Imperial College London

Institute for Molecular Science and Engineering

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The value of additive manufacturing: future opportunities

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Executive summary

- The global additive manufacturing (AM) – 3D printing – industry was valued at $6 billion for 2016, and is predicted to grow to more than $26 billion by 2022[1]. This rapid growth has arisen mainly because of the evolution of AM from primarily a prototyping tool to a useful end-product fabrication method in some high-value manufacturing applications (e.g., in the aerospace, medical device and automotive industries).
- AM has the potential to offer many economic, technical and environmental advantages over traditional manufacturing approaches, including decreased production costs and times, the possibility of flexible and bespoke production, as well as a reduction in energy usage and waste. To realise these benefits, however, several barriers – across the entire AM process chain – need to be overcome. For example, **improved design software, faster printing technology, increased automation and better industry standards are required**.
- To realise a more-efficient and more-profitable industry, 'game-changing' AM research breakthroughs are thus required. Involving more researchers – from a wide array of scientific and engineering backgrounds – will be beneficial, as will a closer working relationship between academia and industry.
- The concept of molecular science and engineering[2] – melding a deep understanding of molecular science with an engineering mind-set – provides an excellent framework for the 'cross pollination' of research ideas. In the pursuit of solving some of the biggest needs in AM, scientists and engineers – from a range of disciplines – can be brought together to communicate and collaborate at all stages of the AM research-to-final-product chain. In this way, costly late-stage changes can be avoided and the route to final, functional end-use products

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can be rapidly optimised. In addition, a new generation of scientists and engineers can be trained in a transdisciplinary manner, e.g., with AM training, to address the current AM skills gap in industrial settings.

- As the UK's AM landscape continues to expand and develop, Imperial College London is equipped to play a leading role in these research endeavours. The current portfolio of AM-based research is varied and encompasses problems across the entire design-to-end-use-product chain. Current research, for instance, includes the development of new design methodologies for optimised multimaterial AM parts, novel metal-based AM printing techniques, investigations of fundamental AM material properties and 3D printing of next-generation biomaterials for medical applications.
- Current AM research at Imperial can be extended by capitalising on the College's world-class scientific and engineering research expertise and facilities, its culture of collaboration and history of effective research translation. Indeed, there are several ways for external partners interested in the AM field to engage with Imperial academics (e.g., focused workshops, bespoke consultancy services, funding for specific research projects and facilities, or student placements).
- Ultimately, ongoing **AM research will be of benefit to a range of additional disciplines** (e.g., quantum technology and photonics) **and will play a critical role in tackling many societal challenges**.

Introduction

What is additive manufacturing?

Additive manufacturing (AM) – popularly known as '3D printing' – is an umbrella term for techniques in which three-dimensional objects are built from sequential layers of material. As shown in Table 1, there are a number of different existing AM methods[3] that can be used with a range of materials. These processes – each with its own set of features, as well as associated advantages and disadvantages – can now be used to fabricate a multitude of products.

Although the AM concept was first proposed in the early 1980s[4–6], the methodology only became a reality after substantial technology advancements were made and costs were reduced. Since then, AM has become a popular and widely adopted tool for rapid prototyping of parts.

Moreover, in the last decade, AM has been implemented for high-value manufacturing applications in many sectors, including the aerospace, medical device and automotive industries (see Table 1; Box 1). The global AM market also continues to grow at an increasingly rapid rate (see Figure 1). Indeed, the total size of the global AM industry (consisting of all AM products and services) was estimated at about $6 billion in 2016 (growing from about $0.4 billion in 1996) and is predicted to grow to more than $26 billion by 2022[1].

This boom has arisen because AM presents several potential economic, technical and environmental advantages over traditional 'subtractive manufacturing' (i.e., machining) approaches, including:

- reduced production costs and times;
- the ability to create objects, with extremely complex geometries, that are optimised for their specific function;

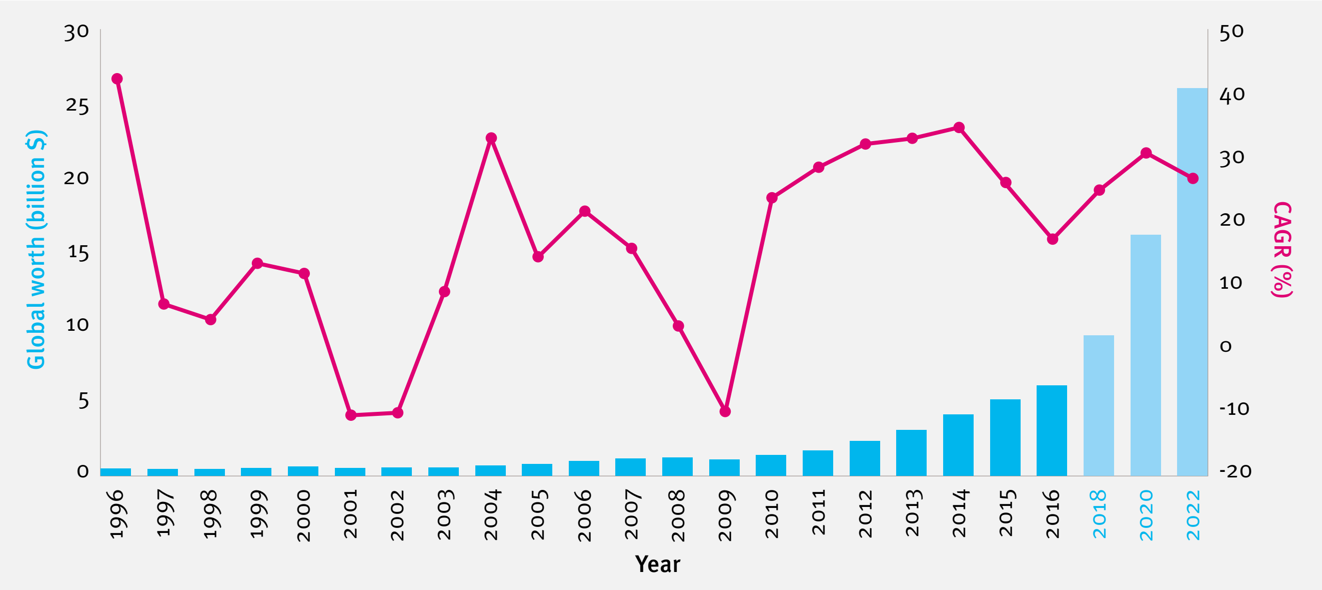


Figure 1. Estimated growth of the global additive manufacturing (AM) industry between 1996 and 2022 (predicted values for 2018–2022). The total worth of the industry (all AM products and services) is given in billions of US dollars. The compound annual growth rate (CAGR) of worldwide revenues is also shown[1].

- the capacity to radically redesign products and to create materials with enhanced properties (e.g., graded materials);
- cost-effective, low-volume and flexible (i.e., bespoke) production;
- less need for expensive and dedicated tooling;
- reduced environmental impact (e.g., reduced energy usage and material waste);
- better-distributed manufacturing;
- increased readiness for the digital revolution (i.e., the 'Internet of Things' or 'Industry 4.0').

AM has already proven to be particularly valuable in the aerospace industry because of the opportunity to reduce the amount of material needed to build parts, to optimise product designs (e.g., in terms of weight and part consolidation) and to substantially reduce lengthy product development times. For example (also see case study 1 in Box 1), Airbus have recently used state-of-the-art AM techniques, as well as new materials, to reduce the overall weight of their A350 aeroplane and to thus ensure more fuel-efficient travel[7]. This aircraft contains more than 1,000 3D-printed components, e.g., a topology-optimised 3D-printed titanium part (70 g) that replaces a conventional steel seatbelt buckle (155 g). Through changes such as these, Airbus expect to save 3.3 million litres of fuel (equivalent to a reduction in carbon dioxide emissions of 0.74 Mt) and €2 million (about $2.4 million) in maintenance costs over the lifetime of one aircraft[8].

What is the UK's position in the global AM market?

The manufacturing industry represents a major proportion (10% of the gross domestic product) of the UK's economy, with 2.7 million people directly employed in the sector[9]. The manufacturing industry also contributes 10% gross value added (GVA) and accounts for 45% of the country's total exports[9]. As one of the world's top ten manufacturing nations[10], it is therefore important for the UK to keep pace with other world-leading manufacturing nations by capitalising on the expanding AM market – and it is well-placed to do so. Indeed, the UK is a global force in important high-value manufacturing sectors (e.g., advanced technology and medical manufacturing). It also has strong research capabilities in universities (with four of the top ten universities in the world)[11], as well as in research and development (R&D) organisations.

Furthermore, the UK is already at the forefront of AM technological advancements, with about 250 organisations currently involved in AM activities[12]. To date, the UK has established a strong foundation of companies who apply AM in product development (i.e., prototyping and tooling)[12]. In addition, researchers in the UK are leading the transition of AM to the production of end-use parts[12]. These research innovations are contributing to commercial success in a number of UK and global companies (e.g., Rolls-Royce, GSK, GKN and HiETA)[12]. The UK's nascent AM supply chain also includes some of the world's leading AM machine, material, part and technology suppliers, as well as software developers (e.g., Renishaw and LPW Technology)[12]. The UK is thus well-armed to combine new AM knowledge and research findings with the country's innovation and production expertise. The country's continued competitiveness in the global AM and wider manufacturing sectors may thus be ensured.

Major challenges to AM progression

Despite the ongoing growth and benefits of 3D printing, the uptake of AM technologies in many industrial sectors is still limited. Indeed, there are several barriers preventing more widespread adoption of AM in the manufacturing industry (i.e., outside of high-value applications)[1]:

- the high cost (i.e., purchase, operation, maintenance and depreciation) of AM machines and materials;
- the need for more-rapid 3D-printing throughput (i.e., new AM technology with faster operating speeds, better resolution and accuracy, larger build volumes, as well as more-optimized loading and unloading procedures);
- the lack of consistency (and maturity) in quality assurance practices across the sector;
- design tools (e.g., software) that do not adequately exploit the full potential of AM;
- a general scarcity of suitably trained personnel working in AM, with few opportunities for collaboration and 'cross pollination' of ideas.

These problems thus present several major ongoing research and industry challenges, across the whole AM process chain (see Figure 2). These issues need to be addressed before AM will be economically comparable (or preferential) to traditional subtractive manufacturing approaches in high-value situations. **Overall, the entire AM process chain would benefit from faster and cheaper methods, improved industry standards, as well as superior intellectual property protection and security measures.**

The UK's growing AM research landscape

The level of publicly funded AM research in the UK reached almost £55 million in 2016 (having been about £8 million in 2007), and involved about 250 different organisations[13]. The majority of this funding comes from general Engineering and Physical Sciences Research Council (EPSRC)[14] and Innovate UK programmes, but the first AM-specific funding call in the UK (for a total of £4.5 million) – Connected Digital Additive Manufacturing[15] – was introduced by Innovate UK in May 2016. The programme's objective is to help companies adopt advanced

AM technologies and to overcome barriers to business growth in AM. Innovate UK is also now running a recurring £15 million funding scheme "to stimulate and broaden innovation in manufacturing and materials"[16]. It is necessary for the funded projects to involve innovation in either a manufacturing system, technology, process or business model; or innovation in materials development, properties, integration or reuse, and is thus specifically relevant to AM research.

As complements to individual research projects being conducted in universities and commercial R&D departments, several cross-community AM-related initiatives have been set up in recent years. For example:

- The EPSRC Centre for Innovative Manufacturing in Additive Manufacturing (2012–2017) was a sustainable and multidisciplinary body of expertise, acting as a national and international focus for AM and its applications[17].

Box 1: Commercial case studies of 3D printing

Additive manufacturing is now being successfully employed as a disruptive technology in several high-value manufacturing sectors, including the aerospace, medical implant, automotive and consumer product industries.

Case study 1: CFM International

First introduced in 2016, LEAP™ engines[18] from CFM International (a joint venture between Safran Aircraft Engines and GE Aviation) are the first aircraft engines to include 3D-printed parts. The combustion system of each engine contains 19 3D-printed fuel nozzles (as shown on the right) that could not otherwise be manufactured, and which are 25% lighter than their predecessors[19]. The parts are also five times more durable than similar components made via conventional manufacturing processes. CFM has already received more than 12,500 orders for these engines, which are 15% more fuel-efficient than earlier versions. About 70 Airbus and Boeing aeroplanes with LEAP engines are currently in service, with a 96% utilisation rate[20].

Source: GE Reports/Adam Senatori

Case study 2: BMW/Rolls-Royce

BMW have been using AM – mostly for production of prototypes and one-off custom parts – for about 25 years, and in 2012 they began 3D printing end-use components as part of their series production activities. Since then, BMW have incorporated thousands of parts (such as those shown on the right) into the Rolls-Royce 'Phantom' and 'Dawn' models. The varied 3D-printed parts include light holders, sockets, mounting brackets for wires, and fibre-optic cables. The utilisation of AM allows production times – especially for components with complex geometries, which could not be produced with traditional manufacturing techniques – to be substantially reduced. It is expected that BMW will continue to expand the use of advanced 3D-printed parts across its whole range of vehicles[21].

Source: BMW Group[22]

Case study 3: Adidas

In 2016, Adidas began production of its limited-edition '3D Runner' shoes (shown on the right). These 3D-printed running shoes – commanding a sale price of $333 – were produced not just for novelty's sake, but also to provide exciting, high-performance features. For example, the 3D-printed mid-sole is engineered to be denser in high-force impact zones and with lighter, less-dense regions where less support is required. The ultimate goal is to be able to produce, through AM, shoes that are completely customised to the individual customer, i.e., their foot shape, running style, performance needs and personal preferences[23].

Source: Adidas[24]

Case study 4: 4WEB Medical

4WEB Medical was founded in 2008 and is now an industry-leader for 3D-printed medical implant devices[25]. The company's success is built upon their 3D-printed proprietary truss implant platform, which exploits the novel '4WEB' geometry in the construction of high-strength, lightweight web structures[26]. The number of products available from 4WEB Medical continues to grow, with four 3D-printed truss systems currently available and approved for surgical use in various orthopaedic (e.g., spinal) implant surgeries. The specialised geometry of 4WEB Medical's products present several advantages over other 3D-printed and titanium implants. For instance, they provide an increased surface interface area for bone implantation, more volume for bone growth and a superior mechanical environment in which biological fusion can occur[25].

Source: 4WEB Medical[27]

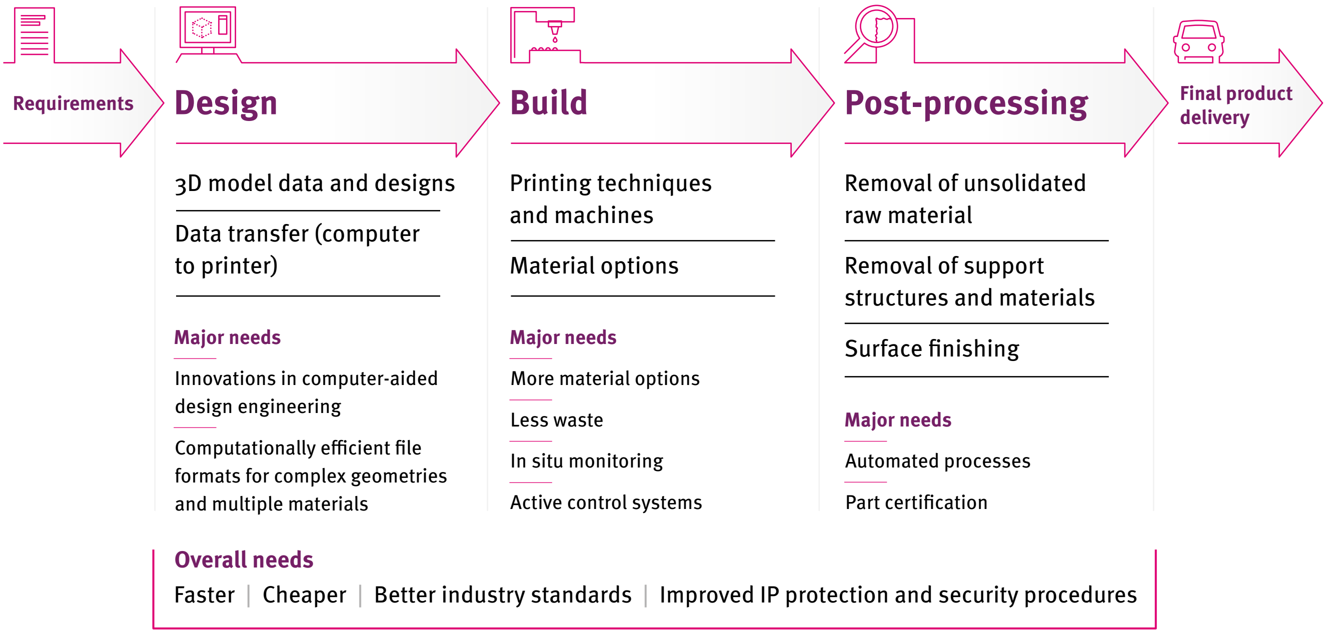


Figure 2. General aspects of the AM process chain and the associated major needs of the industry. Overall, a faster and cheaper route to final end-products is required, with better industry standards, and improved intellectual property (IP) and security measures.

- The High Value Manufacturing (HVM) Catapult is a catalyst for the future growth and success of advanced manufacturing in the UK. Through its seven technology and innovation centres, new ideas are accelerated from technology concept to commercialisation, thus creating a sustainable high-value manufacturing future for the UK[28].

- The National Centre for Net Shape and Additive Manufacturing at the Manufacturing Technology Centre in Coventry – established in 2015 – is funded by both government and industry to ensure that the UK manufacturing industry retains its competitive edge. The Centre is the focal point for AM innovation within the HVM Catapult, and its overall aims are to develop production-ready AM processes, to overcome barriers to wide-scale adoption, and to work on legislative and standardisation issues for AM activities[29].

- Manufacture using Advanced Powder Processes (MAPP) – an EPSRC Future Manufacturing Hub – aims to deliver on the promise of powder-based manufacturing to provide low-energy, low-cost and low-waste high-value manufacturing routes and products, and to thus secure UK manufacturing productivity and growth. By working with academic, commercial and innovation partners, MAPP will drive the research needed to solve many of the fundamental challenges that currently limit the development and uptake of many powder-based processes (i.e., several AM techniques)[30].

- Additive Manufacturing UK (AM-UK) is an independent, government-backed collaboration formed to help position and drive the UK's ongoing AM strategy. This country-wide AM strategy engages all relevant parties (i.e., industry, academia, government and finance) and is an important endeavour as the UK aims to keep pace with countries (e.g., China, Germany, Japan, South Korea and the USA[31]) that already have government-sponsored AM policies in place[32].

AM has also recently been recognised as an integral part of the UK's Industrial Strategy[33], with science, research and innovation activities identified as one of the critical ways to achieve higher levels of productivity in the UK. An additional £4.7 billion has thus been earmarked to support these activities by 2020/2021. The Industrial Strategy Challenge Fund (ISCF)[34] will benefit from this government initiative and will have the aim of "bringing together the UK's world-leading research with business, to meet the major industrial and societal challenges of our time". AM will undoubtedly play a critical role in meeting the six named ISCF challenges – specifically the 'manufacturing and materials of the future' challenge (i.e., the development of new, affordable, lightweight composite materials for aerospace, automotive and other advanced manufacturing sectors).

AM at Imperial College London

Imperial College London is a science-based institution consistently rated amongst the world's best universities (ranked 9th globally and 3rd in the UK, in 2017, by QS)[35].
At Imperial, specific emphasis is placed on innovative research that explores the interface between science, medicine, engineering and business. Indeed, this boundary is perfectly embodied by AM-based research – a growing field of study in College. The **Additive Manufacturing Network**[36] at Imperial

was established in 2016 to help showcase the increasing amount of AM research in College (more than 75 people in 15 departments are currently involved in AM-based research, many with industrial partners and collaborators) and to further exploit Imperial's fundamental science knowledge base for the benefit of AM. In addition, there is an ever-growing number of state-of-the-art 3D printers at Imperial (housed in several departments and centres) that encompass many of the major AM technologies[3]. Full 3D-printing services – ranging from design aspects to post-processing – are also available in College.

AM research at the junction with molecular science and engineering

The emerging discipline of **molecular science and engineering** – melding a deep understanding of molecular science with an engineering mind-set – is a powerful way to create effective and sustainable solutions to global grand challenges[2]. The major AM science and engineering needs (Figure 2) represent one such grand challenge that can be addressed through the molecular science and engineering approach. By bringing scientists together with engineers (i.e., those focused on fundamental research and on industrial-scale end-use products and solutions, respectively) at all stages along the AM-process chain, a faster and more cost-efficient route from research concept to industrial application can be achieved. Merging diverse areas of expertise in this way means that potential late-stage and expensive pitfalls can be recognised – and rectified – early in the lifetime of a project.

Imperial's strong links with industry are also a vital aspect of realising more-profitable and sustainable AM. The results of fundamental scientific and engineering research at Imperial need to be effectively translated into real-world applications. By designing new AM processes with relevant input from industrial partners – from the very beginning – a substantial cost-efficient knock-on effect should be felt. Indeed, there are already several areas of ongoing work at Imperial that sit at the crossroads of AM and molecular science and engineering. The following examples highlight the breadth of such AM-based work around College, and represent various parts of the AM (design–build–post-processing) and the molecular science and engineering (molecular structure–physical properties–material performance–manufacture–function) process chains.

Multifunctional AM

A necessary major step for the future evolution of AM is to increase the functionality of fabricated products. One way to achieve this is an approach known as functional grading, in which gradients of single or multiple materials are utilised intelligently to meet several criteria simultaneously. This technique can be used, for example, in the design of load-bearing compliant mechanisms. The ultimate goal of so-called multifunctional AM (MFAM) is thus to manufacture multifunctional end-use devices, in which various features (e.g., of an electronic, electromagnetic, optical, fluidic, actuation, chemical or thermal nature) are directly embedded as part of the 3D printing process[37].

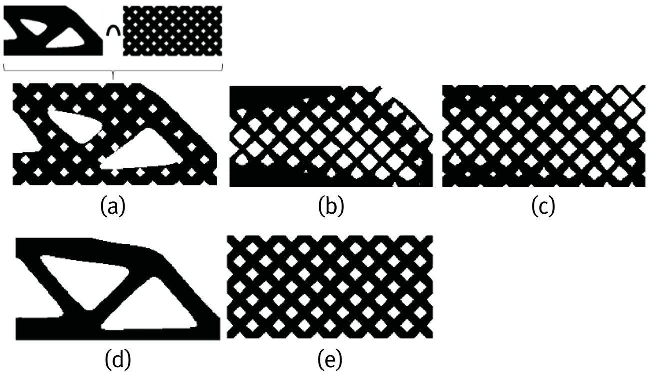


Figure 3. Continuum topology optimization results for the design of functionally graded lattice structures in AM applications. Each structure solution shown here has a 50% volume fraction. Three functionally graded solutions are shown, i.e., for (a) an intersected lattice (intersection between the solid solution and uniform lattice), (b) a graded lattice and (c) a scaled lattice. The solid solution (d) and a uniform lattice (e) are also shown for reference.

To date, much effort has been devoted to the development of hybrid AM systems (i.e., that combine more than one AM technology) in the pursuit of MFAM. For instance, a system that merges elements of vat photopolymerisation (stereolithography) and direct print technologies (e.g., directed energy deposition) has previously been realised for 3D printing of electronic devices[38]. Although steps have been taken to exploit the inherent design freedoms of AM[39,40], little work so far has focused on developing design philosophies for the realisation of novel MFAM concepts. New design, analysis and optimisation methods are therefore required for this emergent technology.

In recent studies led by Imperial academic Dr Ajit Panesar (Department of Aeronautics), strategies for realising functionally graded AM lattice structures[41] and a design framework for MFAM[42] have thus been proposed. In the first of these novel methodologies, continuum topology optimisation results are interpreted and the various solutions (see Figure 3) are investigated for their robustness and effectiveness (in terms of mechanical performance and manufacturing considerations). Furthermore, in the proposed iterative MFAM methodology, system and structural design aspects are coupled so that optimal material and system layouts can be explored. The immediate application of this work is for the design of 3D-printed multimaterial parts that have embedded functional systems (e.g., a structural part with electrically conductive components). The novel approach should also be suitable for tackling a range of other general engineering problems, such as large, functionally graded civil engineering structures (e.g., graded buildings and bridges) that incorporate specific systems (e.g., pipes and cables).

Microstructure–performance relationships in AM materials

Making high-performance and reliable metallic components is one of the remaining challenges in 3D printing of components for aerospace, automobile and medical applications[43–46]. This difficulty arises because of the complex microstructures of materials that are produced via AM, i.e., the microstructures are heavily influenced by specific print parameters[43, 46]. For instance, thermal conditions during the melting and cooling stages of AM printing techniques can cause parts to have microstructures that differ from those produced by conventional methods (e.g., casting or forging). Although much work has already been devoted to understanding the relationships between printing parameters and the pore-structure and mechanical properties of 3D-printed metal products[44, 46–48], an in-depth understanding of the link between microstructure and mechanical properties is still lacking. This is mainly because of the highly complex microstructures involved. There is thus a need for high-resolution investigations into the connection between the microstructure and mechanical response of 3D-printed parts[43, 44, 46–49].

In their recent work, two Imperial researchers – Dr Minh-Son Pham (Department of Materials) and Dr Paul Hooper (Department of Mechanical Engineering) – together with student Mr Bogdan Dovgyy (Department of Materials), have tackled this problem by examining the process–microstructure–performance relationship of 3D-printed stainless steel[50]. Understanding these relationships in AM products is critically important for components that will be used in demanding service environments and loading conditions. The specific material that was the focus of the new study – AISI 316L steel – was chosen because it is widely used in industry (e.g., for medical devices and power plants). This material is particularly popular because of its high corrosion resistance at low temperatures, as well as its high oxidation resistance and good deformation resistance at high temperatures. The mechanical behaviour and microstructures of AM parts made from this material have previously been examined[44, 47, 48, 51–54], but the evolution of the microstructures after deformation has not yet been investigated (i.e., to help explain the material's outstanding properties).

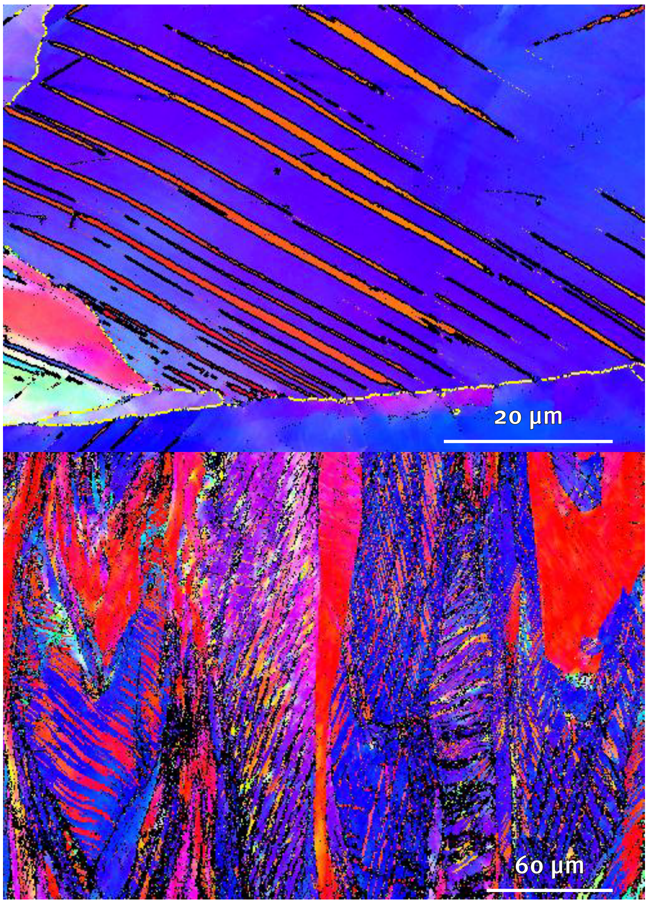


Figure 4. Two examples of deformation twinning observed in 3D-printed 316L stainless steel parts[50].

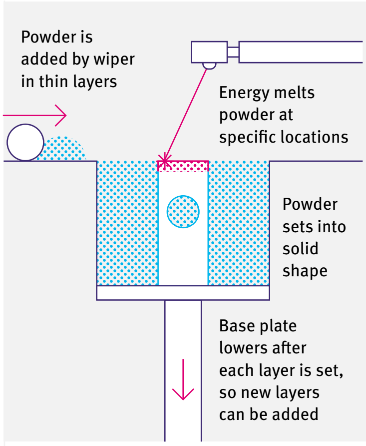
In the new work, the steel samples were printed via laser-based powder bed fusion and then subjected to mechanical testing. The grain structure and microstructure of the samples, both before and after deformation, were examined. The results of the study (see Figure 4) revealed an interesting phenomenon – known as twinning-induced plasticity – that has not previously been reported for 3D-printed 316L steel, and which is thought to be responsible for the good ductility of the material. In addition, the work highlighted that AM can give rise to surprising mechanisms that are not observed in other traditionally produced alloys. By obtaining this kind of detailed scientific understanding of the processes and materials produced in AM – and by embedding this knowledge into predictive modelling and simulation tools – the characteristics of final printed parts will ultimately be improved. Moreover, AM may potentially present a novel method for designing specific microstructures and realizing materials with extraordinary properties.

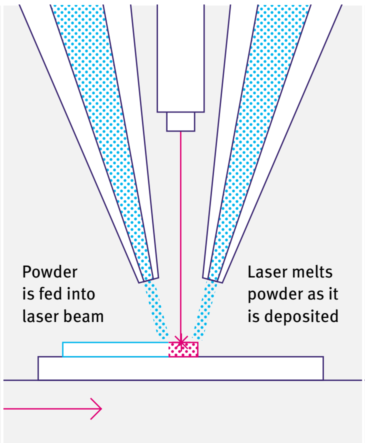
Towards faster, cheaper metal-based AM

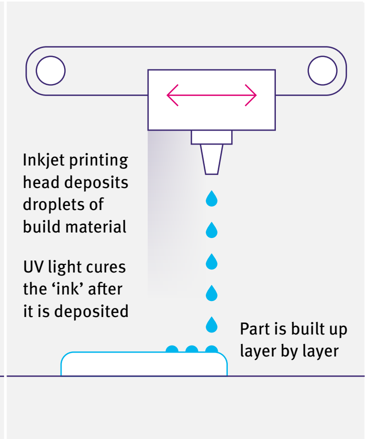
Although direct metal laser sintering (a sub-category of powder bed fusion, in which a laser is used to selectively sinter layers of metal powder[55]) is the most common AM technology for 3D printing metals, its wider commercial uptake – like many AM technologies – is limited by high capital costs, component defects and the inability to work with multiple materials simultaneously. There is thus an ongoing effort to develop a novel non-laser-based 3D printing technique for metals, i.e., one which enables – at reasonable costs – the deposition of multiple materials in functional structures.

Electrochemical AM (ECAM) is a relatively new form of AM that has the potential to meet this requirement, and several different approaches have so far been taken to develop an electrochemical 3D printer[56–59]. In the ECAM technique, thin and highly adherent layers of metal are deposited – via the reduction of metal ions in a solution – onto the surface of a conductive substrate[60]. To date, however, all ECAM methods have been designed to produce only very small (micro- or nanoscale) structures, with limited geometrical complexity. Furthermore, the limited deposition rates for the copper-based systems are

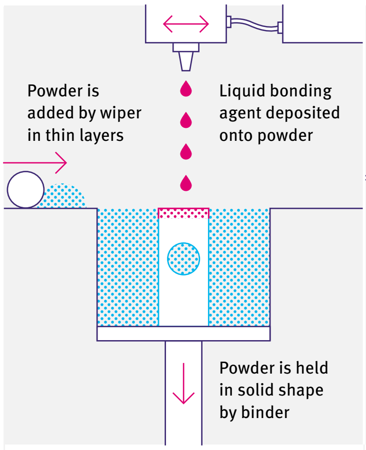
Table 1. Overview of the seven commonly used additive manufacturing technologies[3].







	Powder bed fusion	**Directed energy deposition**	**Material jetting**
	Thermal energy selectively fuses regions of a powder bed.	Thermal energy is used to fuse materials by melting as they are being deposited.	Droplets of build material are selectively deposited.
Commercially printable materials	▪ Polymers ▪ Metals	▪ Metals	▪ Polymers ▪ Ceramics ▪ Metals (in development)
Relative printing speed	SLOW	SLOW	MEDIUM
Relative printing cost	HIGH	HIGH	HIGH
Accuracy	MEDIUM	LOW	HIGH
Major advantages	+ Able to print complex metal parts + High resolution	+ Able to print very large structures + Works in open air	+ Good surface finish + Multiple materials/colours can be printed together
Major disadvantages	– Dangerous – Poor surface finish – High power usage	– Large residual stresses – Poor surface finish – Poor resolution	– Poor durability – Limited material choice
Example application industries	▪ Prototyping ▪ Medical ▪ Dentistry ▪ Aerospace ▪ Automotive ▪ Tooling	▪ Aerospace ▪ Oil and gas ▪ Defense ▪ Energy	▪ Prototyping ▪ Medical ▪ Aerospace ▪ Tooling ▪ Consumer products



Binder jetting

A liquid bonding agent is selectively deposited to join powder materials.

- Ceramics
- Metals

FAST

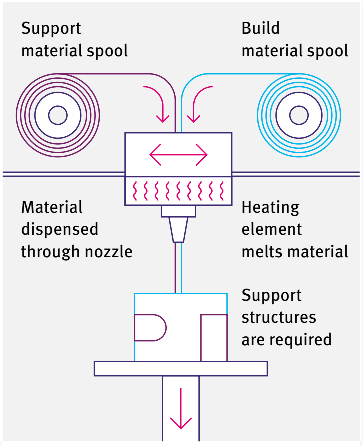
MEDIUM

MEDIUM

+ No supports required
+ Simple
+ Colour can be added

– Produces fragile parts
– Significant post-processing needed to improve mechanical properties

- Prototyping
- Casting
- Model-making



Material extrusion

Material is selectively dispensed through a nozzle or orifice.

- Polymers
- Metals
- Ceramics
- Composites
- Biological

MEDIUM

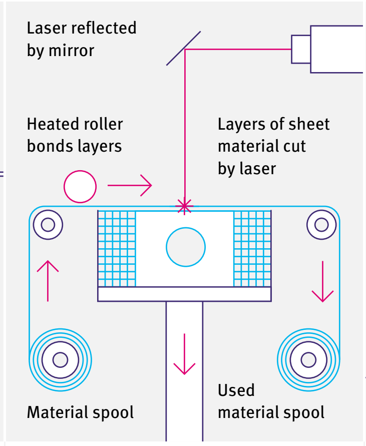
LOW

LOW

+ Widespread usage
+ Simple
+ Desktop

– Poor surface finish
– Support structures required
– Poor repeatability

- Prototyping
- Education
- DIY
- Automotive
- Consumer products



Sheet lamination

Sheets of material are bonded to form a part.

- Polymers
- Metals
- Composites

MEDIUM

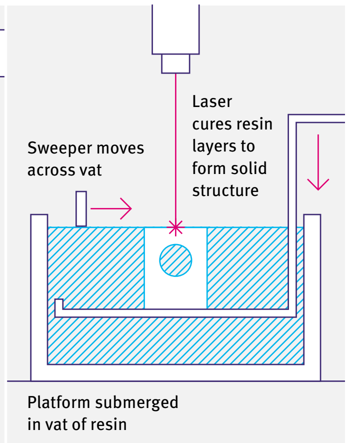
LOW

MEDIUM

+ Can join dissimilar materials
+ Works in open air
+ Simple

– Limited ability to print complex parts
– Mechanical strength determined by bonding

- Prototyping
- Education
- Architecture
- Medical



Vat photopolymerisation

Liquid photopolymer in a vat is selectively cured by light-activated polymerisation.

- Polymers
- Ceramics
- Composites (in development)

MEDIUM–FAST

MEDIUM

MEDIUM

+ Good surface finish
+ High resolution
+ Ability to produce complex geometries

– Limited to photopolymers
– Poor durability

- Prototyping
- Medical
- Dentistry
- DIY
- Consumer products

slow (ranging from about 0.008 to 20.4 $\mu m^3\ s^{-1}$) and remain the primary barrier to upscaling of the technique (so that it can compete with more conventional 3D printing methods).

In ongoing work at Imperial – conducted by Mr Xiaolong Chen, Dr Xinhua Liu, Professor Peter Childs, Dr Billy Wu (all in the Dyson School of Design Engineering) and Professor Nigel Brandon (Department of Earth Science and Engineering) – a novel and simple strategy for ECAM at a significantly larger scale is therefore being developed. In a recently published paper[61], the team presented their meniscus-confined electrode approach, and provided a systematic overview of the factors that influence the speed of deposition in their printing technique and how this affects the product's morphology and physical properties (e.g., hardness and electrical resistivity).

The results of the study show that large-scale printing (using a 400 μm nozzle) with the proposed design is viable. In addition, they have demonstrated that the novel concept of print head movement during printing can be used to enable deposition rates of almost 20,000 $\mu m^3\ s^{-1}$ (i.e., three orders of magnitude faster than previously reported copper deposition approaches), without the occurrence of structural defects. Mechanical and electrical characterisations also revealed that the hardness and electrical resistivity of the printed structures are better than for cold-worked cast copper equivalents (because of the fine-grained 3D-printed structure). This study thus represents an important foundation for the future development of a new low-cost desktop electrochemical 3D printer (see Figure 5). Furthermore, although this initial work was focused on electrodeposition of copper (from aqueous copper sulphate), the methods and findings are also applicable to other chemistries.

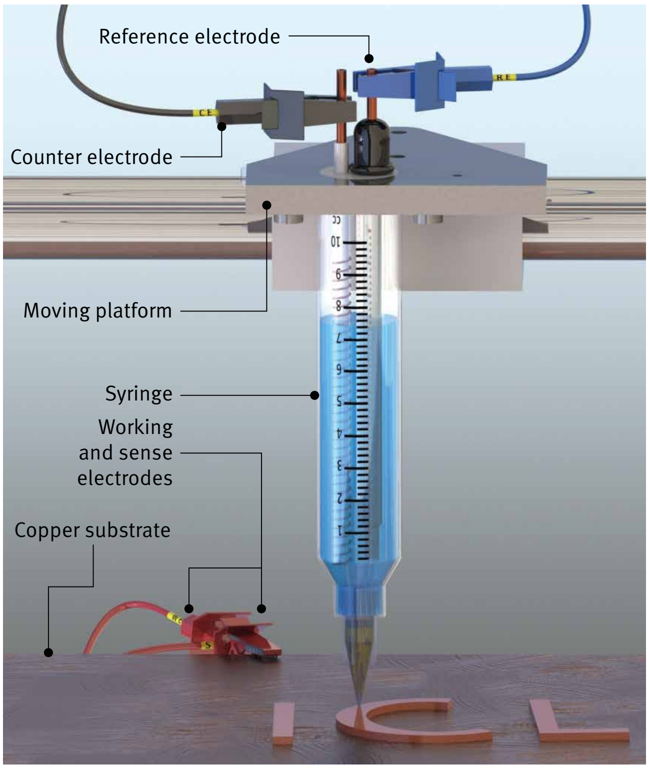


Figure 5. Schematic illustration of the new desktop electrochemical 3D printer developed at Imperial College London, as used here to print copper features (in the shape of 'ICL')[61].

Next-generation 3D-printable biomaterials

The development of advanced materials – i.e., that can be 3D printed and that exhibit the physical characteristics required for a specific function – is partly responsible for the ongoing transition of AM from being primarily a tool for prototyping, to a suitable large scale production method for high-value applications. For instance, AM is already being used successfully to fabricate personalised prosthetics and bone replacements[62–65]. With the development of new high-resolution, multimaterial AM technologies (e.g., material jetting), however, additional application fields are emerging, such as biodegradable or bioresorbable medical devices. Current state-of-the-art tissue regeneration involves the use of scaffolds that act as temporary templates for tissue growth. The complex pore structures required for these scaffolds[66–68], however, are difficult to achieve with conventional manufacturing techniques (e.g., foaming), and 3D printing presents a potential way to design and manufacture these complicated structures[69].

To realise the potential of AM for printing biocompatible tissue scaffolds, it is necessary to create new biomaterials that exhibit specific properties (e.g., rheological, degradation, mechanical and bioactive) and that are suitable for inkjet (material jetting) deposition[70]. In recent work conducted by Imperial's Professor Julian Jones (Department of Materials), together with colleagues from the University of Reading and the University of Nottingham, a novel series of biocompatible polymer systems that are capable of self-assembly into infinite networks were designed, synthesised and characterised for AM applications[71]. In the proof-of-concept study, the team appended hydrogen-bonding motifs to a biodegradable polymer to yield the supramolecular polymer networks, and used a piezoelectric inkjet printer to deposit simple cubic structures of the materials. In addition, the polymers were combined with silica nanoparticles to produce hybrid solutions that could be used to construct more complex 3D structures (see Figure 6). The team also demonstrated the non-toxicity of the materials. The supramolecular materials

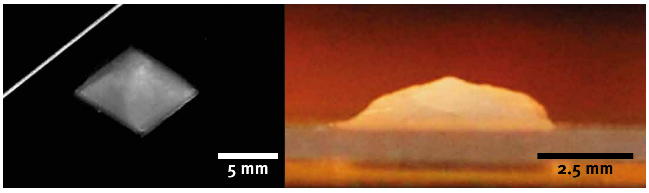


Figure 6. Photographs from above (left) and in profile (right) of an inkjet-deposited twisted 3D pyramid structure made from a biocompatible polymer/silica-nanoparticle composite material. The solid pyramid has a 6 × 6 mm base and a height of 3 mm[71].

and composites therefore show excellent promise for future use as biomedical scaffolds in regenerative medicine.

Ongoing AM work and opportunities at Imperial College London

In addition to the examples of molecular-science-related AM-based research described in the previous section, there is a wide range of other AM projects and activities taking place across Imperial's faculties and departments (see Box 2). Indeed, Imperial's existing collaborative research culture means that it is well-placed to make an even-greater impact in AM research going forward. In particular, several of the College's initiatives – including the Additive Manufacturing Network (AMN) and the Institute for Molecular Science and Engineering (IMSE)[72] – are specifically set up to facilitate transdisciplinary research, and to continue the College's strong links with industry.

The needs in AM for innovative digital design tools and for improved IP protection and security (see Figure 2) are specific areas in which Imperial can bring additional relevant expertise (i.e., by involving researchers from many of Imperial's departments and centres, including the Department of Computing and Department of Mathematics, the Imperial Business School, as well as from the Data Science Institute and Institute for Security Science and Technology). To thus increase the understanding of AM – and its ongoing challenges – at Imperial, the AMN held a successful launch event ('The current state and future of additive manufacturing') in 2016 and is creating a series of AM-focused publications[73, 74]. In addition, IMSE and the AMN joined forces in May 2017 to host an internal workshop (with some guests from industry): 'The Future of Additive Manufacturing'[75]. The range and breadth of the delegates' research interests illustrates the substantial appeal of AM in College, even to those not yet working in the field. In addition, the radical ideas for future AM-based research that were generated by the attendees during a brainstorming session highlight the importance of transdisciplinary collaboration.

Imperial is also supporting future AM work by investing in new facilities around College. For instance, the Imperial College Advanced Hackspace (ICAH)[76] provides students and staff with access to a unique suite of prototyping technologies (including many 3D printers), workshops and laboratories on several of Imperial's campuses. These facilities include the new Invention Rooms and the molecular-science focused hackspace in the Molecular Sciences Research Hub (both on the White City Campus). In addition, the new Dyson School of Design Engineering building (on the South Kensington Campus) will house a dedicated AM research laboratory.

Box 2: Examples of ongoing AM research at Imperial

Waveguides for the twenty-first century

Professor Stepan Lucyszyn and Dr William Otter (Department of Electrical and Electronic Engineering) – together with colleagues from the UK's National Physical Laboratory and Japan – are using novel 3D printing techniques to produce inexpensive high-precision waveguides for communications applications[77]. Their initial 3D-printed metal-pipe rectangular waveguides were operated at microwave frequencies (in the 8–12 GHz range, known as the 'X-band'). Building on the success of these devices, the team developed millimetre-wave (75–110 GHz; 'W-band') waveguides that have smaller dimensions and thus require tighter manufacturing tolerance. To realise their record-breaking terahertz-frequency waveguides, however, 3D printing limitations had to be overcome. The team thus made use of a new class of 3D printer (RECILS), at the University of Tokyo, to obtain the required high-quality surface finish for their relatively large printed structures (with small features sizes), without additional post-processing. Ultimately, the new techniques will permit a range of devices (e.g., high-performance imaging systems for security monitoring, satellite payloads and medical diagnostic equipment) to be developed more rapidly than in current state-of-the-art manufacturing.

Aerial construction

Through the Aerial Additive Building Manufacturing (Aerial ABM) research project, funded by EPSRC and headed by Principal Investigator Dr Mirko Kovac (Department of Aeronautics), a system that enables autonomous 3D printing of building structures by aerial robots will be developed[78]. This approach has the potential to reduce construction times, material and transport costs, and improve safety in the building industry. The team are aiming to miniaturise current ABM systems and provide aerial capabilities so that they can be used to manufacture complex building structures and adapt to diverse site scenarios, as well as to enable parallel production by a swarm of robots.

Combining AM and synthetic biology

A new project – co-led by Dr Guy-Bart Stan (Department of Bioengineering), Dr John Heap (Department of Life Sciences) and Dr Connor Myant (Dyson School of Design Engineering) – aims to create new types of materials with made-to-order shapes, sizes, biological functions and chemical properties[79]. This work, which is one of the first projects to be supported by Imperial's new Excellence Fund for Frontier Research, involves a novel approach that combines AM and synthetic biology, and could open up a host of new avenues in manufacturing. For instance, the production of new sustainable building materials and wearable technology could be enabled.

Summary

To overcome current hurdles in the AM process chain – and ultimately to create a more-effective and more-profitable industry – 'game-changing' materials, design methodologies, printing technologies and software are required. In line with Imperial College London's strength of effectively translating innovative, collaborative and transdisciplinary research into practical solutions to real-world problems, many Imperial researchers (along with several industry partners and collaborators) are already actively involved in cutting-edge AM research. To extend the focus and impact of Imperial's AM research even further, continued support for these activities is required and it is necessary to involve people from an even broader set of backgrounds.

To that end, there are several ways for external partners to engage with Imperial academics in the AM field. For example, there are opportunities to:

- define industry-focused AM problems for future collaborative co-creation workshops;
- benefit from bespoke technical consultancy on AM (for example, on subjects ranging from materials characterisation to market analysis);
- provide funding for AM research (e.g., studentships and fellowships) and facilities (such as new 3D printers or AM-devoted laboratories) at Imperial;
- offer industrial AM-focused work placements for Imperial students, e.g., graduate students on IMSE's new Master's of Research in Molecular Science and Engineering course, which is specifically designed to create a new generation of scientists and engineers who can work across the molecular science/engineering interface[80].

The outcomes of the ongoing efforts and research in AM will, no doubt, ultimately benefit not just the field of 3D printing, but will also cascade through, and provide added value, to a host of other disciplines. For example, the advanced manufacturing techniques presented by AM could be used extensively in the areas of quantum technology and photonics, and be used to tackle a range of societal challenges.

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About the Institute for Molecular Science and Engineering

Founded in 2015, the Institute for Molecular Science and Engineering is the newest of Imperial College London's Global Institutes. The Institute brings engineers, scientists, clinicians and business researchers together from Imperial's four faculties to find molecular-based solutions to grand challenges facing our world. By blurring the boundaries between molecular science and engineering, and changing the way scientists and engineers work together, the aim of the Institute is to accelerate the pace of development to address these challenges. The Institute co-ordinates a range of integrated activities to enable researchers at Imperial and elsewhere to engineer novel products and solutions that are firmly based on advances in molecular science and engineering.

www.imperial.ac.uk/imse

About the Additive Manufacturing Network

Imperial College London's Additive Manufacturing Network was set up in 2016 to showcase AM research activities in College and to increase understanding of AM processes. In particular, the AMN aims to exploit Imperial's expertise in fundamental science to further knowledge of AM product performance, to advance AM technologies and to create novel design methodologies and tools. Supported by the Faculty of Engineering Internal Strategic Fund, the Network's activities are designed to provide strategic direction and a unified front for AM-based research at Imperial, to increase and focus external exposure to Imperial's AM research, and to facilitate interdepartmental collaborative AM opportunities in College (e.g., research seminars, workshops and access to equipment).

www.imperial.ac.uk/additive-manufacturing

About Imperial College London

Consistently rated amongst the world's best universities, Imperial College London is a science-based institution with a reputation for excellence in teaching and research that attracts 13,000 students and 6,000 staff of the highest international quality.

Innovative research at the College explores the interface between science, medicine, engineering and business, delivering practical solutions that improve quality of life and the environment – underpinned by a dynamic enterprise culture. Since its foundation in 1907, Imperial's contributions to society have included the discovery of penicillin, the development of holography and the foundations of fibre optics.

This commitment to the application of research for the benefit of all continues today, with current focuses including interdisciplinary collaborations to improve health in the UK and globally, tackle climate change and develop clean and sustainable sources of energy.

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