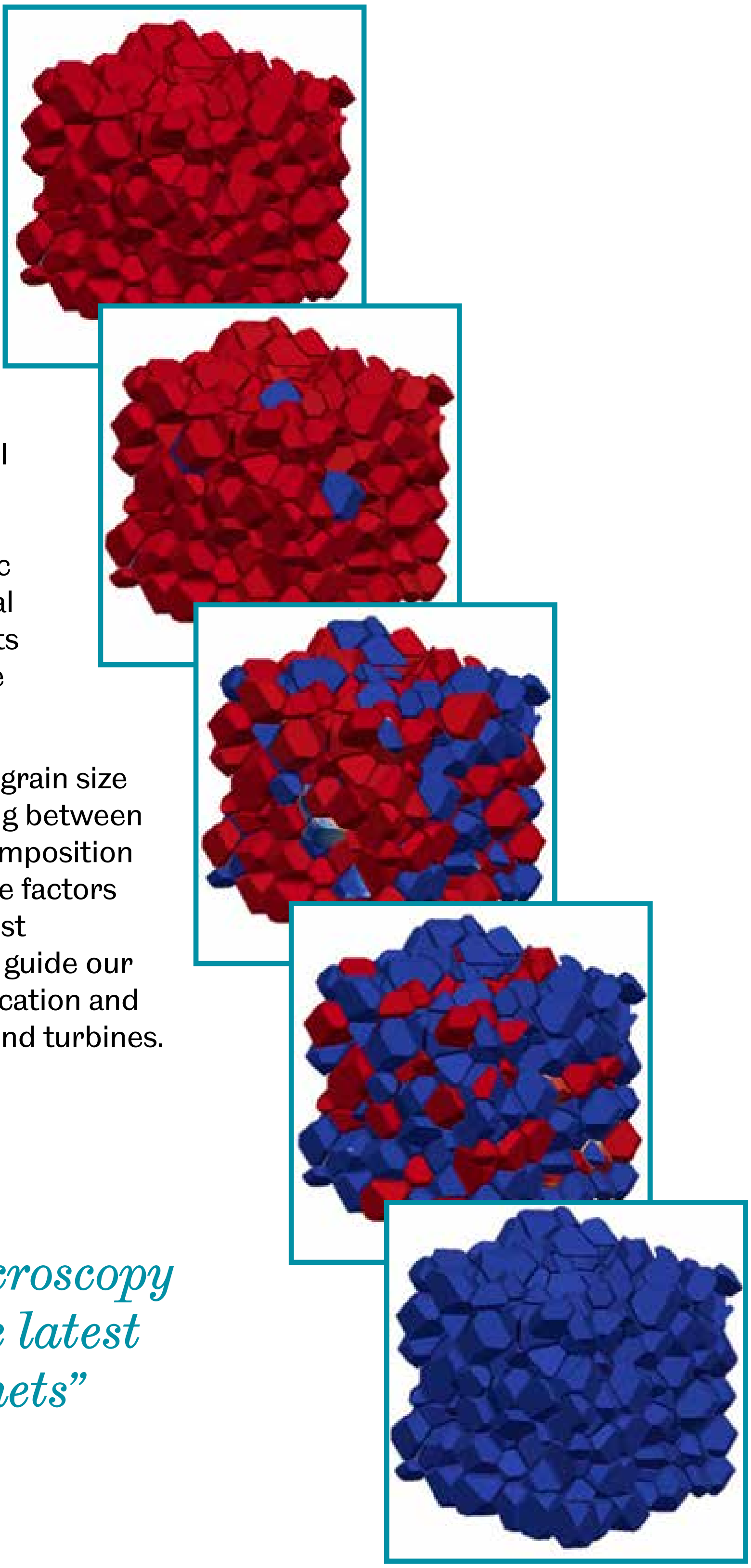
Crystal structure of methyl ammonium lead iodide. Pb occupies the centre of the I octahedral with the methyl ammonium ion in the cuboctahedral interstice.

Microstructural effects on the performance of high strength Nd-Fe-B magnets

High strength permanent magnets such as Nd-Fe-B are vital for renewable energy applications such as wind turbines in order for them to be competitive. Increasing their performance has a direct impact on the electrical generation efficiency and the limited understanding of the role of microstructure in determining magnetic properties is now hampering efforts to improve magnetic properties by changing the magnet's composition and processing.

To help meet this challenge we have developed novel finite element micro-magnetic models that predict how the magnetic behaviour of Nd-Fe-B magnets is affected by microstructure. Our models use realistic microstructures based on microscopy and elemental analysis of the latest commercial permanent magnets and include features such as grain boundaries, triple junctions and twinned grains.

We have used our modelling to explore the effect of grain size distributions and the nature of the magnetic coupling between adjacent grains, which are both easily affected by composition and processing. This reveals a tension between these factors that must be carefully controlled to obtain the highest performance permanent magnets. This is helping to guide our industry partner Siemens Wind Power in the specification and development of new magnets for next generation wind turbines.



> *"Our models use realistic microstructures based on microscopy and elemental analysis of the latest commercial permanent magnets"*

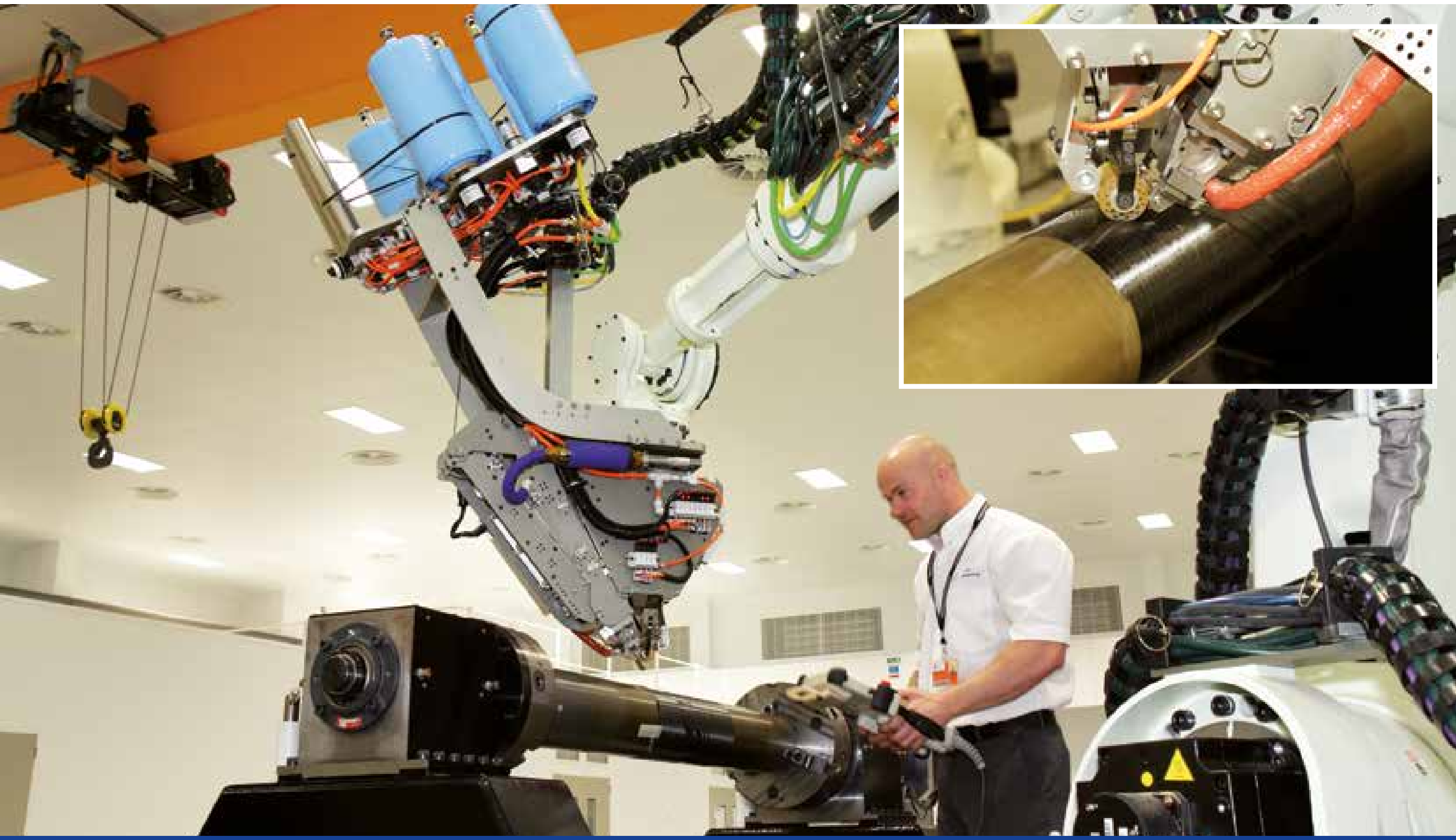
Composite Materials

Composites at Sheffield fuses the academic rigour of the Composite Systems Innovation Centre with the manufacturing and industrial expertise of the AMRC with Boeing. It brings together more than 60 researchers, engineers and academic staff developing composite materials and systems for advanced structures, multifunctional technologies and environmentally friendly products and systems. Examples of projects include:

Multi-functional printed composites: automated multi-layered systems are being developed which incorporate printed self-sensing and self-ameliorating structures. These structures can provide significant improvements in function and performance, while comprising only 0.02% of material and preserving structural integrity.

Multi-scale modelling: We specialise in modelling the behaviour of composite structures from the molecular level up to full structures and systems subjected to complex loading conditions such as blast, ballistic impact and fatigue. This allows us to design materials that are stronger and safer without needing large investment.

Automated manufacturing & machining: We are investigating the use of automated manufacturing cells to increase throughput and reduce errors by minimising human involvement in the production process. We are also developing new cutting tools and machining fluids for cutting composite materials, as well as developing innovative techniques for drilling, trimming, surface machining and stack machining.

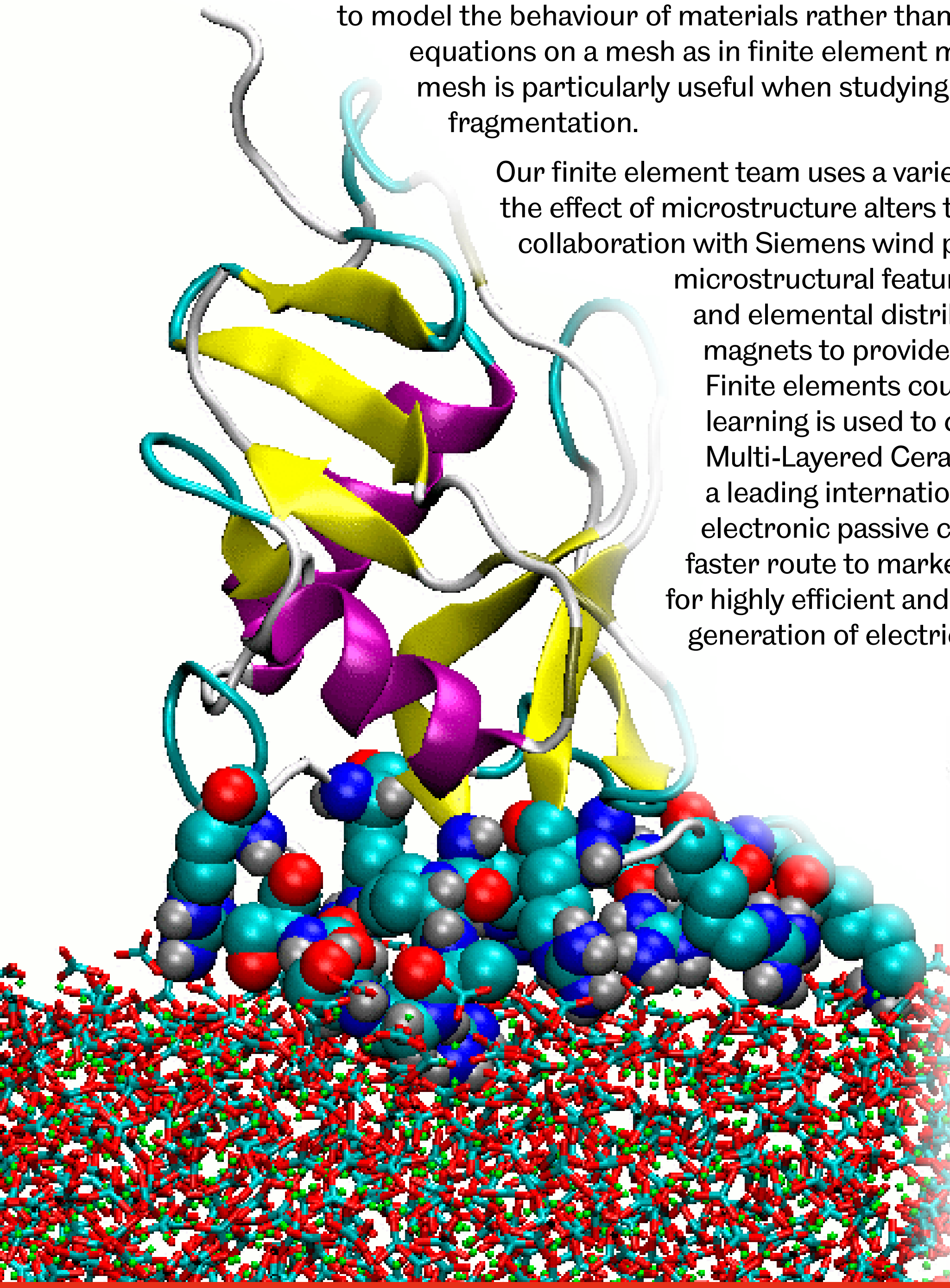


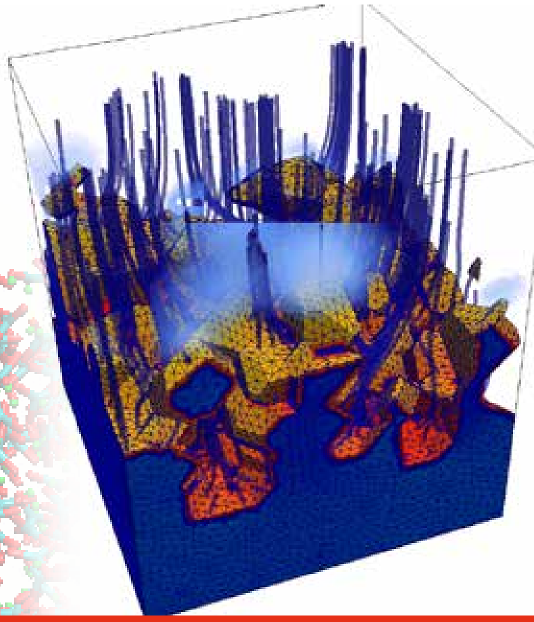
Modelling of Materials and Devices

Our modelling research groups offer state-of-the-art techniques encompassing length scales from the atomic scale to the metre scale and timescales from picoseconds to years. The groups are supported by an in-house Beowulf cluster and use regional and national high-performance computing.

At the atomic scale, density functional theory and molecular dynamics offer understanding of how chemical species interact with each other to form materials. At the mesoscale, smooth particle applied mechanics provides a novel and highly versatile simulation tool that uses particles to model the behaviour of materials rather than discretising the continuum equations on a mesh as in finite element modelling. Avoiding the use of a mesh is particularly useful when studying large deformations, failure and fragmentation.

Our finite element team uses a variety of packages to study how the effect of microstructure alters the response of materials. In collaboration with Siemens wind power, we are looking at the key microstructural features (such as porosity, roughness and elemental distributions) within permanent magnets to provide efficiency gains for wind turbines. Finite elements coupled with data mining and machine learning is used to design the next generation of Multi-Layered Ceramic Capacitors (MLCCs) with AvX, a leading international manufacturer and supplier of electronic passive components. This will produce a faster route to market by providing key design criteria for highly efficient and sustainable MLCCs for the next generation of electric cars.



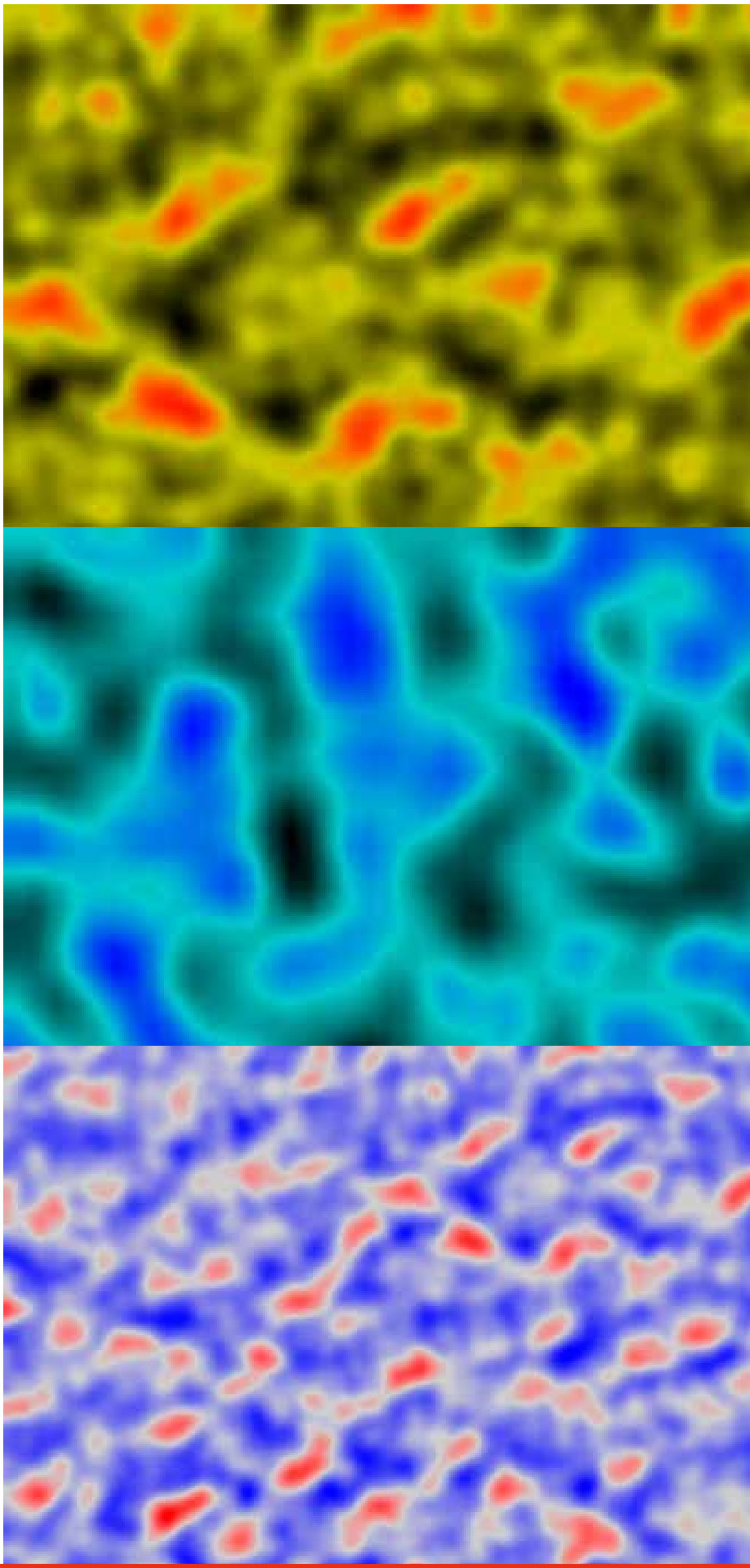


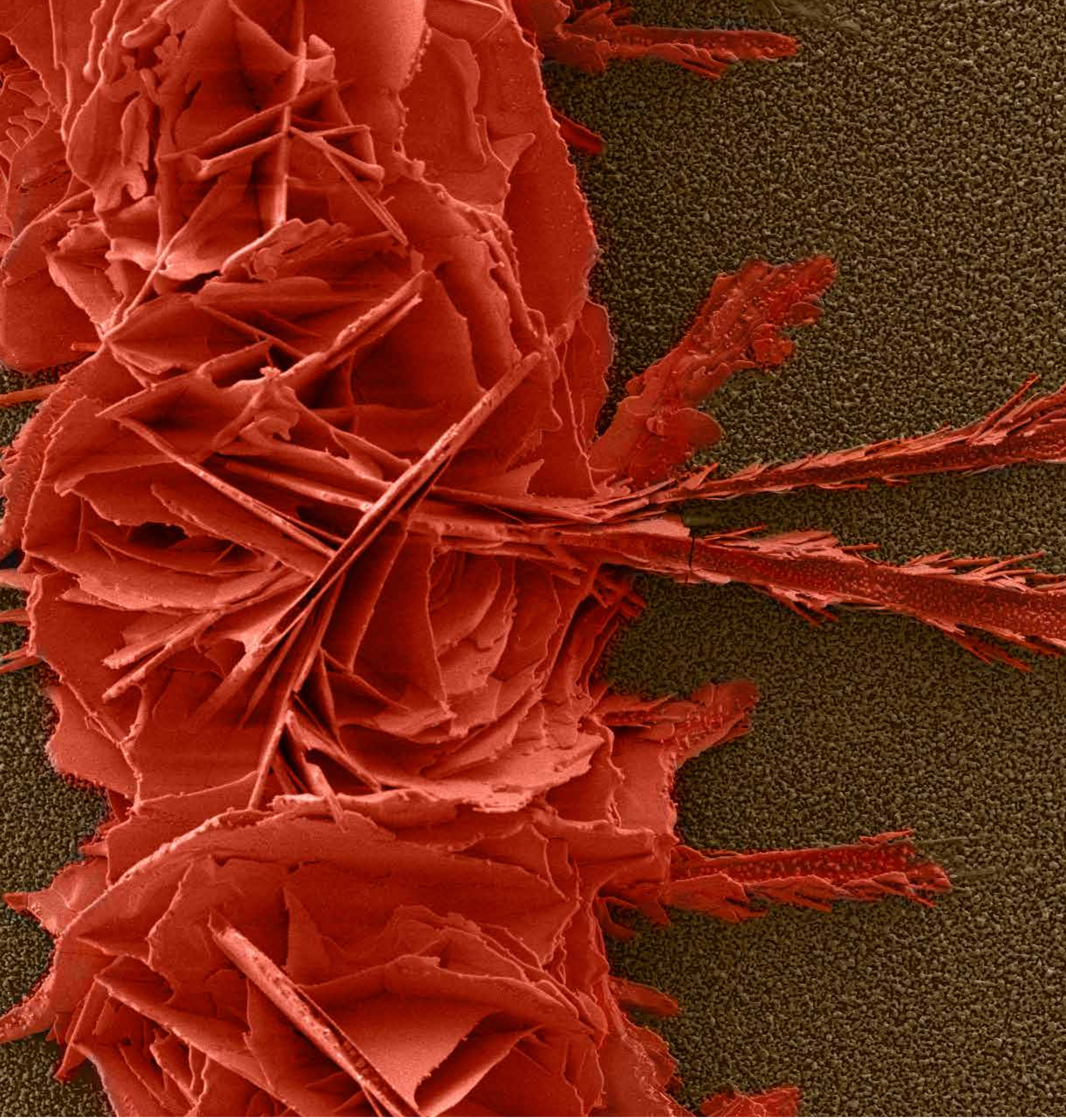
Secondary Electron Hyperspectral Imaging

Electron microscopy is a fundamental technique to characterise and better understand materials. The scanning electron microscope (SEM) is often used on inorganic materials and coupled with Electron Dispersive X-ray (EDX) analysis, can supply high-throughput morphological and compositional information on μm-mm scales. However, SEM-EDX is limited in the case of organic materials (low atomic number, Low-Z) due to sample damage and charging issues.

Researchers in Sheffield are pioneering a new technique to overcome this limitation, called Secondary Electron Hyperspectral Imaging (SEHI), which can be used for high-resolution analysis of polymers in the SEM, as has been demonstrated, for example on silk fibres, where nano-scale regions with different molecular order can be mapped using a suitable peak from the secondary electron spectrum.

A low voltage beam of electrons is incident onto a native surface causing secondary electrons to be emitted. This enables the user to control the energy of the secondary electrons collected, and a signature spectrum with peaks due to the electron emission from all components of the surface can be generated. The different peaks can be isolated to produce high-resolution images of that specific component i.e. the separation of order from disorder of different Low-Z materials. This revolutionary technique now provides material scientists with the equivalent of "SEM-EDX" for organic materials. The technique can also be used for complex materials with an organic component such as perovskite solar cells.





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