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CATAPULT Satellite Applications

Why Space? The Opportunity for Materials Science and Innovation

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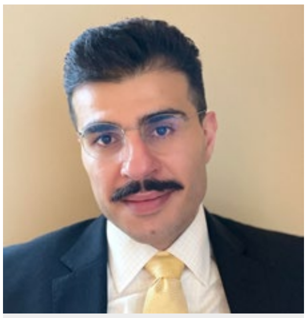

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Executive Summary

Advanced materials (and their manufacturing) are one of the 7 transformational ‘technology families’ identified by UK Government, where there is both a key opportunity for growth and existing globally competitive research and development (R&D) expertise tied with industrial strength. Similarly, at both a local and global scale, the space sector continues to grow in both size and ambition.

With the development of a robust, space launch and provider ecosystem, the ability to access space is accelerating, bringing with it the key opportunity to harness the space environment to augment this technology family’s development heralding solutions to terrestrial challenges. Coupled with this sizable opportunity, are the significant plans for space infrastructure and exploration, that require novel material and manufacturing processes, enhanced properties, and solutions to achieve these.

Therefore, there exists a strong foundation for a cohesive case that could bring these communities together and demonstrate the case to key actors (from funders and policy makers to scientists and entrepreneurs) on the opportunity for materials with space. From fundamental research to applied industry solutions, this paper harnesses perspectives from across these communities to better understand the possibilities for research, innovation, and growth.
To build this foundation, it is important to contextualise that materials science is an extremely broad field where scientists seek to understand the formation, structure, and properties of materials on various scales, ranging from the atomic to the microscopic and to the macroscopic (large enough to be visible).

The properties a material has (such as strength or electrical conductivity) are determined by its structure. Hence, establishing quantitative and predictive relationships between the way a material is processed, its structure (how atoms or larger inclusions are arranged), and its properties is of paramount importance.

Gravity is a major contributing factor to this understanding. Materials processing in general, and metals in particular, are often influenced by gravity-driven mechanisms such as solidification. In this case, the liquid-to-solid transition of pure metals is affected by both convection and sedimentation which will ultimately determine the structure of the material.

To better understand the complex relationship of processing to a material’s structure, scientists are exploring the use of microgravity facilities to conduct materials-science experiments, where the aforementioned undesired effects are reduced. This includes the use of both in-orbit based facilities (such as the international space station) as well ground-based facilities (such as drop towers).

Studying the effects of the space environment on the properties and behaviour of many fluid and solid “terrestrial systems”, could lead to the development of novel manipulation strategies and materials in space, with properties or functionalities that cannot be obtained in normal gravity conditions. For example, this can inform the development of the next generation of advanced materials with superior physicochemical properties to support human space exploration as well as revolutionising established processes on Earth, including design and manufacturing.

R&D in this area, could also help address key roadmap points for space exploration (such as in-situ resource utilisation), as well as those cited in terrestrial R&D roadmaps (such as increasing the efficiency and capacity for novel semi-conductor manufacturing). This in turn can drive global leadership, foster international collaboration and development of novel solutions to terrestrial challenges.

Fundamental to enabling this is recognising, championing, and stimulating this opportunity. This paper, its authored contributions, and the derived recommendations within, aim to provide a ‘small step’ on the journey.

The global use of advanced materials, including composites and alloys, by space industry technologies, from launch vehicles to satellites, amounts to approximately £1.2 billion each year. It’s noteworthy that the value of these materials increases twofold or more once they undergo further processing downstream in the supply chain to form essential parts of larger components and fabricated structures. In line with the growth trajectories of the space industry over the next decade, the value of the advanced materials in the space industry is projected to expand threefold, reaching an estimated £4 billion by the year 2035.

Additionally, as discussed extensively in the position paper, the emerging microgravity research and engineering platforms are poised to open a new market for materials R&D in space. According to a study by McKinsey & Company, the value of R&D on semiconductor materials alone, utilizing these orbital platforms, could reach a value of £150-300 million by the early 2030s. New chemical formulations and various other materials technologies, such as technical ceramics, are additional high-potential candidates for space-based R&D innovations that can expand the value of the emerging commercial microgravity market.

Key Recommendations

In order to harness the interface between the Space and Material communities to foster new research, innovation and translational activities, this report makes five recommendations:

Invest in UK R&D testing platforms: Conducting experiments in space is inherently complex and costly, which is limiting the number and scale of studies that can be undertaken. There are significant efforts to increase the capabilities and facilitate access to the ISS, however there is still a need to develop alternative platforms for in situ manufacturing and testing of materials beyond the ISS for space research applications. In some cases, ground-based facilities can also be used as an alternative to increase capacity, but location, access costs and backlog remain a major barrier for the R&D community. Therefore targeted investment into user driven facilities and resourced partnerships with platform providers are needed to open up access to trial and scale technologies and build a competitive and collaborative R&D system.

Development of a R&D funding strategy and funding framework for space: Often, new materials developed in space are threatened by the classic “TRL valley of death” scenario. As highlighted by several groups, very few ideas actually make the transition from a simple proof-of-concept to a prototype that could be launched into space, due to the lack of more significant investment. This issue can only be addressed with the establishment of an overarching research strategy and robust funding mechanisms for further concept development, supported by collaborations with experienced space contractors and industry primes.

Technical and regulatory process reforms: There is a pressing need for a robust and defined process to design, manufacture and test materials that can be qualified and approved for flight in space applications. Whilst standards for testing of materials for space are well established and routinely used by researchers, the ability to characterise a material’s surface remotely through high-precision measurements in-space is still underdeveloped and will be essential to assess concept performance and viability, alongside creating reference datasets for standard developments where none may exist. As such, focussed investment in regulatory reform with industry and academia is needed to develop a competitive R&D ecosystem.

Development of a cross government space skills framework: The lack of microgravity culture in the UK is still seen as one of the main barriers adversely affecting the exploitation of materials in space. Most undergraduate and postgraduate degrees offered by UK Universities do not cover microgravity-related topics, at least in sufficient detail, to raise awareness and encourage students to develop a professional career in this emerging field. As such it is recommended to have a coordinated approach across policy, funding and industry to address these gaps, increase academic capacity and cross-fertilisation with space and ensure UK competitiveness.

Nurturing national and international R&D networks (academic and industry): So far, the USA, Japan and other European countries such as Germany, Belgium and France have dominated microgravity research targeting space-based electronics and various other materials or processes. However, UK academia has a strong history in these fields, especially with regard to the exploitation of various multiphase systems and the production of inorganic materials of great technological value and interest such as metal alloys and semiconductor substances, with activities led by Bristol, Cambridge, Sheffield, Strathclyde, Glasgow, Cardiff, and other universities. Hence, as the race-to-space intensifies, strategically coordinated industry-academia efforts are needed to fill the gap with other countries.

Opportunity and Alignment to National and International Roadmaps

Edited by Hamid Soorghali – Satellite Applications Catapult, UK

The space industry has been a major catalyst for advances in material sciences and innovations, yielding profound economic and societal benefits. As we enter a new era of unprecedented infrastructure and supply chain development in space — the so-called In-Orbit Economy — the spectrum of materials innovations, both driven and enabled by space, is set to expand remarkably.

Innovation in materials is highly aligned and contributes to the UK government's Innovation Strategy[1], which has identified advanced materials and their manufacturing as one of the 7 transformational 'technology families' that will drive change over the coming decades and where the UK has globally competitive research and development (R&D) and industrial strength. The UK Innovation Strategy sets out the government's vision to make the UK a global hub for innovation by 2035.

This publication highlights the rich and broadening emerging opportunities at the intersection of space industry and material innovation for the UK — home to prestigious institutions and innovation hubs at the forefront of material development to address new technical and applications challenges driven by our rapidly evolving global economy and trends.

Historically from the dawn of the Space Race of the 1960s, the UK has well-leveraged its strong base in materials R&D alongside its advanced manufacturing supply chain to drive and capitalize on materials innovations driven by the continual expansion of the space sector and its demanding technical needs. In this section, we assess how the same foundation can be harnessed and further developed towards advancements in the new age of microgravity or space-based R&D platforms, which promises a new era of radical and cross-sector innovations for materials developments.

Our collective call to action is for UK stakeholders to recognize and invest in the immense potential of Microgravity R&D and Manufacturing for the advancement of material sciences and innovation in the UK. In addition to increasing reference to this emerging field in national strategies and industrial technology roadmaps, investment in facilitating the development and integration of the supply chain of Commercial Microgravity Platforms in Lower Earth Orbit (LEO) with terrestrial advanced materials and adjacent manufacturing supply chains is important. Nations and corporations that proactively invest in such integration today, and drive this new frontier, can shape the trajectory of this emerging field, which promises new scientific breakthroughs and innovative technological advancements.

Major steps are already underway on this front with the recent announcement of 12 projects as part of the Space Clusters Infrastructure Fund (SCIF), including a £8 million project fund to build a pioneering National Microgravity Research Centre[2]. This first-of-its-kind facility is intended to be the central hub for advancing in-space advanced material research and production with state-of-the-art equipment, clean rooms, electronics labs, and payload bays facility, with an initial focus on growth of inorganic crystal structures in microgravity.

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[1] UK Innovation Strategy: leading the future by creating it. Accessed 15th November 2023 *https://www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it/uk-innovation-strategy-leading-the-future-by-creating-it-accessible-webpage*

[2] Space Cluster Infrastructure Fund *https://www.gov.uk/government/news/47-million-investment-to-supercharge-space-infrastructure-across-the-uk - Accessed 26th November 2023*

The evolving symbiotic relationship between space and material innovations

Opportunities enabled at the intersection of space industry advances and materials innovation have been immense for the UK.

During the 1960s Space Race, the need for resilient, lightweight materials capable of withstanding the harsh conditions of space and Earth's re-entry accelerated innovation in advanced composites and high-temperature alloys. Originally developed for space applications, these materials have made their way into revolutionizing various industries, including aerospace, automotive, renewable energy, and construction. The economic implication of this cross-pollination has been significant for the UK's economy. Its advanced composites sector, is now valued at £5 billion market, supporting over 400 companies and 30,000 jobs, underpinned by a strong R&D base[3].

In the last decade, the space industry underwent a major evolution, marked by a significant reduction in launch costs and the large-scale deployment of thousands of miniaturized satellites. This shift has broadened access to the space industry, extending it to a diverse range of new commercial players beyond the traditional defence and governmental entities. The remarkable increase in the deployment of miniaturized satellites, which now perform functions once exclusive to larger and more expensive counterparts, has been made possible by material innovations that were driven by the miniaturization trends of the past decade. In the same decade, the UK by successfully leveraging its space and materials sciences sectors established itself as a key global player in small satellite technologies – which its manufacturing infrastructure and supply chain today is valued at £2.4 billion, forming a crucial component of its £17.5 billion space industry .

As we look towards the next decade, material science innovations, driven and enabled by space, is poised for another significant revolution. The emerging in-orbit economy, characterized by private commercial space stations and sophisticated in-orbit servicing and microgravity R&D and manufacturing platforms, calls a new era of opportunities for innovation in material sciences. This advancement stands to benefit researchers and industrials alike, opening up a landscape rich with potential for new developments and opportunities.

New era of materials innovation opportunities, enabled by emerging microgravity platforms

The commercial microgravity R&D and manufacturing platforms will constitute a major part of the emerging commercial infrastructure deployments in space in the coming decade. The once-niche area of microgravity research, previously only accessible to a select few and available primarily on the International Space Station (ISS), is now set to be democratized with upcoming new platforms facilitating wide and fairly easy access to researchers, innovator and industrials.

These microgravity platforms, either integrated on the new space stations such as Axiom Space or offered by companies like Space Forge on their free flying satellites, provide engineers and scientists with laboratory environments free from Earth's gravitational forces which significantly influence material sciences and development processes on Earth.

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[3] Lucintel, Innovate UK, & HVM-C. (2020). UK Composites Industry Competitiveness and Opportunities. *https://iuk.ktn-uk.org/wp-content/uploads/2021/07/Opportunities-in-the-UK-Composites-Industry-Lucintel-Public-Version.pdf* Accessed 26 November 2023

[4] Size & Health of the UK Space Industry 2022 by UK Space Agency and Know.Space Consulting *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1148037/know.space-Size_Health2022-SummaryReport.pdf* – Accessed 26 November 2023

The growth potential of In-space Materials R&D and production will be driven by the development and expansion of the supply chain, including a series of new microgravity platforms

- Only current platform allowing limited microgravity R&D
- Limited facilities and relevant hardware
- Long waits for access – 2-4 years
- Lack of sufficient automation

A fast-evolving *supply chain* providing access to commercial microgravity R&D with differentiated services

- 17 Commercial Service Providers that own and operate facilities on the ISS or are developing future facilities on new space station)
- 39 Implementation Partners

- **Proliferation** in service providers, driven by demand and lower cost of lunch
- ~50% have emerged in last 3-4 years
- With the growing competition among them, each firm is heavily focused on developing its unique selling propositions and service offerings
- The competition is expected to drive improvements in pricing, services, and access to space

Source: Satellite Applications Catapult, NASA, UKSA

Figure a. Satellite Application Catapult - Roadmap on BSGN Advanced Materials and Manufacturing Accelerator

The research and development conducted under microgravity conditions enabled by these new space-infrastructure platforms are expected to be disruptive, potentially leading to major breakthroughs across new materials and pharmaceuticals. This is particularly significant when we consider that 70% of all technical innovations in technologies around us today, are either directly or indirectly associated with materials innovations developed under the influence of gravity[5]. Thus, removing forces of gravity from the development calculations or even slightly tuning it for engineers, it can unlock new discoveries and allow for significant innovation in materials and chemicals.

According to McKinsey and Company,[6] space-based research and manufacturing could grow significantly over the next decade by capturing a share of existing R&D spending across high-value industries, including advanced materials where R&D expenditure is very high, driven by the intense industry competition to differentiate through innovations and new product development. Therefore, Industrial primes and innovators can use these platforms to develop differentiated products, leveraging microgravity as a novel innovation platform. The involvement of major companies like Adidas[7] and Lamborghini[8] in microgravity R&D to drive new materials innovations underscores the field's growing prominence. Additionally, the growth in microgravity-related patents, from 21 in 2000 to 155 in 2020, further signifies its increasing importance.

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[5] Materials 2030 Manifesto Systemic Approach of Advanced Materials for Prosperity – A 2030 Perspective by Mariya Gabriel, European Commissioner for Innovation, Research, Culture, Education and Youth. *https://www.ami2030.eu/wp-content/uploads/2022/06/advanced-materials-2030-manifesto-Published-on-7-Feb-2022.pdf* - Accessed 26th November 2023

[6] McKinsey & Company: The potential of microgravity: How companies across sectors can venture into space. *https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/the-potential-of-microgravity-how-companies-across-sectors-can-venture-into-space* - Accessed 26th November 2023

[7] ISS National Lab and adidas. (n.d.). Iss National Lab X Adidas – Why We're Sending Boost Into Space. *https://www.adidas.co.uk/blog/400437-iss-national-lab-x-adidas-why-were-sending-boost-into-space* - Accessed 26th November 2023

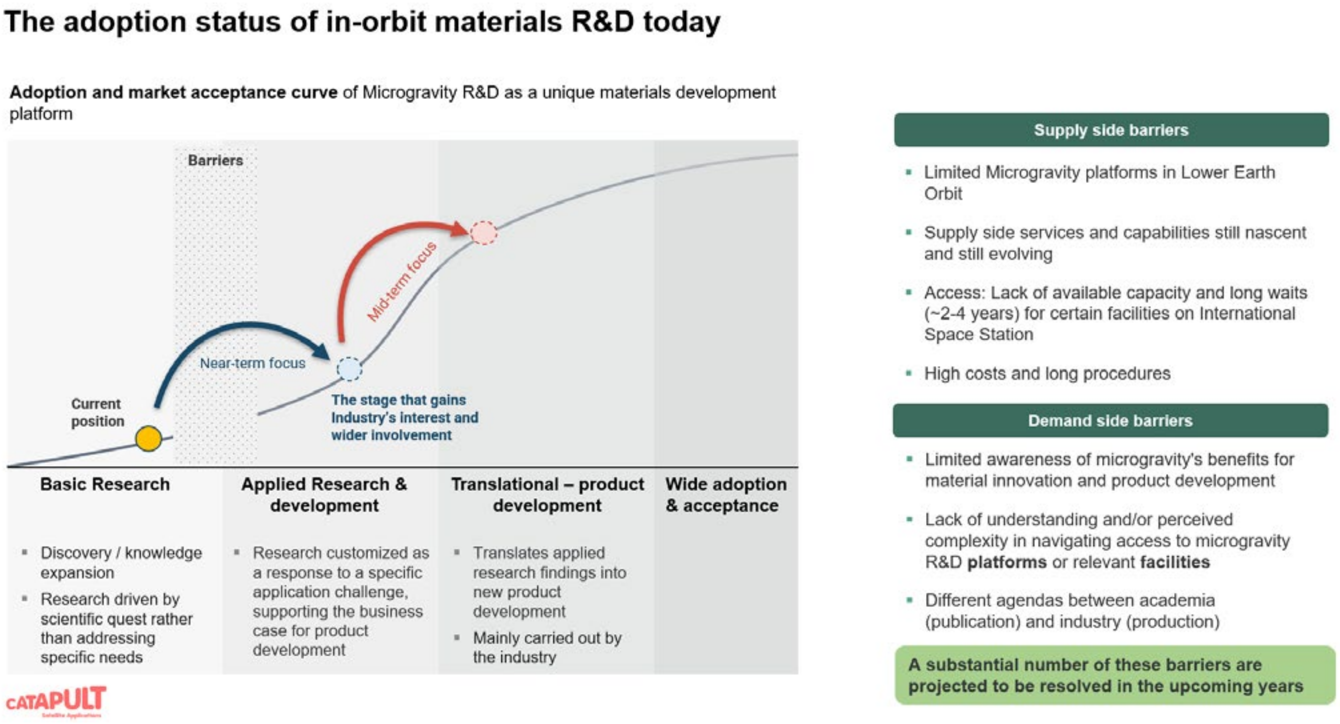
[8] Lamborghini, "Lamborghini's Carbon Fiber in Outer Space," July 20, 2020, *https://www.lamborghini.com/en-en/news/lamborghinis-carbon-fiber-in-outer-space* - Accessed 26th November 2023

The rapid development of new microgravity platforms along with their associated infrastructure and services by new commercial entities is expected to make viable a new age of large-scale, space-based R&D. This expansion, once thought unfeasible, is now becoming a reality due to recent rapid developments and technological advances, including major reduction of payload launch costs that have dropped from $60,000 kg in the 1960s to ~$3,000 today. UK companies like Space Forge, Gravitlab Aerospace Services, Orbex, Skyrora and more will play an important role in both providing access to expanding the supply chain opportunities for microgravity R&D and manufacturing, including for new materials development, such as space-grade semiconductors.

Outlook in the next five years

Over the next five years, it is expected that the development of hardware and processing facilities specifically designed for materials R&D, integrated into microgravity platforms will accelerate. This will enable a broader range of R&D facilities for experiments and open up new opportunities for developments in space for entities in the materials and manufacturing sector. For example, in the UK, Photocentric, a renowned innovator in additive manufacturing not traditionally associated with the space sector, is developing CosmicMaker. This in-space R&D and production module is designed for orbital platforms and new Space Stations. Among the capabilities of this multipurpose facility is the additive manufacturing of niche silicon carbide and other technical ceramic composites, leveraging the benefits of microgravity processing, and aimed at performance-critical applications both in space and on Earth.

Through addressing various identified barriers (such as launch access and cost) on both demand and supply side, this can facilitate a wider acceptance and utilisation of these platforms by researchers and innovators. This will thereby allow them to focus their Materials R&D for addressing specific application challenges, supported by a stronger business case and return on investment.



The adoption status of in-orbit materials R&D today

Adoption and market acceptance curve of Microgravity R&D as a unique materials development platform

Basic Research

- Discovery / knowledge expansion
- Research driven by scientific quest rather than addressing specific needs

Applied Research & development

- Research customized as a response to a specific application challenge, supporting the business case for product development

Translational – product development

- Translates applied research findings into new product development
- Mainly carried out by the industry

Wide adoption & acceptance

Supply side barriers

- Limited Microgravity platforms in Lower Earth Orbit
- Supply side services and capabilities still nascent and still evolving
- Access: Lack of available capacity and long waits (~2-4 years) for certain facilities on International Space Station
- High costs and long procedures

Demand side barriers

- Limited awareness of microgravity's benefits for material innovation and product development
- Lack of understanding and/or perceived complexity in navigating access to microgravity R&D **platforms** or relevant **facilities**
- Different agendas between academia (publication) and industry (production)

A substantial number of these barriers are projected to be resolved in the upcoming years

Figure b. Satellite Applications Catapult status of in-orbit materials R&D today

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[9] Photocentric Group: Welcoming Innovators into the In-orbit Manufacturing Accelerator. Accessed 15th November 2023. *https://photocentricgroup.com/2023/09/welcoming-innovators-into-the-in-orbit-manufacturing-accelerator/*

Current UK status of developments and alignment with national strategies

The emphasis on exploiting space industry advances, including space-based microgravity R&D for driving materials innovations is directly recognised by the UK's National Space Strategy in Action[10]. This framework outlines the implementation of the UK's 2021 National Space Strategy[11]; coupled with the UK Space Exploration Technology Roadmap published in July 2023[12], this underscores the importance of continual institutional investments for commercial exploitation in microgravity environments like the International Space Station or other microgravity facilities.

In terms of academia, UK has a concentrated wealth of microgravity knowledge and research within its universities and research institutions. For example, in this paper alone there are >20 academic authored contributions from across the UK and beyond. Many of the research projects could have high potential business cases, but are in need of more straightforward paths for funding, facility access and streamlined channels to incentivise development thereby increasing spin out of technologies.

The UK has fast growing innovator ecosystem with interest in microgravity-related innovation. For example, a significant portion of the technology development proposals relating to microgravity-based R&D on materials innovations submitted to the European Space Agency's BSGN Advanced Materials and In-Orbit Manufacturing Accelerator were from the UK[13].

Market stimulation activities, both in terms of community building as well as promoting benefits of microgravity R&D in the advanced materials sector, are an important pillar for the development of interest and bringing new capabilities, investment, and resources towards advancement in field of microgravity R&D. For example, these activities have already been stimulated partly through delivery organisations like the UK Space Agency, UK Research and Innovation and the Satellite Applications Catapult, as well as several leading networks, involving a wide range of members from universities, industry, government, and space agencies.

In terms of facilitation of infrastructure and supply chain at the agency level, like the European Space Agency, the UK Space Agency (working with key partners) has been continually planning and maturing strategies for post International Space Station, to continue support UK scientists and engineers to test new technologies and carry out important R&D in microgravity. For example, announcement of recent strategic collaborations and partnerships with new commercial space stations, such as Axiom Space and Orbital Reef, have been made, to ensure not only access of UK scientists and engineers but also contributions from UK companies in the development of this fast-evolving field. Strategic collaborations with space stations, service providers, and international partners can facilitate access for UK companies, fostering a vibrant ecosystem that thrives on innovation and knowledge exchange.

In terms of supply chain of microgravity R&D and manufacturing, several companies are advancing with development of next generation, commercial microgravity platforms, with return capability targeting high-value materials, such as space-grade semiconductor manufacturing in microgravity, an area of significant industrial interest and potential with major project economic benefits. The subject of manufacturing Space-Grade Semiconductors, leveraging microgravity environment is seeing a significant resurgence in attention. In November 2023, a White paper on Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use[14] was co-published by Industry and Academia as part of the the Stanford University Workshop, highlighting the methods, near term possibility as well as benefits of manufacturing semiconductors in space for propelling new industrial advancements and economic growth. For example, in the UK the recent collaboration agreement between Space Forge and Northrop Grumman signals the opportunity for high-performance materials, including semiconductor manufacturing in space, positioning of UK for leadership.

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[10] UK Government Policy Paper: National Space Strategy in Action.
https://www.gov.uk/government/publications/national-space-strategy-in-action/national-space-strategy-in-action - Accessed 15th November 2023

[11] HM Government. (2021). National Space Strategy [PDF]. https://assets.publishing.service.gov.uk/media/6196205ce90e07043d677cca/national-space-strategy.pdf - Accessed 15th November 2023

[12] UK Space Agency. (2021). Space Exploration Technology Roadmap v2 [PDF].
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1183741/Space_Exploration_Technology_Roadmap_v2.pdf: - Accessed 15th November 2023

[13] European Space Agency: Business is Space Growth Network - Advanced Materials & Manufacturing. https://bsgn.esa.int/industries/materials-manufacturing/ - Accessed 15th November 2023

Public funding remains a critical pillar for R&D in high-risk fields like Microgravity R&D. In the UK, for example, several funding areas have emerged, both nationally and internationally through the European Space Agency, including NSIP, CASE and the Business in Space Growth Network. The UK's National Space Innovation Programme, with its £65 million investment, epitomizes this commitment, alongside support for various ESA programmes.

The UK Space Agency, the executive body for space-related activities in the UK, represents UK interests in various international committees and runs dedicated funding calls for space exploration technology and adoption. Under the Department for Science, Innovation and Technology it works with key government and sector stakeholders to develop and empower the UK's space sector.

UK Research and Innovation's mission is to convene, catalyse and invest in close collaboration with others to build a thriving, inclusive research and innovation system that connects discovery to prosperity and public good. As such it does and will play a crucial role in space and unlocking the benefits of space for the broader R&D community. Within UKRI organisations including (but not limited to) the Science and Technology Facilities Council (STFC), Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK have a particular critical role to play in driving this interface. This includes through space related Infrastructure such as the STFC National Laboratories (e.g. RAL Space and the UK Astronomy Technology Centre), as well as materials-related infrastructure, including the Henry Royce Institute, which plays a critical role in the UK advanced materials landscape. Through working with partners, including the UK Space Agency and Catapult Network[15], UKRI can better support the translation of technology, formation of academic-business partnerships and leveraging of private investment to realise the full benefits of space for Materials R&D.

At an international level, the UK Space Agency collaborates closely with the European Space Agency (ESA) through programmes such as the General Support Technology Programme (GSTP), which helps develop technologies for future missions. The UK's commitment to ESA, including a £71 million investment in the GSTP at ESA's Council of Ministers (CMIN) 2022, provides British organisations access to various ESA centres across Europe, enhancing the UK's capabilities in space exploration and technology developments.

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[14] Frick, J. Kulu, E. Rodrigue, G. Hill, C & Senesky. D (2023) Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use. Accessed 15th November 2023 *https://osf.io/preprints/osf/d6ar4*

[15] Catapult Network *https://catapult.org.uk*

Access to the Space environment and Low Earth Orbit: What are the Opportunities?

For many years, scientists have been utilising platforms both in orbit and on Earth to conduct fundamental research. The ESA Erasmus archives[16], contain a database of more than 4100 funded and/or co-founded R&D experiments related to the space sector, from advanced metallurgical processes in microgravity to how biofilms form.

As of September 2023, there are already a number of existing incumbents involved in active flight operations, including Arianne Space, Blue Origin, Boeing, Northrop Grumman, Rocket Lab, SpaceX and Virgin (Galactic) to name a few. There are also a number of active access providers supporting customers to fly R&D payloads in space including organisations like Airbus (Bartolomeo), Axiom Space, Ice Cubes, Space Forge (Forge Star), Kayser Space, Open Cosmos and Sierra Space, again to name a few. These capabilities are augmented through access to analogue platforms on Earth, including Drop Towers (e.g. Zarm Drop Tower), Parabolic flights (e.g. Novespace), Sounding rockets (e.g. Swedish Space Consortium) and centrifuges (e.g. ESA ESTEX Long Arm Centrifuge) allowing researchers to understand the effects of variable gravity on material processes on Earth (examples of research on these platforms is discussed later in this section).

Importantly and in the context of this paper, this capability for space/microgravity access is growing in both scale and diversity. This is coming from both existing and new players developing capabilities to provide and/or support greater access to the space environment for customers including Gravitlabs, Orbex, Skyrora, the Exploration Company, the aforementioned Space Forge and Sierra Space and many more globally. It is important to stress at this point, that whilst this paper has being open to and included several contributions from across the globe, it is more focussed on the UK R&D system. It is therefore recommended if you are not based in the UK to contact your local space agency (or organisation in charge of national R&D strategy) to enhance awareness of local capabilities and intelligence.

At a UK level, there are a number of mechanisms that have been developed to support both understanding and access to opportunities to conduct R&D research with the space environment (some more focused on commercial and others academic). At the early career stage for example, the European Space Agency runs dedicated education initiatives which provide student led research groups with the ability to design and run Space related experiments. These include the Spin, Drop, Fly and Orbit your thesis programmes, where many UK teams have applied and run experiments on (N.B. UK based teams can apply to receive additional support from the UK Space Agency[17]). ESA also runs a number of open call processes for the wider R&D community, including Announcement of Opportunities[18], to support R&D access to space-related platforms.

It can however be challenging to support the connection between existing space sector actors and non-space actors (both academic and commercial). This is a recognised priority in both national and international space strategy's to improve connectivity and collaboration to open up new R&D opportunities, business models for the space economy and drive productivity[19]. As such there are a number of existing and newly established initiatives to support these connections.

For example, the UK for over 12 years has hosted (through the Science & Technology Facilities Council, part of UK Research and Innovation) dedicated funded structures from ESA to facilitate space-related business incubation; ESA BIC UK[20] (N. B. this programme exists in several of the ESA member states). This programme has supported ~100 businesses in the UK, to develop technology, commercialise products and attract private funding. These UK Government funded infrastructures including the Catapult network (in particular the Satellite Application Catapult) and the Innovate UK Knowledge Transfer Network are actively supporting the commercial development opportunity for space, working across

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[16] ESA Erasmus Archive https://eea.spaceflight.esa.int/portal/

[17] UK Space Agency Funding Programs (Including student support for ESA Programs https://www.gov.uk/guidance/apply-for-funding-academic-community-and-educational

[18] ESA Announcements of Opportunity https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/Research_Announcements

[19] UK National Space Strategy https://www.gov.uk/government/publications/national-space-strategy

multiple sectorial areas from in-orbit manufacturing and energy to health and life science. For example, the Satellite Applications Catapult has launched the Space Enterprise Community to help organisations better connect both within and to the space sector[21]. Recognising the opportunity to better connect local expertise to national sector developments, in 2020 the UK Space Agency supported the further development of space clusters across the entire UK. To date there are 17 space clusters in the UK, from established clusters such as Harwell and Space Scotland, to emerging clusters such as North West England and Space East (N.B. more details on UK Space Clusters can be found here[22]).

With the European Space Agency deploying new mechanisms to further stimulate the growth of a sustainable low earth orbit and future lunar economy (through mechanisms such as the Phi-Labs Programme and Business in Space Growth Networks)[23] coupled with the UK's drive to grow a diverse and ambitious space economy, there is an opportunity to further augment cross-sector connection and collaboration to create a sustainable pipeline for the space ecosystem.

In the following section we go into more detail into space-based capabilities and examples of materials R&D research.

Laboratories and facilities available on the ISS:

The list of acronyms and abbreviations below provides disjoint glimpses of the rich variety of multiuser laboratories and facilities accommodated in the different ISS science modules for studies in the field of materials and fluids (e.g., the American Fluids and Combustion Facility, FCF; the European Fluid Science Laboratory, FSL; the Japanese Fluid Physics Experimental facility, FPEF, MSG, the Microgravity Science Glovebox), inorganic material science (e.g., the Materials Sciences Laboratory, MSL with the Low Gradient Furnace LGF, the Solidification and Quenching Furnace SQF and the Float Zone Furnace FMF; the High Gradient Directional Solidification Furnace Experiment Module, HGDS; the Directional Solidification and Vapor Transport Experiment Module, DSVT; the Advanced Tubular Furnace With Integrated Thermal Analysis Under Space Conditions, TITUS; the Quench Module Insert, QMI; the Diffusion Module Insert, DMI; the Advanced Thermal Environment Furnace ATEN; the Advanced Furnace for Microgravity Experiment with X-ray radiography, AFEX; the Gradient Heating Furnace, GHF, etc.) organic material science (the Protein Crystallization Diagnostics Facility, PCDF; the Solution Protein Crystal Growth Facility, SPCF; etc.) and biotechnology (the BIOLAB; etc.).

Previous UK materials-science space experiments and related facilities

The "Thermovibrationally-driven Particle self-Assembly and Ordering in Low grAvity" project (related UK Space Agency Acronym: "T-PAOLA", NASA/ESA Opsnom: "PARTICLE VIBRATION", PI M. Lappa, University of Strathclyde) was originally conceived to explore a new contactless manipulation strategy for the control of solid particles dispersed in a fluid in microgravity conditions, based on the application of "vibrations" and "differential heating". It was selected by UKSA/STFC in the framework of the 2018 AO for UK Microgravity Experiments, and is presented here as a relevant exemplar as it has opened vast perspectives for the production of new materials in space with properties that cannot be obtained in normal gravity conditions, relevant examples being metal or plastic alloys where the position of the minority phase (the dispersed particles) can be controlled precisely and even forced to form well-defined internal structures or "frameworks".

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[20] ESA Business Incubation Centres UK https://esa-bic.org.uk

[21] Space Enterprise Community https://spaceenterprise.uk

[22] Space Clusters in the UK https://www.investorlaunchpad.uk/cluster-directory/

[23] ESA Business in Space Growth Network https://bsgn.esa.int

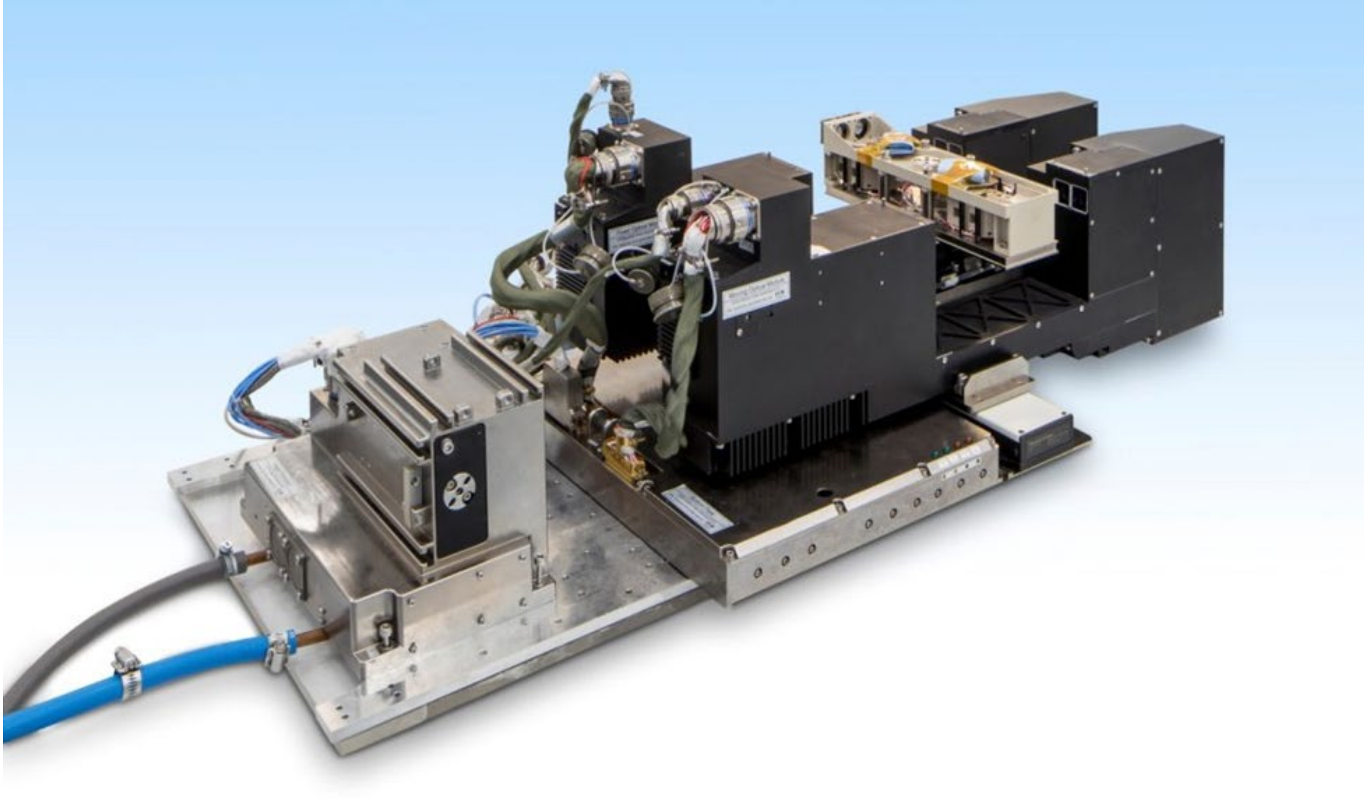

Figure c. The Selectable Optical Diagnostic Instrument (SODI) [Credit: QinetiQ & ESA]

The Selectable Optical Diagnostic Instrument (SODI)

These experiments have been executed in space during 2023 using the Selectable Optical Diagnostic Instrument (SODI). SODI is an instrument for scientific research in the fields of fluid-dynamics, materials science and biology, originally developed by an industrial consortium (led by QinetiQ) in the frame of a dedicated contract with the European Space Agency. Essentially, it is a payload equipped with various optical diagnostics. Moreover, it is based on a modular concept, i.e. it consists of different subsystems, which the astronauts can install in the work volume of the Microgravity Science Glovebox (MSG), a general-purpose NASA Facility.

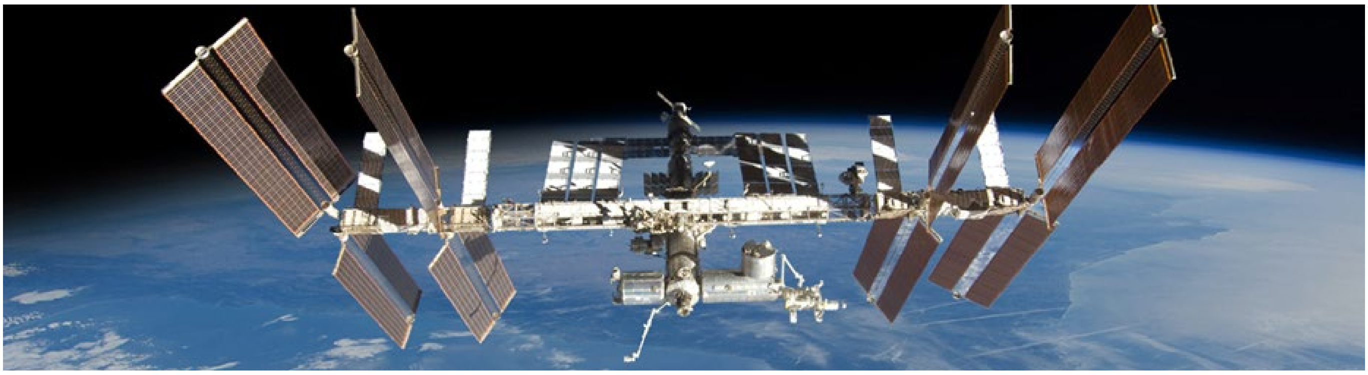

Figure d. International Space Station (Credit: NASA)

Figure e. Frank Rubio installing the PARTICLE VIBRATION hardware in the MSG Work Volume on board the International Space Station (3 Feb 2023) [Credit: ESA & NASA].

The MSG can feed smaller payloads with the required power; it also allows them to exchange data with ground and provides the required level of containment (when potentially hazardous liquids or materials are used for the experiments). The combined exploitation of SODI and MSG for the PARTICLE VIBRATION project has been made possible by a specific PIA (Payload Integration Agreement) existing between NASA and ESA, later extended to the UK Space Agency (UKSA) on purpose to allow this project.

Additional specific hardware has been manufactured directly in the United Kingdom by QinetiQ. It consists of "cell arrays" hosting the containers with the fluid and particles required for the experiments and the Peltier elements needed to establish the required temperature gradients.

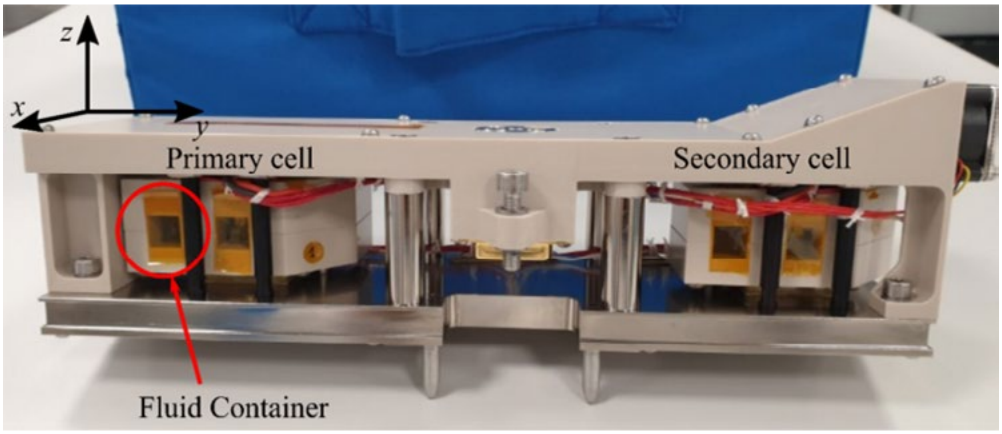

Figure f. PARTICLE VIBRATION cell array, composed of a primary and a secondary cell. Each cell array hosts two fluid containers. Four distinct windows can be seen because each fluid container has two windows (Credit: QinetiQ, UKSA and ESA)

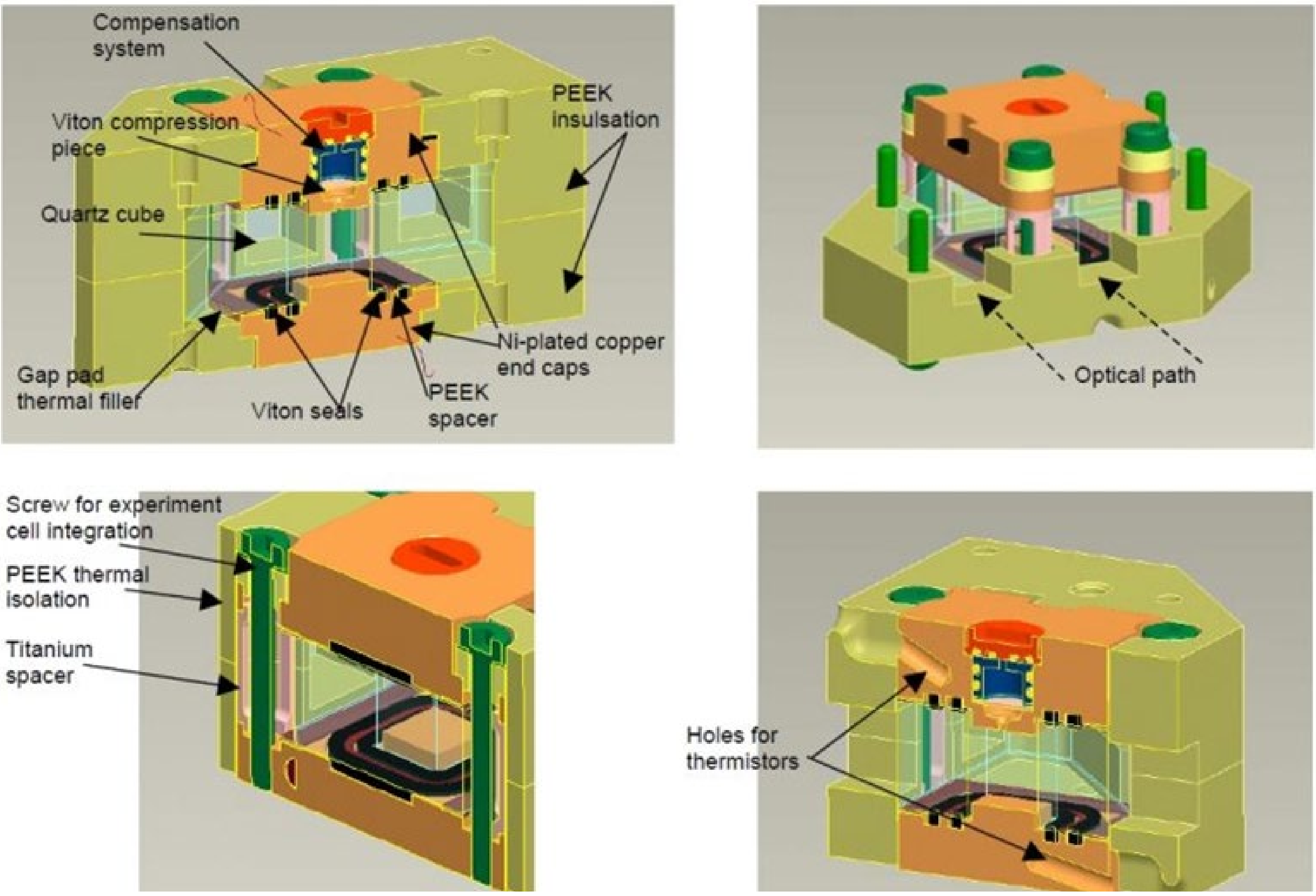

Figure g. PARTICLE VIBRATION Fluid containers (Credit: QinetiQ)

Figure h. SpaceX Falcon 9 launch, Dragon cargo spacecraft approaching the ISS (Credit: SpaceX & NASA)

NASA and SpaceX successfully launched the SpaceX Falcon 70-meter long rocket containing the hardware for the execution of the PARTICLE VIBRATION experiments from Kennedy Space Center Launch Pad 39A on Nov. 26, 2022 (7:20 PM UK Time). The CRS26 SpaceX Dragon cargo spacecraft autonomously docked to the space-facing port of the station's Harmony module at 7:39 a.m. EST, Nov. 27, 2022 (12:20 UK Time). The astronaut Frank Rubio completed without issues the installation of the Particle Vibration hardware in MSG on 3rd Feb 2023. After the hardware installation and the ensuing functional and optical checkouts, more than 160 different experiments were successfully executed over a period of three months (February-April 2023). Throughout the duration of the project, the "data", i.e. the telemetry (temperature) files and 'representative' images generated by the interferometers of the SODI hardware (showing the evolution of the vibrated particles at selected times) were transferred from the ISS to the PI (Prof. M. Lappa, located at the University of Strathclyde) through a complex infrastructure, involving the NASA's Marshall Space Flight Center, located in Huntsville, Alabama, USA (also known as the Huntsville Operations Support Center (HOSC)) and the E-USOC, located in Madrid Spain (one of the ESA User Support and Operations Centres).

Possible applications of this research are special metal alloys characterized by an internal skeleton or backbone able to address stresses or forces acting in specific directions or non-metallic materials able to conduct electricity (e.g. a framework of metal particles in a non-conducting material such as plastic or glass). Other relevant applications concern the pharmaceutical field, where protein crystals are typically obtained as seeds in an external liquid solution.

With regard to this experiment, Science Minister George Freeman said:

> "This experiment paves the way for exciting scientific discoveries that could transform methods of manufacturing, demonstrating just how valuable a resource space can be for growth and industry in the UK and around the world. The organisations behind the experiment, QinetiQ and University of Strathclyde, provide two examples of the diversity of expertise across the UK space sector, which is already worth £16.5 billion to our economy. I look forward to seeing the next steps for this innovative work."

Ground-based facilities

Conducting research in space requires considerable ground based compatibility testing first in order to a) decide the right testing protocol and b) elaborate relevant safety and payload regulations; moreover, c) ground testing can be used as a precursor to a campaign. Below are some examples of ground based facilities. In the UK you can also use the following links to explore space related capabilities including:-

- Satellite Applications Catapult UK Space Capabilities Catalogue *https://sa.catapult.org.uk/space-capabilities-catalogue/*
- UK Space Facilities *https://www.ukspacefacilities.stfc.ac.uk/Pages/home.aspx*
- ESA Ground facilities *https://www.ukspacefacilities.stfc.ac.uk/Pages/home.aspx*
- Finally for students, the opportunities with the ESA Academy to utilise microgravity platforms *https://www.esa.int/Education/ESA_Academy*

Drop towers

The so-called drop towers are long shafts used for dropping experiments. Their fundamental component is a special tube, or pit where vacuum is realised and where a capsule containing the "experiment" and related diagnostic tools is dropped. While the experiments drop, free-fall, or microgravity conditions are attained. Typically, scientists rely on video cameras to observe the experiments as they fall[24].

A relevant example accessible by UK researchers is represented by the Bremen drop tower, one of the tallest and best-

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[24] M.Lappa, (2004),"Fluids, Materials and Microgravity: Numerical Techniques and Insights into the Physics", 538 pages, Elsevier Science (2004, Oxford, England).

known drop tower facilities in Europe. At the heart of the facility is the 146 m high tower surrounded by support facilities that include control rooms, laboratories and hardware workshops. The tower itself relies on a steel tube from which air can be evacuated. It also includes all the technical sub-systems needed to accelerate, guide and decelerate the capsule containing the experiments.

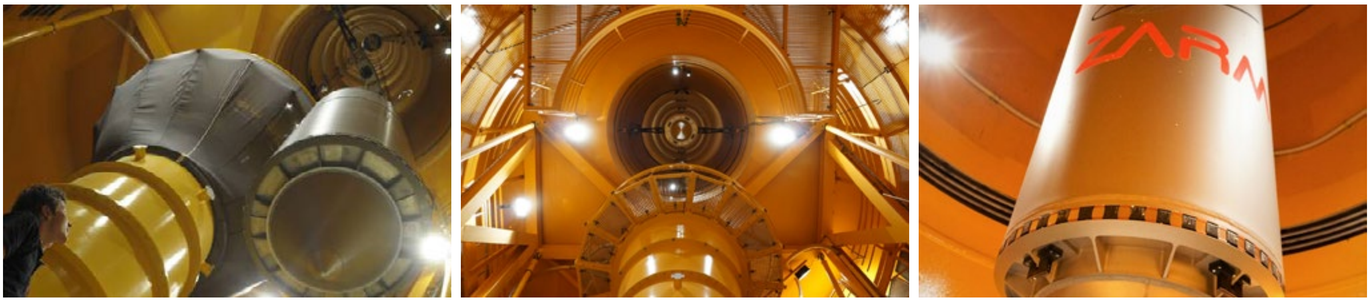

Figure ix. Bremen drop tower capsule (Credit: ZARM Drop Tower)

Figure x ESA astronaut Alexander Gerst during parabolic flight (Credit: European Space Agency)

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[25] M.Lappa, (2004),"Fluids, Materials and Microgravity: Numerical Techniques and Insights into the Physics", 538 pages, Elsevier Science (2004, Oxford, England).

Parabolic flights

Another resource available to UK scientists, researchers and professionals is represented by the parabolic flights organised by ESA. These opportunities can be used for short-duration scientific and technological investigations and should be regarded as the only way to test microgravity with humans without going through lengthy astronaut-training and flights to the International Space Station.

A typical ESA parabolic flight campaign offers 30 periods of weightlessness per flight with three flights conducted over the course of a week. The aircraft is put into a suborbital trajectory that provides free-fall, or weightlessness. Each cycle begins by having the aircraft perform an acrobatic maneuver that starts from level flight and pitches upwards gradually to approximately 50 degrees subjecting the passengers to a 1.8-g pull up lasting about twenty seconds. After that, the pilots cut back on thrust just enough to counter atmospheric drag and the airplane is launched into a ballistic trajectory. During these 22 seconds, in theory, the aircraft is in orbit and as such also in freefall[25]. From a practical point of view, however, because of the atmospheric resistance, only centi-milli- gravity levels (10^{-2}g - 10^{-3}g) can be effectively attained. At the bottom of the parabola, the aircraft slowly pulls out of its dive and levels off for the next arc, restoring weight to the cabin. Given the number of arcs that can be flown on a typical flight, scientists can conduct several experiments or can repeat short runs of a single experiment many times.

Figure xi. Refitted Airbus A310 aircraft for parabolic flights (Credit: Novespace & European Space Agency

In the following section, the method for developing this paper will be outlined coupled with the thematic chapters, which discuss the context of the opportunity of space for materials science and innovation, as articulated from the community engagement with the paper.

Method: Developing the paper Why Space? The Opportunity for Material Science and Innovation

> There is significant opportunity for space related materials sciences innovation in the UK. This is illustrated by both the breadth and depth of existing expertise across a range of disciplinary areas captured in each of the following thematic chapters. Each of the chapters was informed by a rigorous scoping and data capture exercise.

Method

Following the publication of the Why Space paper for Health and Life sciences in 2021, two space community workshops were held at the end of 2021 to understand if this model could be translated to understand the opportunity for materials Science and Innovation. These workshops were attended by government, industry and academic stakeholders, offering an insight into current R&D in the UK and outputs translatable to terrestrial needs.

Following the workshops one-on-one interviews were conducted to gather wider thoughts and inputs and a working group of volunteers brought together to develop the community network.

Subsequent to these activities and based on the feedback we received from the community, a position paper was proposed in 2022 and a call page created and distributed in late 2022. At that point, the community was invited to contribute structured abstracts detailing expertise and capability, applied case experiences of prior or planned work related to space, and recommendations for enabling this work. After an initial peer-review activity by the paper authors and steering board, a second call for abstracts was launched with community webinars in early 2023.

In total, we received over 35 contributions covering a range of topics. This included contributions from academia [N=23], industry [N=10] and wider public sector [N = 3]

After a further review and author revisions, a synthesis activity was conducted and abstracts assigned to the following thematic areas:

- Considerations for Material Properties & Processes in Space & their Impact
- Considerations for using Materials in Space and their Impact
- Considerations for Material Development and Manufacturing in Space (including launch/service providers)

Each thematic chapter collated the inputs and themes from the contributions received. While many contributions can cross multiple themes, for clarity they have been mentioned in the most aligned thematic chapter and readers are encouraged to read the full list of contributors on page 4. We would like to thank and acknowledge each of the contributors for their expert insights.

Considerations for Material Properties and Processes in Space and their Impact

Edited by Professor Marcello Lappa – University of Strathclyde, UK & Dr. Andrew Kao – University of Greenwich, UK

This chapter is a synthesis of authored contributions [# = Contribution number in paper]:

#1 *[Pg. 46]* Anatoliy Vorobev - University of Southampton, UK |Microgravity hydrodynamics of nonequilibrium interfaces

#2 *[Pg. 48]* Andrew Kao, Koulis Pericleous, Valdis Bojarevics - University of Greenwich, UK | Understanding thermophysical properties and solidification in Microgravity

#3 *[Pg. 50]* Augustin Guibaud - University College London, UK|- Influence of reduced gravity on spreading flames

#4 *[Pg. 52]* Patricia Santos Beato, Deepak M. Kalaskar – University College London, UK & Sasha Thomas, Ajay Kumar – Velon Space Pvt Ltd, India | Biomaterials Research in Space

#5*[Pg. 55]* Jamie Williams, National Physical Laboratory, UK | Metrology for in-space manufacturing

#9 *[Pg. 66]* Paul A Smith, Andrew Viquerat, Jasmine Bone, Mark J Whiting - University of Surrey, UK | AgeIng and Lifetime assessment of Composites for Space applications

#10 *[Pg. 68]* Paolo Capobianchi - University of Strathclyde, UK | Magnetic Fluid suspensions in microgravity environments

#12 *[Pg. 72]* Shaun McFadden - Ulster University, UK | Solidiifcation Science Under Microgravity Conditions

#13 *[Pg. 74]* William Blackler - Kayser Space Ltd, UK & Illtud Dunsford - Cellular Agriculture Ltd, UK & Craig Leadley, Campden BRI, UK | Cellular Agriculture for food production in space

#15 *[Pg. 80]* Brian Zielinski-Smith - Gravitilab Aerospace Services, UK | High entropic inorganic materials in microgravity

#16 *[Pg. 82]* Carlo Saverio Iorio - Yoursciencetech Ltd, UK and University of Brussels, Belgium & Yarjan Abdul Samad - University of Cambridge, UK and Khalifa University, UAE & Andrea Carlo Ferrari, University of Cambridge, Cambridge Graphene Centre, UK | In-situ production of Thermal management structures

#17 *[Pg. 85]* Charles Muir, Laura Gonzalez Llamazares - Satellite Applications Catapult, UK | Additively manufactured Inconel 718 for high heat flux applications

#23 *[Pg. 100]* Fraser Burton - BT, UK | Space-grown thermal substrates for efficient wireless communications

#27 *[Pg. 109]* Neil Buchanan - Lodestar Space, UK | Advancing Directed Energy Deposition Techniques for Extreme Environments

#30 *[Pg. 116]* Qianqian Li, George Rigas, Paul Bruce - Imperial College London, UK | Advanced materials development for hypersonic vehicles

#31 *[Pg. 119]* Saptarsi Ghosha, Rachel A. Oliver - University of Cambridge, UK | Wide bandgap transistors for electronics in space

#36 *[Pg. 131]* Marcello Lappa – University of Strathclyde | New methods for the transport and management of lunar regolith

Considerations for Material Properties and Processes in Space and their Impact

Professor Marcello Lappa,
University of Strathclyde, UK

Dr Andrew Kao,
University of Greenwich, UK

Overview

Gravity dominates everything on Earth, from the way life has developed to the way many types of materials are formed. Onboard spacecrafts orbiting the Earth or other vehicles in free-fall conditions; however, the influence gravity is barely felt. In this "microgravity environment", scientists can investigate phenomena, which are impossible on Earth or are masked by the presence of gravity. In this condition various effects are significantly altered, in particular convection, buoyancy, hydrostatic pressure and sedimentation.[26] [27] In this virtual absence of gravity as we know it, therefore, space flight gives scientists a unique opportunity to study various states of matter (solids, liquids and gases), and discern forces and processes that are interwoven or overshadowed in normal gravity. Accordingly, microgravity can be regarded as an important tool for improving our fundamental understanding of several complex phenomena, which are of great interest in several technological fields.

Notably, research conducted in space is also supporting current efforts to identify new principles and strategies for the "active control" of many phenomena or processes. As an example, in such a context, of special interest are the dynamics of the so-called complex fluids, i.e. media characterized by the coexistence of two phases, namely, two immiscible liquids, a liquid and a gas or a liquid and a solid (in the form of dispersed fine particles). These multiphase systems and the related "interfaces" are omnipresent in several fields of engineering (especially materials, chemical, nuclear, pharmaceutical, and food engineering, just to cite a few). UK researchers (e.g., from the University College London and the Universities of Southampton and Strathclyde) are currently involved in relevant international collaborations with ESA, CNES, NASA and even JAXA for the design of new experiments in parabolic flight, in the ISS, and in unmanned orbital vessels to collect new relevant experimental data. Critical knowledge gained from these microgravity experiments is contributing to validate new, more complex models, accelerating the current trend towards predictable and reproducible phenomena, and enabling the development of new "manipulation" strategies or criteria.

Similar concepts also apply to many materials that we use in their final solid state. Before being solid, many of these materials pass through a liquid state and the properties that they display in the final state often depend on the convective phenomena that are established in their liquid state. Whether it is the case of a mould filled with liquid metal to produce a cast component, a permanent joint created by fusion welding between metal plates, a complex component printed from metal powder by laser-based additive manufacturing (3D printing), or a high-quality crystal of a semiconductor or superconductor material being crystallised from a melt, all of these processes depend on a successful solidification step to generate the solid structure from liquid. In the liquid phase, mass and heat transport occur by thermo-solutal convection and/or gravitational separation of the involved phases.

Clarifying the cause-and-effect relationships at the root of these phenomena is key to a full understanding of microstructure development during solidification. During microgravity, the thermo-solutal, buoyancy-driven convection and/or sedimentation phenomena induced by the different density of the involved phases are suppressed and comparison with ground data, enables increased understanding of all these effects. Over the past few decades, UK researchers from the University of Greenwich have actively taken part in relevant ESA activities (e.g., the Peritectic Alloy Rapid Solidification with Electromagnetic Convection – PARSEC - project) and topical teams (e.g. the Solidification of Containerless Undercooled Melts (SOL-EML)). Moreover, researchers from the University of Ulster have already benefitted from microgravity experimentation onboard soundings rockets (MAXUS and TEXUS) and the International Space Station (ISS). The opportunity for the UK materials science sector to utilise the unique microgravity environment to undertake R&D, however, continues to grow, with current and future launch providers (e.g., Virgin Orbit, Lockheed Martin, SpaceForge) and integrated service operators (e.g., Kayser Space, Lodestar Space, Gravitilab) increasing the capacity and availability for payloads.

Along these lines, in addition to the remarkable benefits described above in terms of fundamental knowledge and "know-how", microgravity-based research being conducted in UK is also serving another important objective, that is, enabling the important technological developments required to allow deep space exploration missions and the colonisation of other planets. Many materials used for various applications need to be tested directly in space (e.g., to verify their ability to withstand the adverse effect of radiations or of space debris or other environmental effects), and there are relevant UK national, industrial and academic entities (such as, the National Physical Laboratory – NPL, the Satellite Application

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[26] M. Lappa (2009), Thermal Convection: Patterns, Evolution and Stability", 700 pages - John Wiley & Sons, Ltd (2009, Chichester, England).

[27] M. Lappa (2012), Rotating Thermal Flows in Natural and Industrial Processes, 540 pages, John Wiley & Sons, Ltd (2012, Chichester, England).

There are plans to use regolith as a kind of building material for the construction of lunar bases, feedstock for 3D printing or for oxygen extraction. As food and water shall also be produced in situ, engineers are also investigating the possibility to use regolith as a solid-support substrate for plant growth, a source for extraction of essential plant-growth nutrients, a substrate for microbial populations in the degradation of wastes, a source of O2 and H2, which may be used to manufacture water. With increasing commitments from both global governments as well as private companies in the coming decades to colonise space and nearby bodies, there is still critical fundamental R&D to be done and several UK academic entities have already started to deal with such specific aspects (e.g., the University of Cambridge, the University of Surrey and the University of Strathclyde).

Case Experiences

The UK has leading expertise and capabilities covering several of the subjects described above, ranging from the characterization and control of multiphase fluid systems to the production of several inorganic and organic materials, including a number of active related space research projects:

Fundamental studies on multiphase systems and material solidification:

- Researchers at the University of Southampton are carrying out fundamental studies on the stability of the interfaces between miscible fluids in microgravity conditions to achieve long-term control of multiphase systems and management of interfacial heat and mass transfer, needed for the development of new chemical engineering and materials processing technologies in space.
- Researchers at the University of Strathclyde are looking at the potential use in space of ferrofluids, i.e., a class of smart materials composed of magnetic particles dispersed in a conventional carrier liquid, which can be forced to target desired locations using magnetism and may therefore lead to innovative lab-on-a-chip devices, microrobots technologies, and even new methods to delivery drugs inside the human body.
- Researchers in the Department of Civil, Environmental and Geomatic Engineering at University College London are currently involved in two international collaborations (CNES-JAXA and ESA-NASA) for the design of experiments in parabolic flight, in the ISS, and in unmanned orbital vessels to collect new experimental data on fire ignition mechanisms, flame spread, and particulate/smoke emission over a range of materials. These will be used to develop new theoretical models and improve existing space fire safety systems.

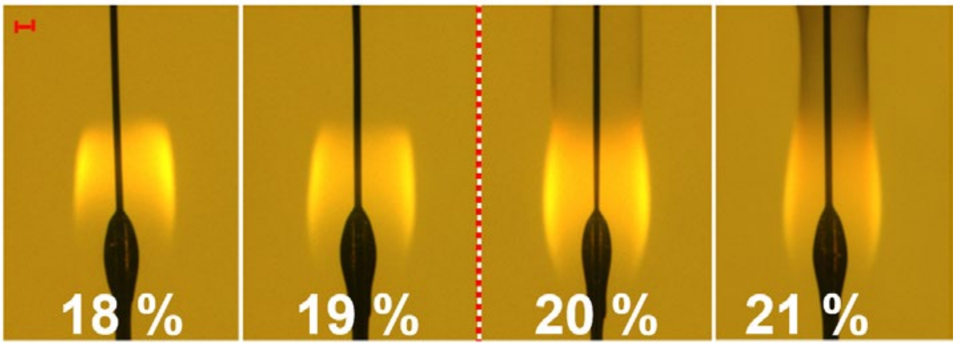

Figure xii. Flames spreading over electrical wires in microgravity at standard pressure for a range of oxygen contents. As oxygen content is increased, the flame starts to emit thick smoke.

- Researchers at the Department of Bioengineering of the University College London are interested in exploring the opportunities offered by research conducted in microgravity to optimise 3D bioprinting and develop tissue models that would otherwise be impossible to manufacture on Earth.
- Researchers at the University of Ulster have benefitted from microgravity experimentation onboard soundings rockets (MAXUS and TEXUS) and the International Space Station (ISS), which they conducted to investigate metal alloy microstructure development. Through comparison with terrestrial results, this endeavour has led to the elaboration of a new theoretical model to account for the impact of thermo-solutal convection.
- Yet, with regard to the solidification of metal alloys and the need to understand how convective current being present in the fluid phase can influence their final properties, researchers at the University of Greenwich have derived a novel approach to measure precisely the thermophysical properties of these alloys in the fluid phase through the use of contactless levitating devices that can imitate microgravity conditions.
- The UK-based company “Gravitilab Aerospace Services” has been leveraging, in collaboration with the University of Manchester, its suborbital rockets (such as the ISAAC) and remotely controlled miniaturised microgravity platforms to investigate the conditions leading to “high entropic inorganic materials” in space. These are a new class of substances with increased disorder at a microscopic (atomic) level and are currently being considered as candidates for a range of different applications in physics (superconductors, optoelectronic materials), materials science (battery materials, thermoelectric materials, nanomaterials), and chemistry (catalysis, electrocatalysis).
- Engineers at Lodestar Space aim to develop Directed Energy Deposition (DED) techniques for additive manufacturing, welding, and repair within the space environment. These methods, which rely on a plasma arc, a laser, or an electron beam, can deposit material on a substrate within the microgravity environment in a safer way with respect to other powder-based techniques. Engineers have already conducted research into DED within space, specifically for constructing improved efficacy micrometeorite and orbital debris shielding.
- At British Telecommunications, engineers aim to develop technologies which can increase the efficiency of electronic components through the integration of high-quality, space-grown heatsink substrates with embedded microfluidic cooling. This technology will lead to unprecedented high power efficient GaN (gallium nitride) RF devices for high frequency 5G “terrestrial” communications.
- Researchers in the Department of Materials Science and Metallurgy of the University of Cambridge are considering silicon carbide (SiC) and gallium nitride (GaN) as Wide-bandgap semiconductors for use in specific space-based applications, e.g., for the development of transistors to be used inside interstellar probes or low-earth orbit satellites. They are therefore interested in exploring the electrical activity of these materials and their properties (such as the radiation immunity) in the space environment.

Supporting Space Exploration:

To support space exploration there are a number of other translational capabilities from research active groups that could address future exploration needs, but also drive further fundamental R&D terrestrially:

- Researchers at the National Physical Laboratory (NPL) have considerable experience in high precision measurement systems and methods for manufacturing. They can deliver detailed, independent analysis to accelerate development, increase performance and quality, and identify failure modes of many types of materials, products or structures. This may in time enable analogous capabilities to support in-space manufacturing technologies, especially those relying on the in-situ utilisation of locally available materials such as the Lunar and Martian regoliths.
- The company Yoursciencetech Ltd (Surrey), together with researchers from the University of Cambridge and in collaboration with ESA, have recently elaborated an innovative approach for the production of regolith-based aerogels that could be built directly in-situ with a minimal or reduced provision of Earth materials.
- The University of Strathclyde is collaborating with ESA in the framework of an OSIP project to explore the potential application of high-frequency vibrations as a new method to force lunar regolith, which is typically characterized by strong internal inter-particle friction, to behave as a ‘fluid’, thereby making its transportation and utilization in the context of several applications much easier.

- In partnership with ESA three UK industry specialists (Kayser Space ltd, Cellular Agriculture Ltd, and Campden BRI, with relevant skills in Cellular Agriculture, Space and Food and Drink, respectively), have assessed the viability of cellular agriculture and through modelling, sized a system utilizing a hollow fibre bioreactor capable of providing the nutritional protein requirements of a crew on long duration space missions.
- The University of Surrey has extensive experience in selecting and modifying materials and coatings for flight hardware destined for particularly challenging environments, such as polymer membranes, thin composites, and inflatables for use in drag-deorbiting from low Earth orbit. More recently this work has broadened to include parallel research on the manufacture and performance of metal matrix composites.
- Similarly, Researchers at Imperial College London are currently developing advanced new materials and surface treatments for hypersonic applications. This is being achieved through a multidisciplinary approach that relies on the ability to predict the severe conditions established during transitional and turbulent hypersonic flows and test experimentally the ability of metal alloys, ceramics of various types and their composites to withstand such conditions.
- Yet, with regard to the development of materials that can cope with extreme conditions in the context of space exploration, the Satellite Applications Catapult has recently exploited its in-house facilities to fabricate a variety of research and development thrust chambers utilizing Inconel 718, a nickel superalloy, which retains exceptional strength and corrosion resistance at high temperatures. This research, which has been funded through the Innovate UK Edge Program, relies on recent advancements in additive manufacturing methods.

Overcoming Challenges

Within the contributions there were a number of challenges critically discussed, which could be used for the definition of new opportunities, the implementation of adequate “countermeasures” and new strategies for producing “impact”.

Growing access: A number of groups highlighted that currently there are barriers to the development of this research in UK especially because of the lack of access to the required environmental conditions. This is in part due to the current excessive focus on orbital missions (especially experimentation on board the ISS), which have long lead times and huge costs and legislations associated with them. Improving access to research in microgravity through suborbital missions might be regarded as a viable option for many research institutions, however access is limited due to lack of services within the UK.

Creating relevant networks: So far, the USA, Japan and other European countries such as Germany, Belgium and France have dominated microgravity research targeting space-based electronics and various other materials or processes. However, UK academia has a strong history in these fields, especially with regard to the exploitation of various multiphase systems and the production of inorganic materials of great technological value and interest such as metal alloys and semiconductor substances, with activities led by Bristol, Cambridge, Sheffield, Strathclyde, Glasgow, Cardiff, and other universities. As an example, the recent ‘National Semiconductor Strategy’ roadmap pointed out, know-how for semiconductor design and high-throughput manufacturing already exists in companies clustered throughout the UK. Hence, as the race-to-space intensifies, strategically coordinated industry-academia efforts are needed to fill the gap with other countries.

Driving Research and innovation

There are many opportunities for research and innovation in space, including studying the effects of gravity-independent forces (and, indirectly, of gravity) on the properties and behaviour of many fluid and solid “terrestrial systems”, and developing new manipulation strategies and materials in space (as well as new in lab-on-a-chip devices and microrobots technologies) with properties or functionalities that cannot be obtained in normal gravity conditions. Moreover, from an ISRU (in-situ resource utilisation) standpoint, the development of new and improved materials is the driving force behind the definition of novel closed-loop processing cycles that address the paucity of accessible resources in space. These simple arguments clearly indicate that the unique environment of space offers many opportunities to create new “principles”, technologies and materials that can benefit both space exploration and life on Earth. Because of this breadth, contributors highlight the need for dedicated funding, facilitation mechanisms to access the microgravity environment and the creation of new and more extended links among researchers, manufacturers, and space agencies (to establish comprehensive guidelines, standards, and testing protocols).

Considerations for using Materials in Space & their Impact

Edited by Dr Marco Domingos – University of Manchester, UK & Dr. Philip Carvil – Daresbury Laboratory, Science and Technology Facilities Council (Part of UK Research and Innovation), UK

This chapter is a synthesis of authored contributions [# = Contribution number in paper]:

#7 *[Pg. 60]* Otto L. Muskens, Kai Sun - University of Southampton | Metasurfaces for thermal radiation control in space applications

#9 [*Pg. 66*] Paul A Smith, Andrew Viquerat, Jasmine Bone, Mark J Whiting - University of Surrey, UK | AgeIng and Lifetime assessment of Composites For Space applications

#11 *[Pg. 70]* Peter C.E. Roberts, Steve Edmondson - University of Manchester, UK | Aerodynamic Materials for Very Low Earth Orbits

#16 *[Pg. 82]* Carlo Saverio Iorio - Yoursciencetech Ltd, UK and University of Brussels, Belgium & Yarjan Abdul Samad - University of Cambridge, UK and Khalifa University, UAE & Andrea Carlo Ferrari, University of Cambridge, Cambridge Graphene Centre, UK | In-situ production of Thermal management structures

#17 *[Pg. 85]* Charles Muir, Laura Gonzalez Llamazares - Satellite Applications Catapult, UK |Additively manufactured Inconel 718 for high heat flux applications

#19 *[Pg. 90]* Bahijja Raimi-Abraham – King's College London, UK & Cameron Alexander – University of Nottingham, UK & , Clare Hoksins – University of Strathclyde, UK & Daniel Campbell - SpacePharma Limited, UK | Space-induced polymer degradation mechanisms for medical applications

#20 *[Pg. 93]* Dharshun Sridharan - Piston Labs, Australia | Radiant revolution: The potential of solar skin in space and on earth

#21 *[Pg. 96]* Dikai Guan - University of Southampton, UK | Light Alloys for Liquid Hydrogen Storage

#25 *[Pg. 105]* Manus Hayne - Lancaster University, UK | Compound semiconductor manufacturing and use in space

#26 *[Pg. 107]* Wern Ng, Daan Arroo, Michael Leverentz, Neil Alford – Imperial College London, UK | Maser amplifiers: hearing the faintest space calls between the blue marble and the stars

#28 *[Pg. 111]* Peter Lewis, Andrew Tarrant - Materion UK Ltd, UK & Andreas Frehn - Materion Brush GmbH, Germany & Fritz Grensing, Nick Farrah, Martyn Acreman - Materion Corporation, USA | Metal matrix composites and hypereutectic alloys for space

#30 *[Pg. 116]* Qianqian Li, George Rigas, Paul Bruce - Imperial College London, UK | Advanced materials development for hypersonic vehicles

#31 *[Pg. 119]* Saptarsi Ghosha, Rachel A. Oliver - University of Cambridge, UK | Wide bandgap transistors for electronics in space

#35 *[Pg. 129]* Aled Roberts - University of Manchester, UK | Regolith biocomposites for extraterrestrial construction

#36 *[Pg. 131]* Marcello Lappa - University of Strathclyde, UK | New methods for the transport and management of lunar regolith

Considerations for using Materials in Space and their Impact

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Overview

The potential for both using materials in space and harnessing them (both as a resource and through manufacturing processes) is a vast and rapidly evolving field of R&D. Space vehicle and satellite manufacturing alone is a complex and multifaceted process, with considerations varying from how to develop more resistant alloys for variable environments while balancing the need for low cost, reusable and lightweight materials to resilient electronic and optical technologies. The environment of space brings both more challenges as well as untapped opportunities for the materials sector from the reduced effects of gravity, increased radiation (including solar), change in resource availability and increased distance from Earth. The increased governmental and commercial focus on space, has resulted in an increase in space operators (beyond government operators) as well with diverse vehicle design and operational offerings. These include existing commercial incumbents such as Space X, Blue Origin and Virgin Galactic to new vehicle and platform operators such as SpaceForge, Clyde Space, Gravity Lab, Sierra Space, Axiom Space and many more. With the increasing access to space, this offers further opportunity for cross-sector interactions to understand how space can support new R&D developments on Earth, as well as for space exploration.

Within the context of this paper, it is clear there is a significant emerging community looking to address challenges and opportunities posed by the space environment that align to both UK and International Roadmaps. For example the expertise in compound semiconductors in the UK is well recognised and was recently captured in the National Compound Semiconductor strategy. Space applications offer both an opportunity for this market to harness the environment of space for new applications (such as enhancing solar energy processes) as well as realising the opportunity for advanced computing in space. Further afield, groups are already investigating opportunities to harness regolith in extreme environments (such as Lunar and Mars) from proposed new transporting and assembly techniques to bio-processes. Such advancements for space based applications then offer new opportunities for industries on Earth such as Aviation, Automotive and Telecommunication to name a few through the direct benefit of advanced materials that can better handle thermal and shear stresses whilst being low in mass.

It is clear there is still a great opportunity for further development of this interface between the materials and space communities, particularly with citing of immediate opportunities for tech transfer. Whilst increased access to space will naturally facilitate improved volume of materials R&D there is a need for appropriate ground-based test facilities that can allow the rapid prototyping and testing of these technologies such as radiation testing facilities. To support further industry-academic collaborations, directed funding of R&D networks is needed to bridge the translational gap, which (as demonstrated in several contributions) can in turn support new spinouts from universities. It is also clear that Space remains a grey area for several funding organisations (both public and private) therefore increased education and uptake by the R&D and investment community is needed to recognise the opportunity for space. Finally with the evolving space landscape there is an increasing need for investing into technical and regulatory frameworks working with space agencies to agree key principles for high value opportunities for the UK, from new orbital configurations and Centres of Excellence for material design to in-orbit manufacturing.

Case Experiences

Contributors to this paper bring leading expertise and capabilities covering several of the subjects described above, ranging from aerodyanamics and materials assembly, to advanced fabrication and optical methods. Existing space related developments include:

- Bridging research between aerodynamics, materials characterisation and research into gasflows through nanochannels made from 2D materials, researchers at the University of Manchester have developed processes including coatings that can be optimised to improve resistance to atomic oxygen erosion and drag thereby supporting development of Very Low Earth Orbit platforms.
- Researchers in Physics and Astronomy at the University of Southampton have recently completed two European Horizon 2020 projects for spacecraft thermal management named Metareflector and Smart-Flex. These included the development and validation of two novel metal oxide metasurface-based optical solar reflectors (meta-OSRs). As the next generation solution, these flexible OSR foils can significantly reduce the assembly cost and launch cost of spacecraft.
- Utilising expertise in Selective Laser Melting (SLM) with proposed superalloys (namely Inconel 718), teams at the Satellite Applications Catapult have been testing this process for developing complex thrust chambers that can be adapted for various operators and propellant combinations which could support a more efficient and agile manufacturing process for complex space components.
- Researchers at the University of Southampton in collaboration with AMRC North West and Baylor University in the USA, have been developing novel light alloys with the aim for these to have a high hydrogen embrittlement resistance and high impact toughness at cryogenic temperatures that can support space craft and launch operations such as hydrogen storage. This could also have implications for Earth based applications including advanced automotive and aviation technologies.
- Building on a long history of materials research and usage, Materion working with academic and space partners is developing next generation materials for harsh environments, these include lightweight Metal Matrix Composites (MMCs) and hypereutectic alloys to meet situational demands such as hypereutectic aluminum-silicon alloy to address thermal management issues.

Figure xili. University of Manchester's deployed Satellite for Orbital Aerodynamics Research (SOAR) which measured the aerodynamic performance of different materials.

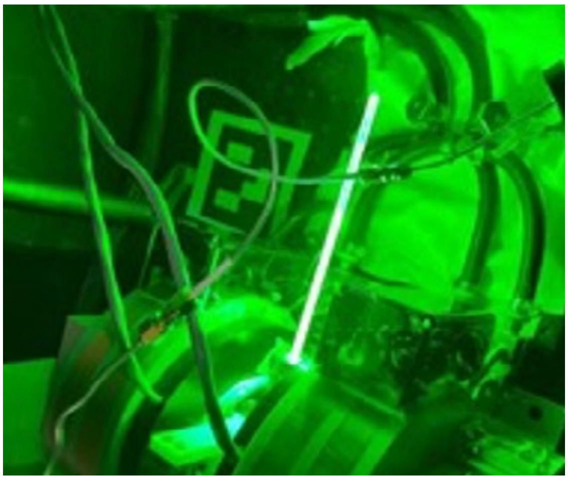

Figure xiv. Excitation of a diamond MASER by green laser light. The diamond gain material is positioned inside a resonator and embedded in test tube, which is reflecting the green light from researchers at Imperial College London

- Researchers at Imperial College London have developed room-temperature solid-state masers, including miniaturisation of key components to support the translation of this technology. Applications include Radio-astronomy where diamond masers could offer more efficient and low cost alternatives, use in ground stations and satellites to support wider connectivity and boost telecommunications ranges.
- Using a combination of regolith and plant derived biopolymers a team from the Future Biomanufacturing Research

Hub at the University of Manchester, is investigating the potential of bio composites for extraterrestrial construction. These developments for off world applications also have potential for terrestrial markets such as ceramic tiles and the team has spawned a start-up, DeakinBio to investigate this potential as well.

Supporting Space Exploration:

To support space exploration there are a number of translational capabilities from research active groups that could address future exploration needs, but also drive further fundamental R&D terrestrially:

- Building in extensive experience selecting and modifying materials for spaceflight, researchers at the University of Surrey have brought together this aligned expertise in material ageing under the umbrella of the Surrey Centre of Excellence in Materials Ageing, Performance and Lifetime Prediction (CoE). Recent translational developments includea novel approach for the assessment of coating degradation for aerospace applications.
- Researchers at the universities of Cambridge and Brussels as part of an ongoing ESA-Sponsored activity, are investigating the production of regolith-based aerogels, using pristine regolith and a freeze-drying process optimised for proposed Lunar and Martian conditions. This could support the development of composite materials with reduced reliance on Earth based components.
- A consortium of partners (King's College London, University of Nottingham, University of Strathclyde and SpacePharma) are developing an approach to further understand the real-time degradation of polymers in microgravity in order to develop the next generation of multipurpose SMART polymers that can be adapted for various situational needs from construction to medical applications.
- Exploring the potential for Solar skins for space applications, the team at Piston Labs has been conceptualizing how these energy generating materials could be applied to space craft. From applying the exterior surface of vehicles to provide additional energy generation at low mass costs to thrust generating solar sails.
- Building on extensive research at Lancaster University, a recent spin out Quinas Technology, is working to commercialise compound semi-conductor technology that is highly efficient and non-volatile; ULTRARAM™ memory technology. In space, applications for this technology could include use to increase efficiency of solar cells, critical components for in-orbit edge computing and more.
- Within the Department of Aeronautics at Imperial College London, a team is aiming to develop a new class of aerodynamically smooth metallic/ceramic composite material for application in the design of hypersonic vehicles. Via the suppression of hypersonic boundary layer transition, these materials could offer a highly tunable capability that would minimise the need for complex active cooling systems to manage thermal stress.
- A team at the Department of Materials Science and Metallurgy, University of Cambridge is seeking to address the potential for wideband gap transistors for use in electronics in space, where there is need for longer term operation in hazardous environments (including radiation). By strategically coordinating industry-academia efforts around space-qualified WBG transistors this could place the UK as a global leader in this upcoming semiconductor value chain.
- Collaborating with the European Space Agency (ESA), researchers at the University of Strathclyde are working on a framework project to look at how vibrations can be used as a tool for particle self-assembly and regolith vibro-fluidization in lunar applications where there is potential to use vibrations to force regolith to behave as a 'fluid' thereby making its transportation and utilization more viable.

Overcoming Challenges

Within the contributions there were a number of challenges critically discussed, which could be used to facilitate the use of engineering materials in space applications.

Development of Manufacturing Frameworks: The application of both existing manufacturing technologies (such as additive manufacturing) to space as well as the use of novel materials in the manufacturing process (such as regolith or biological materials) are emerging areas that would benefit from collective input from standards bodies, industry, regulators, and academia in order to develop operational frameworks to guide the robust assessment of such developments and utility for space exploration and/or terrestrial markets.

Infrastructures: Conducting experiments in space is inherently complex and costly, which can limit the number and scale of studies that can be undertaken. Despite significant efforts to increase the capabilities and facilitate access to the ISS, there is still a need to develop alternative platforms for in situ manufacturing and testing of materials for space research applications. In some cases, ground-based facilities can be used as an alternative to increase capacity, but high access costs, especially for radiation testing, remain a major barrier for the scientific community.

Funding: Most innovations in space materials are threatened by the classic “TRL valley of death” scenario. As highlighted by a number of groups, very few ideas actually make the transition from a simple proof-of-concept to a prototype that could be launched into space, due to the lack of more significant investment. This issue can only be addressed with the establishment of an overarching research strategy and robust funding mechanisms for further concept development, supported by collaborations with experienced space contractors and industry primes.

Technical and regulatory processes: There is a pressing need for a robust and defined process to design, manufacture and test materials that can be qualified and approved for flight in space applications. In terms of design, the development of computational models to inform experiments and vice versa (through an optimisation framework) are necessary to guide the selection of optimal geometric patterns and design. Manufacture and upscaling will be a major concern and still has a long way to go. This will inevitably impact material selection for the application, material interface design and material inspection during life-cycle application (e.g., to assess inner-stresses, detection of initial cracks, surface coating degradation, etc). Whilst standards for testing of materials are well established and routinely used by researchers, the ability to characterise a material’s surface remotely through high-precision measurements in-space is still underdeveloped and will be essential to assess concept performance and viability.

Skills: The lack of microgravity culture in the UK is still seen as one of the main barriers adversely affecting the exploitation of materials in space. Most undergraduate and postgraduate degrees offered by UK Universities do not cover microgravity-related topics, at least in sufficient detail, to raise awareness and encourage students to develop a professional career in this emerging field.

Driving Research and Innovation

Space offers a great opportunity for innovative developments in materials science and technology with immediate application in space-related research but with potential to impact on many terrestrial applications. The unique environment of space enables the study of materials behaviour under extreme conditions that can’t be found on Earth, whilst understanding the impact of different space stressors (e.g. microgravity, radiation, etc.) on material properties. This knowledge can be instrumental for the development of the next generation of advanced materials with superior physicochemical properties to support human space explorations as well to revolutionise established processes on Earth, including design and manufacturing.

The UK is world leading in materials science and has a thriving community of researchers and scientists in physics, nanotechnology, and manufacturing. However, to deliver on the above and place the UK at the forefront of space research, it is essential to stimulate the establishment of more interdisciplinary collaborations between academics, and linking academia with the industry. This can only be possible with better coordination, dedicated funding, and facilitation mechanisms. Such an environment, could only lead to the discovery and commercialisation of new products and applications under ESA roadmaps and in key sectors of UK strength, including healthcare, aerospace, automotive and defence. Additionally, innovation in materials technology can lead to the production of lightweight components with higher performance, energy efficiency and reliability, permitting significant energy savings and contributing to Net Zero targets on Earth.

Considerations for Material Development and Manufacturing in Space

Edited by Professor Ian Hamerton – University of Bristol, UK, Dr Peter C E Roberts - University of Manchester, UK & Dr Philip Carvil – Science and Technology Facilities Council (Part of UK Research and Innovation)

This chapter is a synthesis of authored contributions [# = Contribution number in paper]:

#4 [Pg. 52] Patricia Santos Beato, Deepak M. Kalaskar – University College London, UK & Sasha Thomas, Ajay Kumar – Velon Space Pvt Ltd, India | Biomaterials for human tissues and organs printing in space

#6 [Pg. 58] Ken Shields Sierra Space, USA & Jonathan Volk ,formerly Sierra Space, USA | A Commercial solution for in-space manufacturing

#8 [Pg. 62] Marcello Lappa - University of Strathclyde, UK | New In-Orbit Self-assembly principles and Manufacturing techniques

#14 [Pg. 77] Alex Goodhand, Laura González Llamazares - Satellite Applications Catapult, UK | Evolution of in-orbit manufacturing: A new frontier in space

#18 [Pg. 88] Chyree Batton, Divya Panchanathan, Jana Stoudemire - Axiom Space, USA | Infrastructure for Advanced Material Fabrication in Space

#22 [Pg. 98] Enya Collier - Lucideon Ltd, UK | Lucideon – Expertise in advanced ceramics exposed to harsh environments

#23 [Pg. 100] Fraser Burton - BT, UK | Space-grown thermal substrates for efficient wireless communications

#24 [Pg. 102] Mahdi Bodaghi - Nottingham Trent University, UK | 4D Printing 4 Space

#25 [Pg. 105] Manus Hayne - Lancaster University, UK | Compound semiconductor manufacturing and use in space

#26 [Pg. 107 Dr Wern Ng - Imperial College London, UK, Dr Michael Leverentz -Department of Materials, Imperial College London, UK, Professor Neil Alford, Department of Materials College London, UK, | Maser amplifiers: hearing the faintest space calls between the blue marble and the stars

#28 [Pg. 111] Peter Lewis, Andrew Tarrant - Materion UK Ltd, UK & Andreas Frehn - Materion Brush GmbH, Germany & Fritz Grensing, Nick Farrah, Martyn Acreman - Materion Corporation, USA | Metal matrix composites and hypereutectic alloys for space

#29 [Pg. 114] Ian Hamerton - University of Bristol, UK | Designing Inorganic/Organic Hybrid Resin Matrices for Extreme Environments

#32 [Pg. 121] Aakash Bansal, William Whittow - Loughborough University, UK | 3D Printing for fast and secure satellite communications

#33 [Pg. 124] Yarjan Abdul Samad - University of Cambridge, UK and Khalifa University, UAE & Carlo Saverio Iorio - Yoursciencetech Ltd, UK and University of Brussels, Belgium | 2D Materials for space applications

#34 [Pg. 127] Simon Pope - University of Sheffield (on behalf of the UK Metamaterials Network), UK | Metamaterials for space

#35 [Pg. 129] Aled Roberts - University of Manchester, UK | Regolith biocomposites for extraterrestrial construction

Considerations for Material Development and Manufacturing in Space

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Overview

Both the current national and international government roadmaps emphasise the likely existence of crewed space missions of longer duration and the consequent need to construct extraterrestrial habitats. In both cases, existing materials and the methods employed to manufacture them face severe challenges when operated in such harsh conditions and under microgravity making further research and development a necessity. Many of the key enabling technologies that may form future campaigns are still the subject of low TRL research and far from a state of maturity, requiring further targeted research to enable their exploitation. Fortunately, the need to tackle these challenges, and the huge potential that these opportunities present, from harnessing the microgravity environment to manufacture components for terrestrial applications (for use in e.g. healthcare), to considerations over the shape and scale of future lunar habitat development, has sparked interest and many conversations within academia, RTOs, and up and down the supply chain. As outlined in the previous chapters, the environment of space presents a unique opportunity to study the behaviours of processes and mechanisms that can lead to novel material developments and application of manufacturing methods to enable these opportunities.

For example, the effects of gravitational forces on manufacturing related processes, such as sedimentation, solidification, convection and more, offer the opportunity to tailor and enhance physical characteristics like uniformity leading to greater structural regularity, higher density, more crystallinity, or homogeneity. From the perspective of chemical reactions and novel synthesis, the unique environment may lead to faster kinetics, increased reaction yields, higher atom efficiency, and greater enrichment of selected isomeric products. Within functional materials, it may impart enhanced desirable characteristics (such as higher thermal conductivity substrates for electronic components), while reducing competitive side reactions or minimizing damaging structural defects such as porosity. When allied to existing modern manufacturing methods, like additive manufacturing, the conditions can facilitate more complex assembly techniques without the need for scaffolds, thereby opening new industrial applications for complex structural assembly (for example tissue engineering).

These applications require both regular access to and/or return from space to support these R&D applications and future business models for an in-orbit servicing and manufacturing economy. Commercial and government entities are actively addressing this with new launch vehicles (including Sierra Space) and commercial space stations (including Axiom Space) which seek to address this with other market players, thereby creating a robust and accessible space infrastructure. Such developments can then propel initiatives for further space exploration beyond low earth orbit and provide an environment to further test key technologies ahead of deployment on proposed colony sites (including lunar), which may even look to harness residing regolith materials or reclaimed structural materials to manufacture (or remanufacture) structures, thereby reducing transportation costs. The following chapter outlines some of the existing case examples and future possibilities for material development and manufacturing in space alongside recommendations.

Case Experiences

Contributors to this paper bring leading expertise and capabilities covering several of the subjects described above, ranging from the development of new materials, from composites to metamaterials, developing manufacturing technologies suitable for application in orbit, through to the provision of access to the space environment. Existing space related developments include:

- Researchers at the University of Strathcylde are working on the identification of new concepts to manipulate matter on different scales and develop novel strategies for contactless solid-particle manipulation. Projects include JEREMI "Japanese European Research Experiments on Marangoni Instabilities" funded in the UK by the EPSRC and the PARTICLE VIBRATION project (also known as T-PAOLA i.e. "Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity") funded by the UKSA.
- The world's first commercial space station in low Earth orbit is under development by Axiom Space to support the growing needs of civil, commercial, and government bodies. Attached to the International Space station, the first module will support initial development of the station, followed by future R&D and manufacturing modules (including an external payload facility) added before the ISS is decommissioned at the end of the decade.
- Linked to this, Sierra Space is developing solutions to provide access to facilities to enable manufacture in space. Through a proposed in-space manufacturing solution called LIFE™ habitat (Large Integrated Flexible Environment), that will offer the capability to experiment with and manufacture materials. This will be supported through its launch vehicle developments with the Dream Chaser® spaceplane.
- Researchers at Luciedon have been investigating the behaviour of regolith including properties such as particle size, shape, and rheology, in order to develop a possible utilisation programme that would support the handling of regolith for novel structural applications. They have also been assessing the use of flash Sintering technology as a potential method for manufacturing space batteries powered by americium-241 (241Am).
- Researchers in the 4D Materials & Printing Laboratory at Nottingham Trent University, in collaboration with national and international research institutes, have been investigating the potential for shape-morphing structures created through 4D printing of smart material systems for different applications including for adaptive soft robotics, meta-materials and magneto-electroactive shape memory polymer composites.
- Materion has been involved with numerous space materials research projects, including repair optics for the Hubble Space telescope to NASA's James Webb Space Telescope. Material developments include lightweight metal matrix composites (MMCs) and hypereutectic alloys which provide additive characteristics to support operation in the extreme environment of space.
- Researchers in the Bristol Composites Institute, University of Bristol, have recently conducted two UKSA-funded composite development projects with the European Space Agency (ESA) and Centre National d'Etudes Spatiales (CNES) Euro Materials Ageing Campaign. In AO-2020-EMA (Q2, 2024), four nanocomposite CFRP specimens, designed to have improved resistance to atomic oxygen, and manufactured in Bristol will be exposed on the Bartolomeo platform of the International Space Station for up to 18 months. Within another ESA programme, AO-2022-IBPER, during 2024-2025 the same team will explore the potential of the same polybenzoxazine and cyanate ester nanocomposites to act as low mass radiation shields by exposing CFRP laminates within the heavy ion accelerator at the GSI Helmholtz Centre for Heavy Ion Research and measuring radiation attenuation.

Figure xv Representation of Sierra Space Dream Chaser® Spaceplan with LIFE™ habitat (Credit: Sierra Space)

- Working with partners from across industry and beyond, researchers at Loughborough University have been working on additive manufacturing techniques for RF applications. This includes synthesising 3D printed metamaterials, graded index lenses, beamforming antennas, and anisotropic materials for satellites.
- Researchers at the University of Cambridge are working with 2D materials, i.e. graphene and related materials (GRMs) to explore their space related applications, currently using microgravity platforms including parabolic flights and sounding rockets to understand these. Possible applications include thermal management, electrical energy transmission, radiation protection, and more with the further potential for terrestrial applications.

Supporting Space Exploration:

To support space exploration, a number of translational capabilities were highlighted from groups that could address future exploration needs, but also drive further fundamental R&D terrestrially, including:

- Researchers from University College London discussed the potential to find new biological applications with space, including biomaterials (from antimicrobial costing to wound healing), organ manufacturing, how gravity could affect gene up-regulation and bio-printing.
- In the Telecoms field, a contribution from British Telecoms (BT) highlighted the opportunity to use space for the development of components for communications systems with increased efficiencies, together with improved thermal performance to limit active cooling costs.
- A spin out of Lancaster University, Quinas Technology expanded on the opportunity for semi-conductors and space through their ultra-efficient, non-volatile ULTRARAM™ memory technology with applications for the space sector.
- The UK Metamaterials Network, funded by the EPSRC to develop a network of entities from academia, industry, and government, working in metamaterials in the UK has formed a challenge area for space to explore the possibly for interaction between communities and space entities, through the thematic area. The first theme, which has been discussed by the group, is Spacecraft Performance with the second theme is Observation and Sensing.
- Researchers at the Future Biomanufacturing Research Hub, University of Manchester, are pioneering the development of high-performance biocomposites for extraterrestrial construction. They discovered that ordinary potato starch could be employed serve an effective binder for both Lunar and Martian regolith – producing materials with high compressive strengths.

Overcoming Challenges

Within the contributions a number of challenges were critically discussed, which could be used to facilitate the use of material development and manufacturing methods.
Development of Manufacturing Frameworks: The application of both existing manufacturing technologies (such as additive manufacturing) to space as well as the use of novel materials in the manufacturing process (such as regolith or biological materials) are emerging areas that would benefit from collective input from standard bodies, industry, regulators, and academia in order to develop operational frameworks to guide the robust assessment of such developments and utility for space exploration and/or terrestrial markets.

Investment into interdisciplinary R&D:

Owing to the complex ecosystem of space and its access requirements there is a clear need to increase the link between existing space operators (academics, industry, government, agencies) and market sector actors. This is essential to increase the potential for microgravity research, enhance the uptake from end users and develop new business models for a sustainable space economy.

Support for Proof-of-Concept Trials: In order to unlock a full-scale manufacturing capability in space, linked to end user need, there is the need to gather more data on the feasibility, deployability, and utility for manufacturing demonstration. These can then support the case for developing further orbital facilities to develop larger scale processes/facilities and once use cases have gathered sufficient data for analysis, to design these facilities iteratively and support the verification/testing of linked products and integration with supply chains.

Driving Research and Innovation

Space provides a clear opportunity to both further understand fundamental processes linked to materials development/ manufacturing (such as multiphasic systems) and allow the development of complex structures and three-dimensional materials which are inherently influenced through the effects of gravity on Earth. Implications from this can lead to enhanced components for use in space and on Earth (including semi-conductors), build cases for new business models (such as tissue engineering in space) and support space exploration (with new manufacturing and in-orbit servicing economies).

To enable this, more data are needed from the trial and deployment of these technologies in supported proof of concept demonstrations. This can then guide future frameworks to facilitate the verification and validation of product developments that can then guide future industries (including for critical technology areas like Quantum and engineering biology) to adopt these manufacturing technologies. This will then accelerate the uptake of products made in space by terrestrial industries and create robust supply chains. Interdisciplinarity will be a key requirement for this, through bringing in existing space sector perspectives with non-space market sectors (including end-users), to solve key challenges around market creation and/or space agency roadmaps.

If appropriately stimulated this could lead to the development of advanced, multifunctional materials with enhanced properties thereby supporting the construction of more robust and resilient structures; advancements in robotics and autonomous systems to transform manufacturing processes; and the development of in-situ resource enterprises to harness resources away from Earth. These proof-of-concept developments could thereby support future exploration/ colonisation of space, and reduce the burden on limited Earth resources.

Summary: Opportunities, Gaps and Challenges for the UK

The UK is home to cutting-edge space research with well-established strategic partnerships with international agencies and notably strong collaborations with the European Space Agency.

In the materials sector, the UK boasts world leading capability, often merging disciplines. This is highlighted in the thematic chapters and the considerable number of contributions received from the community (see Appendix pg42), with case studies spanning across all TRL levels and across all the main groups of materials (metals, ceramics, polymers and composites). Each of the thematic chapters showed how these activities are driving research and innovation and supporting space exploration. The chapters showcased the breadth and depth of opportunities linking the UK and International roadmaps of fundamental understanding, to exploiting the space environment, and translating terrestrial expertise into space.

However, the community has also detailed challenges that need to be overcome to realise new opportunities. This includes developing and growing access to infrastructure, creating relevant national and international networks, connect space sector actors and non-space actors, funding and investment into interdisciplinary R&D, support for proof-of-concept trials, technical and regulatory processes, creating a pipeline of new talent and skills at degree level, and developing frameworks with input from standard setting bodies, industry, regulators, and academia.

This paper also detailed available facilities and access opportunities for UK researchers, which has been growing both in scale and diversity with new commercial offerings supporting R&D payloads to space, supplementing existing access to the ISS, parabolic flight and ground-based facilities (drop towers, sounding rockets, centrifuges etc.). It highlighted mechanisms that have been developed to support access, in particular for early career researchers.

In summary, the preceding community outreach (workshops, webinars and call for contributions) culminating in this paper, aimed to capture the opportunities and challenges from the perspective of the materials community. This paper sought to emphasise the scope and scale of support for building capability and capacity for materials research in space, with an emphasis on the UK (but including associated/interested international contributors). Contributions were received from diverse researchers and interests, encompassing commercial and industry activities and views from early to senior career academics. Derived from the community’s broader input, five key recommendations have been proposed. Implementing these suggestions would support the materials community and ensure that the UK maintains its position as a world leader in space-based research.

Appendix: Author contributions - The Case for Why Space? The Opportunity for Materials Science and Innovation

Through the open calls in 2022/2023 over 35 contributions were received from Academia, Industry and wider public sector contributors. In the previous Thematic chapters a synthesis from these was presented. Here, the full contributions by the authors are presented, which cover a breadth of activity and input from the Space and Materials Community. All contributions were authored independently of each other and sight of other contributions to this paper was not available prior to authorship. Lastly, challenges were requested from each contributor, stating these would be removed in the final publication to allow greater freedom of expression, these challenges and recommendations are therefore synthesised and expressed in the thematic chapters.

Table of Contributions

The listing of affiliations attributed to each contributor does not represent an official endorsement of this overall paper or the contribution by the organisation listed.

Microgravity hydrodynamics of nonequilibrium interfaces

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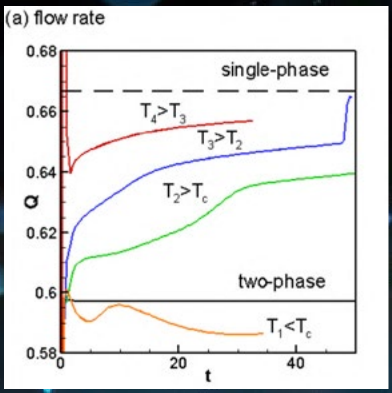

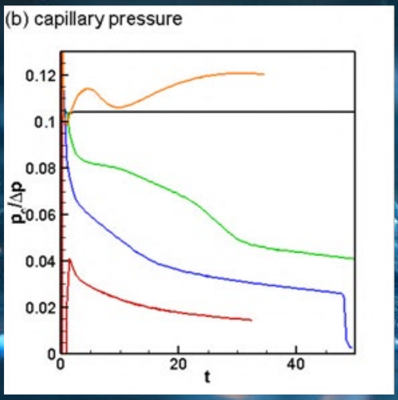

Figure. Miscible liquid/liquid displacement: flow rate and capillary pressure depend on the state of mixing

Overview

In Space, fluids are subject to unavoidable non-inertial movements (g-jitters), which action is equivalent to unsteady gravity (microgravity). Inertial (oscillatory) forcing can be also introduced deliberately in order to control dynamics of fluids. Combination of gravity (or external accelerations) with fluid/fluid interfaces (and with density differences) lead to fluid instabilities, which emerge and develop differently on Earth and in Space.

An example is the (molecular level) mixing of liquids, which is a common pre-requirement for many chemical engineering technologies. Mixing is determined by a competition of convection and diffusion, and it is additionally complicated by the presence of (miscible) interfaces. If a fluid system is subject to mechanical vibrations, dynamic (process-dependent) interfacial stresses associated with miscible interfaces compete with external accelerations, making mixing more complex, inducing waves, fingering and other surface phenomena [1].

Case Experience

In our recent studies of dissolution of a droplet that is moving in a miscible environment, [2] we found that at first a droplet pulls into a spherical shape, and only later it behaves like a droplet with zero surface tension. The nonequilibrium non-zero surface tension plays a critical role in the dissolution dynamics, setting droplet's disintegration.

The surface tension forces are particularly important for fluids in confined geometries, in micro-reactors and porous media. We examined miscible displacements, [3] and found that the nonequilibrium capillary pressure remained different from zero for a long time, slowing down movement of a meniscus. The role of the nonequilibrium capillary pressure is however ignored by the current theories that are available for practical modelling of miscible displacements (which is the basis for cleaning, drying, solvent extraction, liquid waste storage, etc.).

A consistent theoretical basis for description of coupled convective and diffusive evolution of miscible systems (with interfaces) can be given by the phase-field approach. In the University of Southampton we develop this method to reveal intrinsic details of mixing. [4] We also study the dynamics of miscible interfaces subject to external accelerations. [5,6]

Opportunity for Research and Innovation

A strange (and novel) behaviour of multiphase fluids in microgravity environments complicates fluid management, but, at the same time, presents new unique opportunities. For instance, the phase-field approach introduces new phenomenological parameters, which direct measurements require separation of diffusion and convection that can be only achieved in a (long) Space-based experiment. This could become the first experimental measurement of a diffusion-based evolution of the nonequilibrium surface tension, ultimately, leading to improved understanding and optimisation of technologies in chemical engineering and materials processing.

Even today, handling of fluids in Space is needed for management of fluids in life support and propulsion systems. In the future, handling of fluid/fluid interfaces will be needed for exploitation of microgravity environments, for resource extraction, for development and production of new materials. These are the important long-term objectives of Space Exploration. The particular examples are the earlier experimental studies of crystal growth and polymerization processes set in Space, when confident (long-term) control of interfaces and management of interfacial heat and mass transfer are the keys to success.

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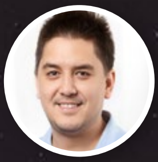
Understanding thermophysical properties and solidification in microgravity



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Overview

Phase change studies in materials science and fluid physics deal mostly with the liquid state of matter, the properties of which can be masked by gravity-induced effects. Yet such studies are important for understanding and modelling processes in metallurgical, chemical, and biotechnological industries, as well as for developing future materials technologies. The relationships between the structure, processing, and eventual performance of materials, as manufactured structural components, are governed by their properties which may include physical, chemical, electronic, thermal, and magnetic characteristics.

Materials science microgravity programmes run in parallel by the world's space agencies (e.g. NASA, ESA, JAXA, ROSCOSMOS, etc.) use the unique characteristics of the microgravity space environment on the International Space Station (ISS) to measure material properties that are impossible to obtain under gravity, yet are vital for the study of the fundamental relationships governing solidification and crystal growth in the production of advanced alloys and composites. On Earth, when a melted alloy solidifies, it forms Christmas-tree-shaped crystals called dendrites, which play a key role in alloy properties and its subsequent usefulness. Dendritic solidification is strongly influenced by gravity-induced flows (convection) in the liquid phase. This type of physical process is very complex and difficult to measure or predict, and even more difficult to control. In space, gravity-related phenomena such as convection are minimised, thus simplifying the process for study. Computational models such as the ones developed in Greenwich can now simulate the solidification process and the intricacies of the evolving microstructure with high accuracy, but models often lack equally accurate properties at the high temperatures present in molten metals.

Case Experience

Over a period of three decades, we have developed models for electromagnetically levitated melts in both terrestrial and microgravity conditions. Our models follow the dynamic coupling between a deforming liquid envelope and the surrounding field, to determine electromagnetically driven convection and heat transport within the melt.
This knowledge has been used to derive corrections for thermophysical property measurements such as surface tension, viscosity, thermal conductivity and expansion coefficient, density, and electrical conductivity on levitated melts, as carried out on TEMPUS, EML and terrestrial levitators. We have also experimented with the levitation of non-conducting para/diamagnetic liquids, valuable for biochemical sciences. As part of the ESA international topical team (Solidification of Containerless Undercooled Melts (SOL-EML)) and the ESA Peritectic Alloy Rapid Solidification with Electromagnetic Convection (PARSEC) project we have studied the effect on microstructure from thermoelectrically induced micro-convections. The latter activity showed the potential to use magnetic fields to tailor the microstructure, hence improve properties.

Opportunity for Research and Innovation

With an eye to the future and the need for sustainability and the protection of the environment, microgravity materials research becomes very important, as it will contribute to future models of industrial and manufacturing processes. This will potentially lead to new, stronger, lighter alloys with never-seen-before properties key for space exploration, aviation, transport, power generation, or the production of advanced intermetallic catalysts for hydrogen production and storage.
Microgravity experiments, such as those conducted on the ISS, are essential to realise these future developments. Experiments can be conducted over extended periods, in contrast to those that are terrestrially based, e.g. drop towers and parabolic flights. This paves the way for long term opportunities from not only understanding fundamental materials science, but to understanding how to manufacture in Space.

Influence of reduced gravity on spreading flames

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Overview

Fire safety is a prime are of concern for human space exploration. The risk of accidental fire remains innately high, as highlighted by past incidents, jeopardizing the safety of the crew and the integrity of the spacecraft. Safety becomes all the more critical as fire hazards are set to increase in upcoming low-pressure oxygen-enhanced exploration atmospheres (26.5% oxygen and 70kPa for the Gateway module; 34% oxygen and 56.5kPa for the Lunar Lander). In addition, fundamental mechanisms of heat and mass transfer within a flame are affected by buoyancy, thus fire properties are dramatically altered at reduced gravity levels. For instance, flames can spread faster at lunar gravity than at normal gravity in certain conditions, questioning the performance of present ground-based tests to design a fire-safe spacecraft or lunar module.

Fundamental experiments in academic configurations must be developed to obtain critical information regarding ignition, flame spread, and particulate/smoke emission over a range of material at low gravity.

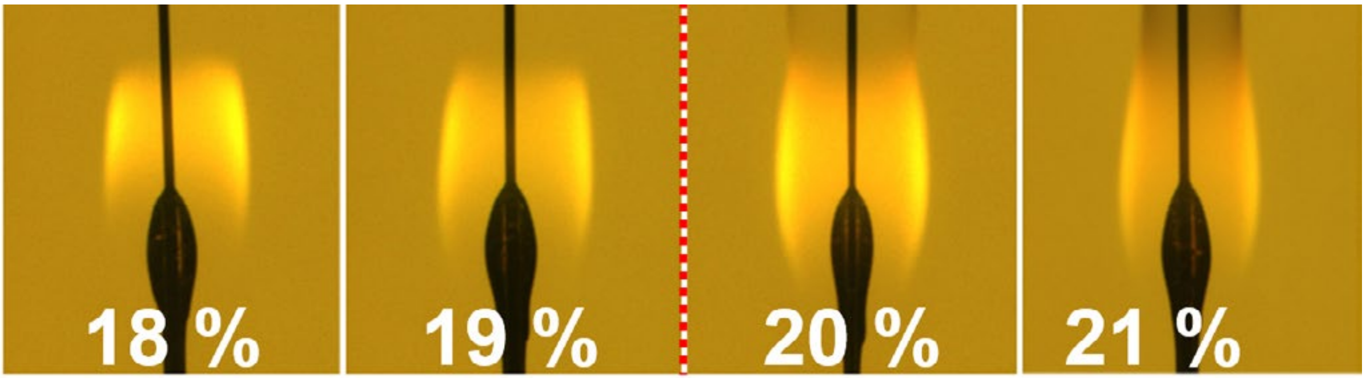

Figure 1:Flames spreading over electrical wires in microgravity at standard pressure for a range of oxygen contents. As oxygen content is increased, the flame starts to emit thick smoke. Pressure and oxygen content can be adjusted to support extravehicular activities, with direct repercussions on fire hazard.

Case Experience

Researchers in the Department of Civil, Environmental and Geomatic Engineering at University College London are currently involved in two international collaborations (CNES-JAXA and ESA-NASA) which develop experiments in parabolic flight, in the ISS, and in unmanned orbital vessels to collect experimental data points which feed theoretical and numerical models under development [1,2]. The author has been leading fundamental developments on smoke emissions over the last decade, with an internationally recognized expertise in optical diagnostics for microgravity experiments used in the International Space Station through the project FLARE. He has a track record of award-winning papers in the field of combustion, and has contributed to ESA's 2021 White Paper as well as NASA's 2022-23 Topical papers on fire safety. He has been Co-I or PI during nine microgravity parabolic flight campaigns sponsored by CNES and ESA.

Opportunity for Research and Innovation

Improving fire safety in the scope of space exploration offers numerous opportunities for experimental, numerical, and fundamental research and innovations. Combustion experiments are especially challenging in reduced gravity conditions due to the need to develop compact and automated setups, while retaining a high spatio-temporal resolution in the measurements. Required technological developments can lead to the production of robust sensors which will benefit fire detection and mitigation systems on Earth. In addition, the introduction of gravity as a unique parameters allows operators to study the response of fire resistant material or products boosted with fire retardants without the natural coupling of dripping observed on Earth. Refining the chemical and physical properties of fire safe material will be of great benefits to the material science community. Numerical modelling also benefits from the decoupling of buoyancy with other mass transfer mechanisms to better absorb uncertainties in dynamic flame spread representations, and efforts are being made to develop data-driven fire spread models which could one day inform firefighters and the public of the dynamics of an existing large-scale fire in real time, to protect lives.

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Biomaterials research in space

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Overview

Biomaterials research in space offers unique opportunities and comes with distinct challenges. The microgravity environment of space presents a unique opportunity to study the behaviour of biomaterials and biological processes in novel ways, potentially leading to breakthroughs in fields like tissue engineering, drug development, and materials science. Additionally, space-based research can yield insights into how microgravity impacts human health, informing advancements in medical biomaterials.

Biomaterials research in space is still in its infancy, due to the need for specialized equipment, limitations on experimental duration, and the cost of conducting experiments in space. However, progress made in fundamental understanding of microgravity on biomaterials and its applications in biology has been exciting.

Case Experience

Recent studies have established that biological materials, proteins, and hydrogels behave differently in microgravity [1]. Thus, materials and processes used to fabricate implants, tissues, or organs, and pharmaceutical products on Earth may not work in space. For example, it is difficult to use low-viscosity materials on Earth. However, as these materials behave differently in space, they have potential to find new biological applications [2].

Recent work by Jemison & Olabisi (2021) extensively reviewed biomaterials for human space exploration and highlighted various research from bio-suits for astronauts, antimicrobial coatings, and wound healing biomaterials with extended shelf life and microgravity-healing capabilities aid in treating burns, diabetic wound, and abrasions in space [3].

One of the areas which excite biomaterials use is the manufacturing of living tissues and organs in space. We are unable to fabricate large organs as they collapse under gravity in a laboratory setting here on Earth [4]. However, with the use of the right material combinations and the presence of microgravity, we might be able to overcome this challenge. Most studies in this area have focused on fundamental understanding of cells, biomaterials assembly, and interactions.

Silvani et al. (2021) used two distinct biomaterials, gelatin methacryloyl (GelMA)-Alginate and GelMA-Fibrin, to study a glioblastoma multiforme (GBM)-on-a-chip model [5]. This model intricately replicated the GBM microenvironment and tumor vasculature in microgravity and provided a means to study these tissue models which otherwise were not feasible on Earth.

In another study by Han et al. (2021), a bioscaffold from CELLINK AB was used to study epigenetic changes in boundary cap neural crest stem cells (BCs) exposed to space flight or simulated microgravity [6]. The research illustrated that space flight exposure prompted the upregulation of genes linked to proliferation and survival, whereas simulated microgravity exposure on Earth led to the upregulation of genes associated with differentiation and inflammation.

Windisch et al. (2023) achieved a breakthrough in biomaterial ink development by formulating an innovative blend of alginate (Alg) and methylcellulose (MC), boasting exceptional biocompatibility, and stabilizing attributes, thus enhancing printability [7]. This groundbreaking Alg-MC bioink demonstrated its potential for space missions and was chosen as the primary bioink for utilization in space endeavors. Impressively, Alg-MC bioink was the inaugural choice of bioink for the OHB company during the ISS mission Cosmic Kiss, spearheaded by German ESA astronaut Matthias Maurer. A handheld printer was instrumental in crafting constructs with Alg-MC bioink, coupled with dermal fibroblasts, with the goal of expediting the healing process for extensive skin injuries.

In the realm of the NeuroBeta project [8], researchers used CELLINK LAMININK 521 bioink material to study the influence of microgravity on beta cells, a critical facet of diabetes research. Outcome of this study is still awaited.

In a recent development, in 2022 RevBio, Inc launched an experiment to study Tetranite®, the company's regenerative bone adhesive biomaterial, onboard the International Space Station (ISS).

Aim was to examine the biomaterial's ability to regenerate bone when used in a microgravity environment [9], outcome of study is awaited.

Opportunity for Research and Innovation

The unique environment of space offers many opportunities to create innovative technologies and materials that can benefit both space exploration and life on Earth. Microgravity, or the condition of near weightlessness experienced in space, is important for biomaterials research for several reasons:

1. Microgravity has a significant impact on the **behaviour of biological cells**. In the absence of gravity, cells experience reduced mechanical stress, sedimentation, and buoyancy. This allows researchers to study cellular responses, including cell differentiation, growth, and tissue formation, in a fundamentally different environment. This can provide insights into how biomaterials interact with cells and how they can be optimized for tissue engineering.
2. The microgravity environment can promote the formation of **more complex and three-dimensional tissues**. In traditional cell culture on Earth, gravitational forces can limit tissue growth and organization. In microgravity, tissues can develop with greater homogeneity and complexity, making it an ideal setting for studying tissue formation using biomaterials.
3. **3D bioprinting**, which combines cells and biomaterials to create complex tissue structures, can benefit from microgravity. The absence of gravity-related issues, such as settling and deformation of printed structures, makes it easier to produce precise and intricate tissue constructs.
4. Biomaterials are often used as platforms for **drug delivery and testing**. Microgravity can alter the behaviour of biological molecules and cells, affecting drug interactions and responses. This environment can be valuable for drug development studies involving biomaterials.
5. Research conducted in microgravity settings can have direct applications in space exploration. Biomaterials research in space can contribute to the **development of life support systems, bioregenerative habitats, and medical treatments** for astronauts on long-duration missions.
6. Insights gained from biomaterials research in microgravity can have significant implications for **biomedical applications** on Earth. Discoveries made in space can lead to the development of advanced biomaterials, tissue engineering techniques, and medical treatments for various terrestrial diseases and injuries.

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Metrology for in-space manufacturing

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Overview

In-space manufacturing provides unique material properties for use in terrestrial applications. Microgravity enables unique alloys and compositions, eliminates voids, and minimises defects[1]. Gallium arsenide production in space, explored since the 1980s[2], can provide benefits related to single crystal size and defect suppression[3]. Additive manufacturing in space is growing, with a plastics 3D printer on the International Space Station since 2014[4], and Airbus planning to launch a metals 3D printer in 2023 in preparation for a future "space factory" [5]. As humanity looks to explore the Moon and beyond, in-space manufacturing for space applications will grow in importance, with benefits including reduced costs[6,7], through reduced mass of spacecraft at launch.

Metrology, the science of measurement, provides assurance for the quality of a product, component or device. It identifies defects, enables process optimisation, and shows variations between, and within, samples. Metrology of a material's physical properties can be done in batch, off-line, and in-line, tailored to the individual product or production line. In-space manufacturing will eventually require production processes optimised for locally available, non-homogenous materials, and hence appropriate metrology solutions to ensure the viability, integrity and safety of space-made products.

Case Experience

The National Physical Laboratory (NPL), as the UK's National Metrology Institute, provides confidence in measurement results and data traceable to SI units, delivering detailed, independent analysis to accelerate development, increase performance and quality, and identify failure modes of materials, products or structures. For example, NPL's metrology capabilities have supported in-line characterisation of graphene nanoplatelet production to enable new quality assurance/control (QA/QC) techniques[8], and enables non-destructive examination (NDE) of mechanical wear and defect detection of manufactured components[9].

NPL's capabilities, which support UK manufacturing, may in time enable analogous technologies for in-space manufacturing. Manufacturing beyond Earth's orbit will likely utilise locally-available materials for long-term space exploration[10]. Lunar and Martian regoliths have been suggested as space-based materials to be utilised for longer term bases, e.g. as a "cosmic concrete" [11], although there are toxicity concerns about both materials[12, 13]. Lunar regolith includes rock chips, mineral fragments and Moon-unique agglutinates, in ratios varying significantly between samples[14]. In-space manufacturing utilising local raw materials will require metrology solutions, likely with remote- or self-calibration capability, throughout production:

- Space-based production would require characterisation of the raw material and after any processing steps(s), e.g. homogeneity of the material's chemical/mechanical properties. X-ray and optical-based spectroscopic techniques (e.g. Raman, EDS) could play an important role here.

- NDE to identify faults and fatigue of the final product will be crucial for both QA/QC and throughout the product's lifetime, especially for safety reasons. New techniques, such as resonant ultrasound spectroscopy, that are able to identify potential failure modes via non-destructive testing of 3D printed components could provide a solution.

Opportunity for Research and Innovation

For long-term exploration travel beyond Earth, utilising and manufacturing local materials with confidence while ensuring safety will be crucial. Innovation in metrology for space-based engineering of locally-available materials, processed locally on distant worlds, will provide confidence in the structural integrity and safety of products and processes, and the technologies to enable long-term presence beyond Earth. Translation, demonstration and optimisation of metrology capabilities for in-space manufacturing will benefit from close collaboration between NPL's world-leading metrologists alongside the UK's space sector to continue to grow the opportunities for the UK in space.

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A commercial solution for in-space manufacturing

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Overview

Microgravity has shown to be a very promising environment to manufacture various types of advanced materials more optimally than on Earth. This is primarily due to defects occurring during many ground-based manufacturing processes from gravitational forces such as buoyancy, convection, and sedimentation. These defects can ultimately affect a material's performance (strength, flexibility, conductivity, etc.). Manufacturing in microgravity could significantly decrease the number of defects in produced materials. This could also lead to microgravity enabling more efficient manufacturing processes compared to how materials are made on Earth. A recent study conducted by Butler University [1] compiled data from nearly 50 years of crystallization experiments done in space and concluded that >90% of crystals grown (both organic and inorganic) in the microgravity environment showed improvement in at least one of the key analytical metrics (size, structure, uniformity, resolution, mosaicity). These encouraging results demonstrate that additional manufacturing methods should be explored in space with the goal of full-scale production in Low Earth Orbit (LEO).

Case Experience

Currently, the main platform to conduct research in persistent microgravity is the International Space Station (ISS). However, the ISS will be decommissioned by the end of this decade and alternative solutions are needed. This is especially true for manufacturing of materials and products in space, as the ISS was never designed for full-scale manufacturing. In-space manufacturing has become a hot topic in the space sector, for both space and earth benefit. Focusing on the earth benefit, there is also an additional challenge of material return to Earth. Materials manufactured in space need to be safely returned to Earth for utilization, without the risk of fracture or other damage during return and landing. In addition to the crystallization work, other types of manufacturing have shown benefits from microgravity including 3D printing, electrodeposition, and chemical vapor deposition (CVD). However, for these manufacturing techniques to be fully utilized in space, a new solution must be made available over current offerings. Many commercial companies are in the process of developing platforms to support these initiatives.

Opportunity for Research and Innovation

Sierra Space is developing an in-space manufacturing solution through its LIFE™ habitat (Large Integrated Flexible Environment), which will become a main component of a commercial space station in LEO, as well as its Dream Chaser® spaceplane. The LIFE habitat infrastructure will offer the capability to experiment with and manufacture various advanced materials using the types of processes described above. This commercial platform will also contain state-of-the-art manufacturing equipment and analytical tools, compared with current ISS offerings. There is also the expectation this platform will function at times as both crewed and uncrewed. Unlike the ISS, which is fully crewed, the uncrewed option could provide the opportunity to conduct specific manufacturing processes without possible safety concerns for habitants, such as in high temperature manufacturing, etc. Additionally, the Dream Chaser® will be able to land on any compatible commercial runway worldwide, ensuring that materials produced in the LIFE™ habitat will be safely returned to Earth. These offerings tie directly into a key focus area for UK innovation in space. The UK Catapult has been a primary driver for establishing the Advanced Materials and Manufacturing Accelerator under the Business in Space Growth Network (BSGN). This accelerator will help drive new innovations in microgravity research and manufacturing by UK and European entities. This "complete solution" that will be offered by Sierra Space and its partners will vastly grow the opportunity to perform manufacturing (by UK organizations and others) in space to benefit life on Earth.

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Metasurfaces for thermal radiation control in space applications

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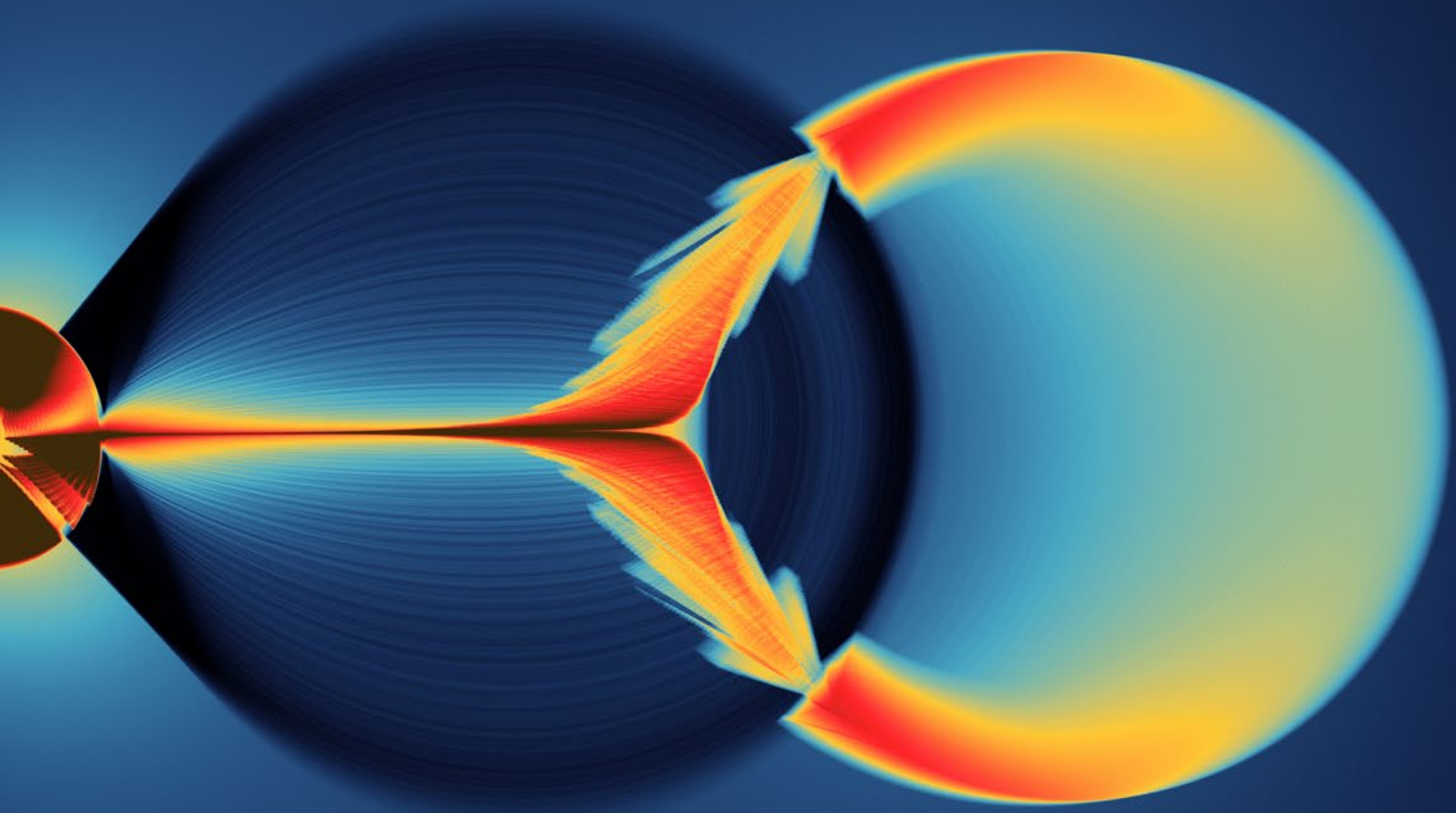


Overview

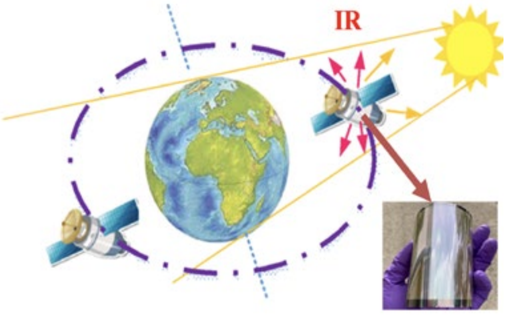
Thermal management of spacecraft is critical for the functioning and lifespan of on-board electronic systems; it has to be achieved in the form of radiative cooling through black-body emission as thermal conduction and convection are unavailable in the space vacuum. For spacecraft, radiative cooling is achieved using optical solar reflectors (OSRs) combining a low solar absorption to avoid heating up by the sun with high infrared emission for efficient radiative cooling[1]. Conventionally, OSRs are made of aluminium coated glass tiles, whose fragility and density impact both manufacturing and the launch costs. Consequently, novel designs are needed, ideally to provide flexible foil solutions with reduced weight and assembly costs. In addition, a smart OSR system with tunable infrared emissivity as a response to variations in temperature is highly desirable as a passive thermal management solution.

Case Experience

Researchers in Physics and Astronomy at the University of Southampton have recently completed two European Horizon 2020 projects for spacecraft thermal management named METAREFLECTOR and SMART-FLEX. These included the development and validation of two novel metal oxide metasurface-based optical solar reflectors (meta-OSRs) on flexible polyimide substrate, with the advantages of being lightweight and easy to assemble [1]. The first type of meta-OSR is based on a transparent conductive oxide, Al:ZnO, which has a low solar absorption ($\alpha = 0.12$) and high infrared emissivity ($\varepsilon = 0.76$) for radiative cooling [2]. The second type, a smart meta-OSR, is based on a thermochromic material ($W:VO_2$) which switches from a dielectric phase below room temperature to a metallic phase above room temperature, providing a tunable infrared emissivity for passive thermal management [3]. Through a comprehensive development involving structure design, material optimisation and fabrication process, the researchers demonstrated a smart meta-OSR with low solar absorption ($\alpha = 0.22$), high infrared emissivity contrast ($\Delta\varepsilon = 0.33$), room-temperature transition ($T_{trans} = 30^{o}C$) on polyimide substrate. Both OSRs are formed on 10 × 10 cm^2 polyimide substrates and have passed qualification tests including thermal cycling, ageing, bending and radiation, reaching TRL 6 [4,5]. As the next generation solution, these flexible OSR foils can significantly reduce the assembly cost and launch cost of spacecraft.

Opportunity for Research and Innovation

A thriving community of researchers and scientists in physics, material science, nanotechnology/nanofabrication exists in the UK. Through close collaboration with space industries, these UK scientists are able to provide novel solutions to existing issues and emerging challenges under ESA roadmaps, utilising extensive technologies and expertise developed over past decades in optoelectronics. These novel solutions provide opportunities for further cost reduction in assembly and launch, and new space explorations, such as Moon, Venus and Mars. The work being developed for space missions by UK scientists also has strong benefits for potential use in terrestrial industries. These materials and designs can also be used in existing applications, particularly in defence, aerospace, cars, energy and architecture, and their adoption can provide additional benefits, e.g. higher performance, higher energy efficiency and smart functions, with applications such as temperature regulation, energy saving and contributing to Net Zero targets.



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New in-orbit self-assembly principles and manufacturing techniques

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Overview

Many materials (e.g. different types of inorganic and organic alloys) in the liquid state consist of fine particles or droplets dispersed in an external (fluid) matrix. Once the effects of gravity are no longer felt, the different densities of the involved phases no longer represent a constraint forcing the dispersed particles or droplets to separate from the fluid through sedimentation or flotation; exploring self-assembly principles becomes therefore possible. Self-induced particle ordering is indeed emerging as one of the most relevant or promising approaches to develop in-space heterogeneous systems or materials consisting of parts that can recognize and bind to each other or form specific templates or patterns.

Case Experience

The author has almost 30 years experience in the exploration of microgravity phenomena and processes. Relevant examples pertaining to this branch of microgravity research at the University of Strathclyde are the JEREMI project, i.e. the Japanese European Research Experiments on Marangoni Instabilities (funded in UK by EPSRC) and the PARTICLE VIBRATION project (also known as T-PAOLA i.e. “Thermovibrationally-driven Particle self-Assembly and Ordering mechanisms in Low grAvity” (funded by STFC/UKSA) experiment (*www.t-paola.co.uk*).

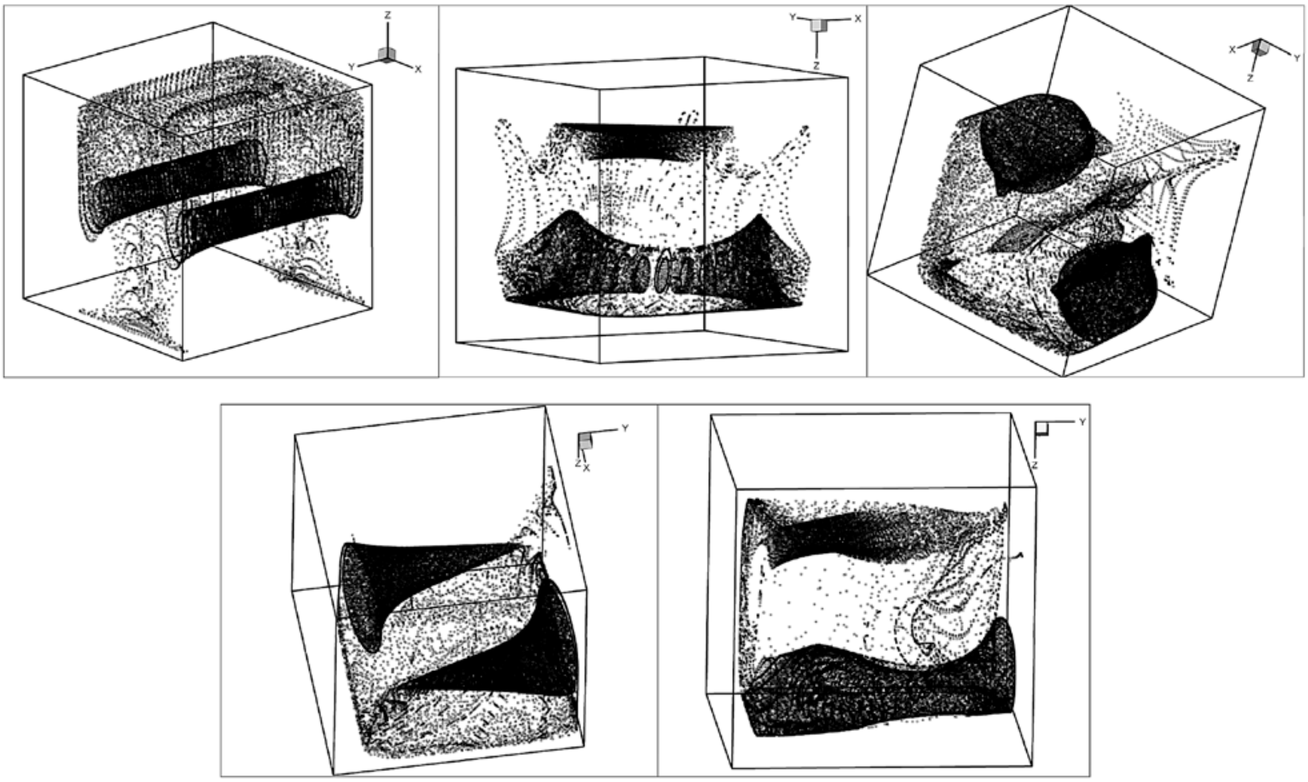

Figure: Examples of structures spontaneously formed by particles in a non-isothermal vibrated dilute liquid-particles system in microgravity (computer simulations).

These projects have been conceived to identify or define new concepts to manipulate matter on different scales and develop accordingly new contactless solid-particle manipulation strategies, i.e. novel methods to force particles dispersed in a fluid matrix to target certain regions of the physical space without touching them. In particular, while the former experiment relies on thermocapillary (Marangoni) effects, for the latter, the main mechanism driving macroscopic fluid flow and particle self-organization is driven by thermovibrational effects, namely, convection induced in a non-isothermal cubic enclosure by the application of vibrations with given frequency and amplitude. The PARTICLE VIBRATION experimental campaign (PI M. Lappa) was conducted on board the International Space Station from the beginning of February to the end of April 2023, resulting in a successful validation of the proposed vibration-based particle control approach. All the required experiments were executed using the Microgravity Science Glovebox (MSG NASA facility) in combination with the Selectable Optical Diagnostic Instrument (SODI, ESA facility).

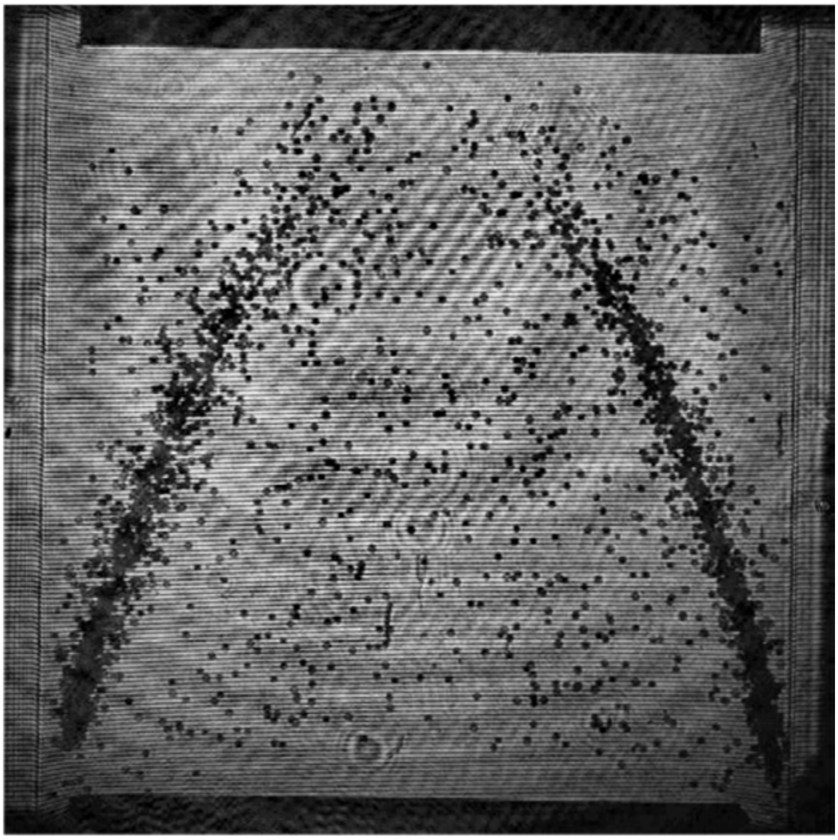

Figure: Side view of particle structures formed in microgravity conditions (T-PAOLA experiment).

Opportunity for Research and Innovation

The new level of understanding provided by these experiments conducted in space is opening the way to innovative applications in chemistry, physics, and biomaterials and inorganic materials science. The availability of a new method to control multiphase systems, which consist of a minority phase dispersed into a majority phase, will lead to improved and/or completely ‘new’ materials in space with properties that cannot be obtained on Earth. These include, but are not limited to, immiscible metal alloys, polymers composites, plastic materials and even many macromolecular substances used for the production of drugs and medicines (which are typically obtained in the form of seeds which nucleate in an external fluid phase). The new proposed technique based on the use of thermocapillary or thermovibrational effects can be regarded as a much more universally applicable method because, unlike other control strategies based on the application of magnetic or electric fields, it does not require the considered media to be electrically conductive or sensitive to magnetism.

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Ageing and lifetime assessment of composites for space applications

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Overview

Continuous fibre composites have outstanding specific stiffness and strength, making them excellent candidates for structural space applications. The combination of challenging environment and structural functions required of both polymer and metal matrix composites for space applications gives rise to a number of degradation and ageing mechanisms that limit component life. Our interest is in understanding, measuring, and modelling the effect that the combination of these mechanisms has on the performance and lifetime of a variety of continuous fibre-reinforced composites and hybrids.

Case Experience

The University of Surrey has extensive experience in selecting and modifying materials for space flight. This includes materials and coatings for flight hardware destined for particularly challenging environments, such as polymer membranes, thin composites, and inflatables for use in drag-deorbiting from low Earth orbit, see [1].

The School of Mechanical Engineering Sciences has a track record, going back many decades, in studying the fabrication, structural mechanics, performance and damage accumulation that occurs in polymer matrix composites during service. This includes seminal contributions on fatigue performance of composites, e.g. [2]. More recently this work has broadened to include parallel research on the manufacture and performance of metal matrix composites [3].

Surrey's expertise in Materials Ageing has recently been brought together under the umbrella of the Surrey Centre of Excellence in Materials Ageing, Performance and Lifetime Prediction (CoE). Recent research has explored the effects of temperature, pressure, and loading on moisture diffusion in polymer composites and correlated this with the subsequent degradation of the material and reduction in material properties [4]. A novel approach for the assessment of coating degradation for aerospace applications has also been developed, which would be applicable to space materials [5].

Opportunity for Research and Innovation

The CoE acts as a hub for engineers, chemists, physicists to work with key external partners, including AWE, dstl, NCC, NPL, Tisics, etc. Future priorities include validation of testing methods, correlating accelerated test data with in-service degradation and exploring the synergistic effects of a combination of degradation and ageing mechanisms. A particular interest would be developing a research focus in the synergistic effect of ageing phenomena to assess the combined impact of thermal fatigue and the flux of electromagnetic radiation on polymer composite performance and life.

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Magnetic fluid suspensions in microgravity environments

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Overview

Magnetic fluids such as magneto-rheological fluids and ferrofluids are a class of smart materials composed of magnetic particles dispersed in a conventional carrier liquid which find widespread use in many scientific and engineering problems. Recently, a range of new technological applications based of magnetic-amagnetic fluid pair systems exploiting the ability of the magnetic phase to target desired locations using magnetism for manipulation, transport and actuation guided by magnetic fields have appeared. While in the presence of micro-sized drops buoyancy is often negligible, at larger scales gravity becomes relevant and affects the dynamics of the system. Hence, a need has emerged to investigate the magnetic field-induced motion of large particles of magnetic fluids filtering out the effect of buoyancy through dedicated experiments in microgravity conditions.

Case Experience

In recent years, members of the James Weir Fluids Laboratory (JWFL) at the Department of Mechanical and Aerospace Engineering of the University of Strathclyde have started exploring systems constituted by ferrofluid drops surrounded by non-magnetisable liquids under the influence of magnetic fields [1,2]. It is well-known, in fact, that when a binary system of immiscible liquids, in which one phase is susceptible of magnetisation, is subjected to a magnetic field, a force appears at the interface. In the event of non-uniform magnetic fields, the force arising around a ferrofluid drop is uneven, and a net force propelling the drop arises. In order to investigate this mechanism in the absence of buoyancy and other gravitational effects, an experiment is being designed for execution on-board a parabolic flight or a sounding rocket. The experiment will consist of the observation of the motion of macro-sized ferrofluid drops subjected to a non-uniform magnetic field. A permanent magnet will be placed on one side of a container filled with a non-magnetisable liquid, while the ferrofluid drop is injected on the other side; the droplet motion will be recorded with a high-speed camera. The consideration of different drop sizes will allow the exploration of a wide range of conditions. These experiments might eventually be executed using the International Space Station if relevant calls or opportunities become available.

Opportunity for Research and Innovation

The magnetic field-induced motion of magnetic fluids droplets plays a crucial role in a variety of contexts of practical interest such as in lab-on-a-chip devices [3], microrobots technologies [4], in targeted drug delivery for cancer treatments and in electronic devices [5]. A comprehensive knowledge of the dynamics of these systems is therefore deemed necessary in many situations, and filtering out the effect of gravity provides ideal conditions for the investigation of the dynamics induced by the sole magnetic field. Owing to the multifaceted nature of the approach, and to the variety of conditions that will be considered, the study will provide a thorough understanding of the dynamics of magnetic fluids suspensions which will contribute to significant innovation in sectors relevant to mechanical, chemical, electronic, and biomedical engineering, with relevant repercussions on the growth of the UK's industrial assets.

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Aerodynamic materials for Very Low Earth Orbits

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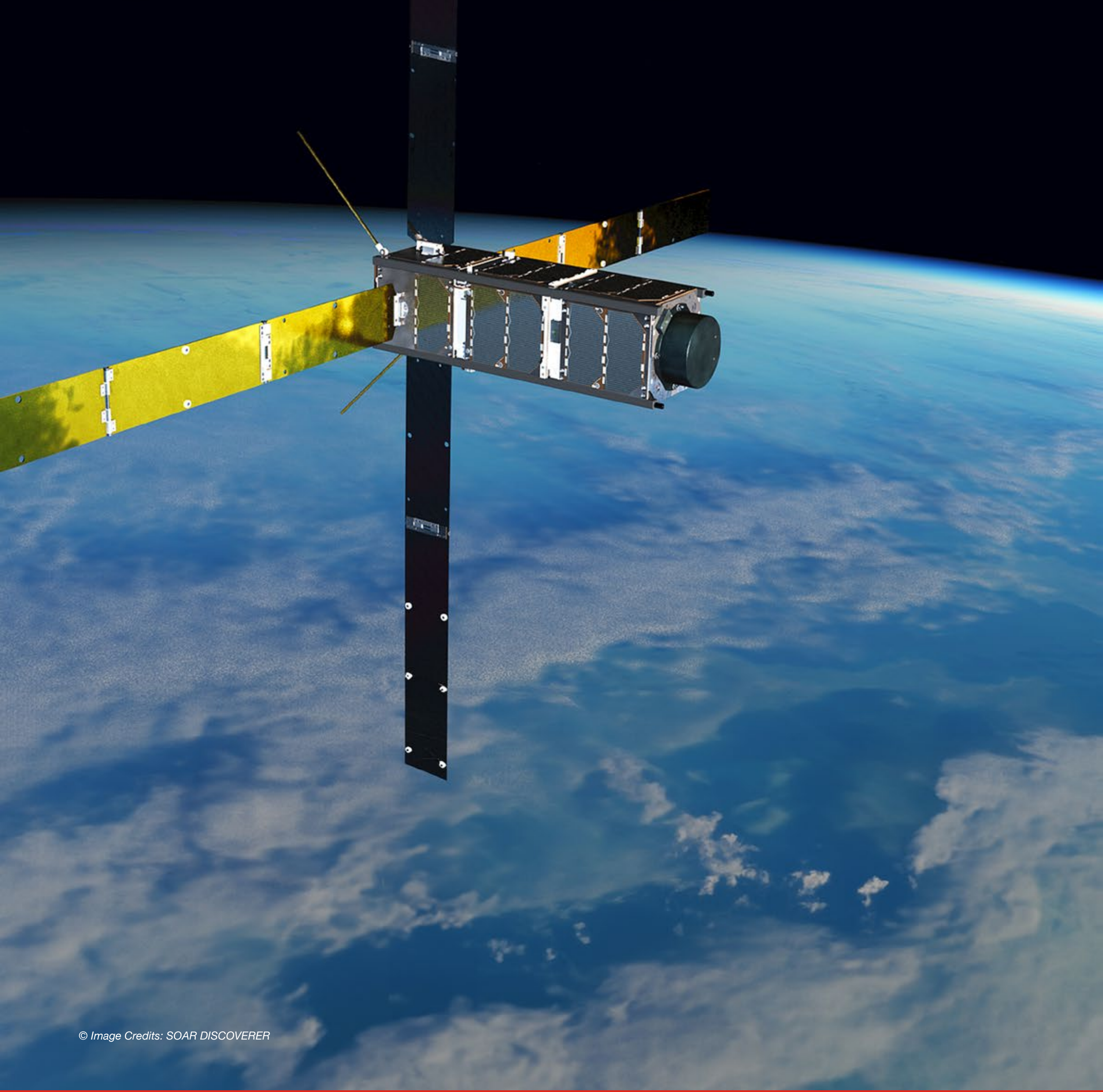

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Overview

Orbit altitude is a driving parameter in the performance of satellites used for communications and remote sensing. Operating communications satellites closer to the ground reduces the time taken for signals to be transmitted and received (reduced latency) [1], whilst remote sensing satellites can take higher resolution images or have smaller optics [2]. These application performance benefits are accompanied by reduced launch costs (rockets can launch more mass to lower altitude orbits), a more benign radiation environment, and satellites are pulled from orbit quickly due to increased atmospheric drag making lower altitude orbits uniquely sustainable [2]. Very Low Earth Orbit (VLEO), typically considered to be orbits below around 450 km, therefore have a great number of benefits, however atmospheric drag must be minimised and compensated for during the active life of satellites.

The nature of aerodynamics in VLEO, including drag, is considerably different from conventional aerodynamics. Whilst orbital speeds are very high, of the order of many kilometres per second, the atmosphere is also highly rarefied. Orbital aerodynamics is therefore driven by the interaction of individual gas molecules, particularly the predominant gas species atomic oxygen, directly with spacecraft surfaces. How the gas scatters from those surfaces determines their aerodynamic properties, and is known to depend on how smooth the surface is, and its material composition [3]. A new field has therefore opened in recent years, which aims to identify materials with preferential scattering properties that can be used to reduce drag in VLEO, and produce useable lift for aerodynamic control.

Case Experience

The University of Manchester has been involved in a number of activities to develop new materials with both good aerodynamic properties and atomic oxygen erosion resistance, and methods to characterise their scattering properties. Building on our fundamental research on gas flows through nanochannels made from graphene and other 2D materials, we have developed practical coatings containing these nanoflakes, optimising for both specular reflection and resistance to atomic oxygen erosion through passivation. We have explored both “top down” assembly and “bottom up” growth methods for the fabricating these coatings, allowing us to probe the effect of roughness across all scales.

Characterisation approaches have included the development of ground-based atomic oxygen beam scattering facility, the launch of a satellite to directly measure the induced aerodynamics of different materials, and the exposure of materials samples on the exterior of the International Space Station. However, the strongest case for these materials would be the on-orbit demonstration of drag minimisation on a VLEO satellite as part of an operational mission.

Opportunity for Research and Innovation

The use of VLEO for communications and remote sensing has significant potential performance and cost benefits. These can only be realised if the commercially viable, sustained operation of satellites in this lower orbital range can be enabled by new technologies including aerodynamic materials. The fact remains that these developments are in an early stage, and investment in foundational research is needed to improve characterisation, and carry out in-orbit demonstration of key technologies to make commercial VLEO use a reality.

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Solidification science under microgravity conditions

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Soyuz TMA-1 spacecraft transfer to the launch site

Credits: ESA - S. Corvaja

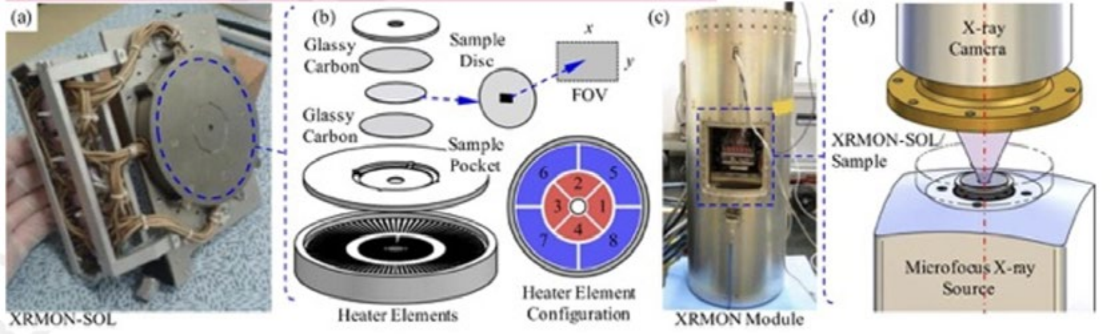

Figure 1: In situ X-ray diagnostics configuration inside the XRMON module (source:[1]*)*

Overview

Solidification is a key step in the processing of metal alloys. Whether it is the case of a mould filled with liquid metal to produce a cast component, a permanent joint created by fusion welding between metal plates, or a complex component printed from metal powder by laser-based additive manufacturing, all of these processes depend on a successful solidification step to generate the solid structure from liquid. In the liquid condition, mass and heat transport occur by thermo-solutal convection and diffusion. Understanding of both of these phenomenon, liquid convection and diffusion, are key to a full understanding of microstructure development during solidification. However, on ground, with gravity being inherent, convection and diffusion are inseparable. During microgravity, the thermo-solutal, buoyancy-driven convection is suppressed; hence, diffusion-controlled solidification occurs in isolation. By comparing with ground data, differences in the solidification behaviour under similar conditions are attributed to gravity-driven convection. Theories in crystal nucleation and growth begin with an assumption of diffusion-controlled behaviour with further thought given to the effects of convection as conjecture. Crucially, microgravity conditions achieved under freefall or during planetary orbit provide the means to conduct solidification experiments that validate fundamental theories of diffusion-controlled nucleation and growth. An example of cutting-edge research in microgravity solidification research is in-situ x-ray characterisation of thin samples that has provided video sequences of dendritic nucleation and growth in a grain-refined aluminium alloy. Figure 1 shows an example of a furnace X-ray diagnostics capability that was flown during a microgravity campaign onboard the MASER 13 sounding rocket as part of the XRMON project [1]. This research was able to capture the temperature-controlled nucleation, growth, and impingement of Al-Cu dendrites grown under microgravity conditions.

Case Experience

Dr McFadden has been involved with solidification microstructure model development that has benefitted directly from bespoke microgravity experimentation onboard soundings rockets (MAXUS and TEXUS) and the International Space Station (ISS). In particular, he has developed a new theoretical approach to modelling nucleation and growth in alloys [2,3] called the Nucleation Progenitor Function approach. This was successfully applied during an EPSRC feasibility study to the problem of grain refinement in aluminium alloys [4]. A new model of the Columnar-to-Equiaxed Transition was developed using experimental data from experiments conducted on the ISS [5].

Opportunity for Research and Innovation

Ongoing research in this area will accelerate and uncover fundamental understanding in key areas of alloy solidification that are yet to be fully understood, such as the impact of the so-called ‘silicon poisoning’ effect that occurs in the great majority of grain-refined aluminium alloys used in industry. (Grain refinement is used extensively in aluminium processing to give stronger and higher quality castings, but is a highly inefficient process.) Studies of diffusion-controlled nucleation and growth in primary and recycled metals will lead to better understanding of the problems that occur during reprocessing of alloys (for example, the deleterious nucleation of intermetallic Ferrite inclusions in aluminium). Diffusion-controlled experiments in metals of sufficient duration can only be conducted under the microgravity conditions of Space. If dedicated funding, for example PhD studentships, could be identified then this would help leverage the existing significant spend on flight hardware, experimentation, etc. If additional funding could be identified then this would maximise research output to the benefit of the metals processing industry, especially the solidification processing industry.

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Cellular agriculture for food production in space

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Overview

Currently, a recurring supply of provisions are necessary to sustain the crew onboard the International Space Station. Up-mass availability is a current bottle neck for ISS research with shipments of prepackaged food impacting the available cargo volume which could otherwise be allocated to experiments. To tackle this, a new area of interest is on-orbit food production. Having the capability to produce nutrient-rich food in-situ increases the self-sufficiency of, e.g. a lunar outpost, which is key to long duration space travel. Cellular agriculture or "lab grown" meat is the cultivation of animal (I.e. Cow, Pig, Chicken and fish) muscle cells in bioreactors for human consumption, requiring significantly less resources kg for kg when compared to traditional farming techniques. For space habitats, conventional methods of livestock rearing is unlikely to be viable, hence cellular agriculture represents a promising alternative with clear downstream terrestrial benefits..

Case Experience

In partnership with ESA and STFC three UK industry specialists spanning Cellular Agriculture, Space and Food and Drink, have assessed the viability of cellular agriculture and through modelling, sized a theoretical system utilizing a hollow fibre bioreactor (HFB) capable of providing the nutritional protein requirements of a crew on long duration space missions. A miniaturized HFB breadboard was then produced with existing space hardware and packaged into an ISS interface container as a proof of concept for a cellular agriculture ISS experiment.

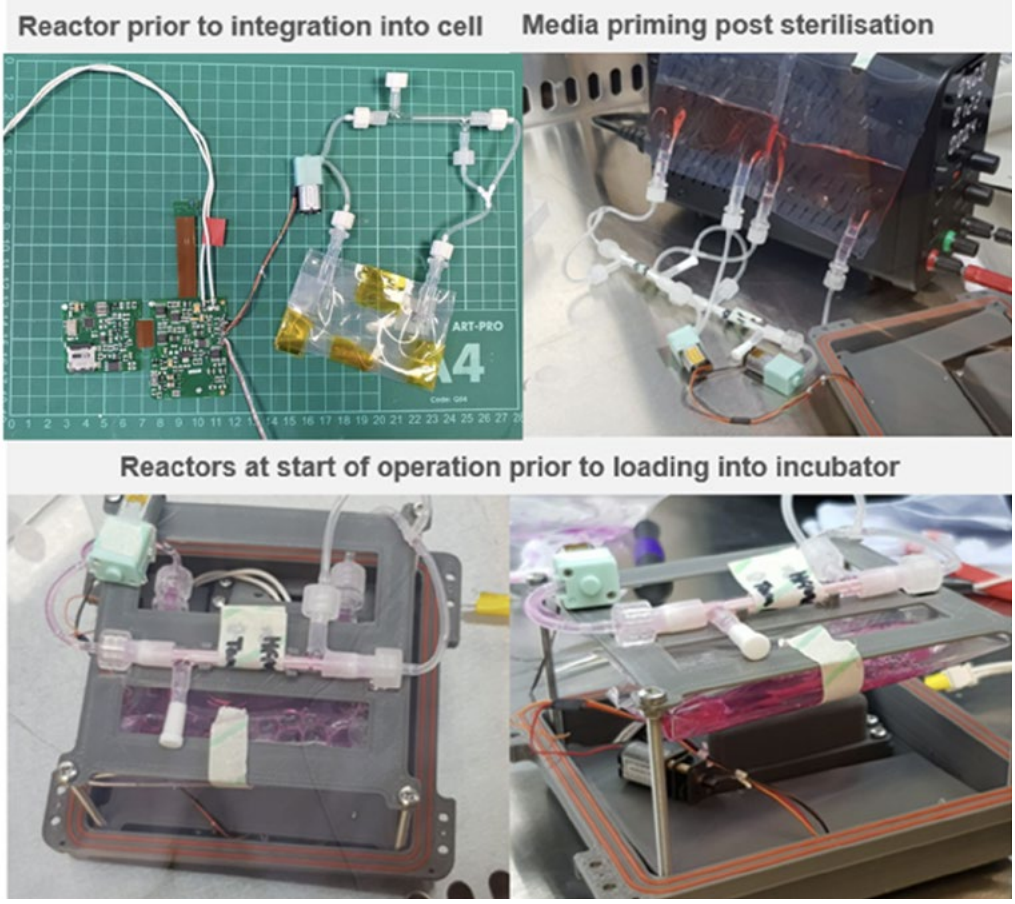
An early pioneer in the bioprocess field for the production of cultured meat is Cellular Agriculture Ltd. Aligned with researchers at the University of Bristol they have developed novel hollow fibre substrates and have characterized the growth of cells in such systems. Their role focused on the conceptual design and optimization of the bioreactor bioprocesses. Producing a system which met the astronaut's nutritional requirements while maintaining a minimalistic operational footprint.

Kayser Space is specialised in the design, manufacture and verification of payloads and systems for microgravity-based research. The engineering competencies was essential for ensuring the selected cellular agriculture technology and the implementation of its technologies were capable of operating within the constraints of the space environment while maintaining the stringent safety requirements of crewed vehicles.

Campden BRI, an independent Research & Technology Organisation provides consultancy, training and analytical services to the food and drink industry. Their involvement was key to understanding and identifying the nutritional content of different livestock cells suitable for a nutritiously dense product.

Opportunity for Research and Innovation

The space industry is renowned for working to stringent requirements, ultimately leading to space hardware that is miniaturized, automated, robust and reliable. These attributes are essential for a successful cellular agriculture system to provide in-situ high quality nutrition to astronauts of a lunar or Martian outpost. Immediate challenges revolve around the development of efficient culturing mediums to tailor cultured meat into being more nutritious than conventional meat. At the same time mediums needs to be ethical with the introduction of sustainable growth factors. Engineering solutions that reduce the footprint, consumables and crew-time of a space-based system are directly transferable to terrestrial applications and may springboard cultured meat scale-up, enabling it to achieve price parity with established industries. The Earth is experiencing excessive deforestation along with frequent climate disasters impacting food production, exacerbated by the demands of a growing global population. Cultured meat offers the opportunity to address future world food security with a scalable food source which is both ethical and sustainable. The combined expertise of this partnership, with the backing of organizations such as ESA and STFC, could be key in securing this technology's future sooner rather than later, positioning the UK as a leader in this emerging field.



Reactor prior to integration into cell

Media priming post sterilisation

Reactors at start of operation prior to loading into incubator

Evolution of in-orbit manufacturing: A new frontier in space

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Overview

The development of in-orbit manufacturing, a major component of In-Orbit Servicing and Manufacturing (IOSM), is poised to reshape the landscape of space exploration, enabling the construction of complex structures and systems in the space environment. It has the potential to reduce the need for costly launches, minimise payload constraints, and improve the overall sustainability of space missions. This paper will provide an overview of the evolution of in-orbit manufacturing, discuss certain examples, and identify opportunities for further research and innovation.

In-orbit manufacturing has its roots in the 20th century, with early research on the Skylab mission focusing on the feasibility of producing materials in microgravity. Since then, technological advancements have enabled the development of various manufacturing methods, including additive manufacturing, and robotic assembly. A key driver behind the growth has been the increasing demand for space infrastructure such as communication satellites, scientific instruments, as well as scoping for future projects with space solar bringing an unprecedented scale.

The emergence of commercial space ventures has also played a significant role in the evolution of IOSM. Companies such as Northrop Grumman and Made in Space (now Redwire) have invested in the development of relevant technologies and demonstrated their potential through various missions. As a result, the industry is witnessing a shift in appetite from traditional manufacturing methods to in-orbit production and assembly.

Case Experience

Several notable IOSM missions have been undertaken in recent years, showcasing the capabilities and advantages of this technology. Redwire, for example, has launched multiple 3D printers to the International Space Station (ISS), successfully manufacturing a range of polymeric tools and components in microgravity [1].

Others are the OSAM-1 and 2 missions led by NASA and partnered by Tethers Unlimited and Redwire respectively, these are not expected to launch before 2024 [2,3]. OSAM-1 will look to manufacture structural components in-situ with composite materials, whilst OSAM-2 will look to utilise robotic systems to assemble large structures in orbit. These complimentary missions aim to demonstrate the feasibility of constructing space infrastructure in-situ, reducing the need for heavy and expensive launches from Earth.

Additionally, the European Space Agency's (ESA) Metal3D project aims to develop closed-loop life support systems that can convert waste into valuable resources, enabling long-duration missions and reducing the reliance on supply from Earth [4]. These case experiences highlight the progress and potential of in-orbit manufacturing technologies.

Opportunity for Research and Innovation

As in-orbit manufacturing continues to evolve, there are numerous opportunities for research and innovation. Key areas of interest include:

- Advanced materials: Developing new materials with enhanced properties, specifically designed for use in space, can lead to the construction of more efficient and robust space infrastructure.
- Automation and robotics: The development of advanced robotic systems and artificial intelligence can improve the efficiency, precision, and scalability of in-orbit manufacturing processes.
- Modular and reconfigurable systems: Designing modular and reconfigurable space infrastructure can enable adaptability to different mission requirements and facilitate upgrades, repairs, or repurposing.
- In-situ resource utilisation: Exploiting resources available in space, such as regolith from asteroids or the Moon, can

reduce reliance on Earth-based materials and promote sustainability. The lunar surface is receiving arguably the greatest interest currently, through the Artemis programme which looks to create sustainable infrastructure for future missions, and private organisations such as ispace looking to provide alternatives.

The space sector has ever-improving knowledge, technology, and experience through each mission it facilitates, simultaneously, what would be traditionally terrestrial applications are also improving. With the assistance of the UK's Catapult network, non-space organisations can break into this emerging sector by forming partnerships with established space companies, leveraging their expertise in areas such as advanced materials, robotics, and/or advanced manufacturing. Additionally, they can explore technology transfer opportunities, adapting their existing technologies for the unique challenges of manufacturing in the space environment.

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High Entropic Inorganic materials in micro-gravity

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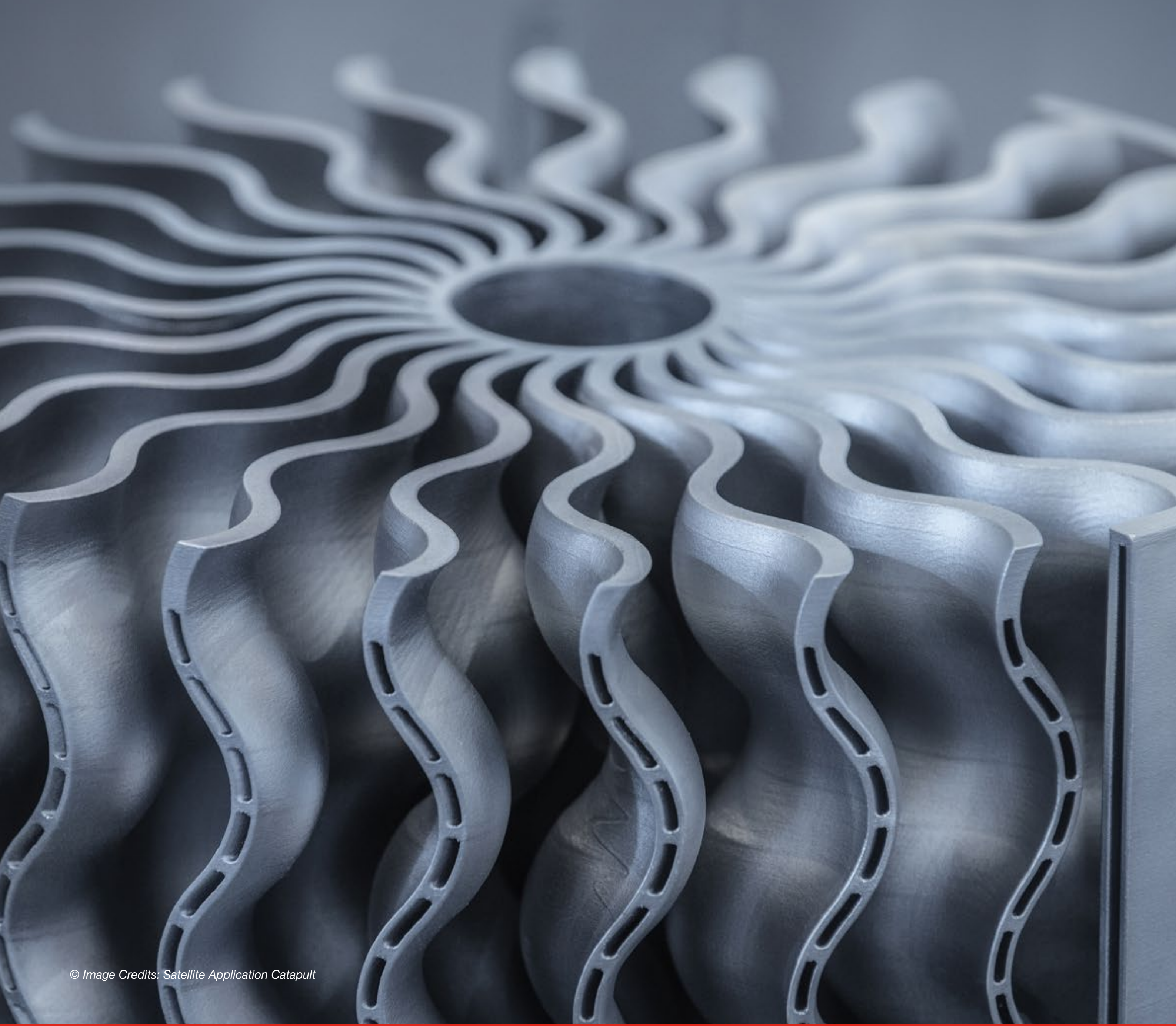

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Overview

Stable inorganic solid state compounds traditionally minimise their free energy, thus maximising the magnitude of the enthalpic term, by making strong bonds in an ordered crystalline lattice. Disorder is accepted in some instances to increase the entropic term such as defects, etc. However, in general, the presence of high levels of disorder in traditional crystalline materials can create poor quality structures. High entropy materials form a new area of study which defies traditional views, utilising increased disorder to minimise their free energy. The synthesis of high entropy metal sulfides and oxysulfides by the molecular precursor approach within microgravity could lead to materials with maximised entropic disorder, culminating in perfect high entropy materials.

Case Experience

Gravitilab Aerospace Services and the University of Manchester are currently conducting research into the field of inorganic high entropy compounds. These are a new class of extremely exciting materials being considered currently as candidates for a range of different applications in physics (superconductors, optoelectronic materials), materials science (battery materials, thermoelectric materials, nanomaterials), and chemistry (catalysis, electrocatalysis), often because they have novel and often unexpected properties with transformative performance in applications.

The overarching aim of this study is to produce, for the first time, high entropy metal sulfides and oxysulfides that exhibit perfect disorder on the metal sub-lattice that will be considered as paradigm materials for benchmarking. Enabling researchers to produce high entropy sulfides and oxysulfides in microgravity from the molecular precursor approach will allow the comparison of material synthesised in gravity and in microgravity at a fundamental physical level.

The microgravity element of this study will be provided via the use of ISAAC, a suborbital rocket developed by Gravitilab Aerospace Services. The sounding rocket will achieve a high enough altitude to deliver microgravity at a quality level of 10-4 to 10-6 over a 5 minute duration. The material samples will be sandwiched between heating plates within a payload container designed by Gravitilab to rapidly heat the material within an atmospherically controlled microgravity environment. The precursive steps to this are defined as being laboratory derived testing in normal gravity conditions (i.e. 1g), within an environmentally and atmospherically controlled unit whereby the material samples are heated to a specified temperature rapidly as with molecular precursor approach, rapid decomposition occurs from the melt state. The samples are then recovered and analysed to explore crystallisation in microgravity vs that of the lab at normal gravity.

With this development and research accelerating in this field, it is the correct time to produce a ‘standard’ category of materials so that the native properties can be clarified and studied, enhancing applications, and identifying new ones. This work has the potential to become a landmark study for many existing research areas and in those areas not yet discovered.

Opportunity for Research and Innovation

Within the UK there is a flourishing network of scientists focused on growing our understanding of materials and developing new and innovative materials for novel uses. This network is hugely active within the space industry and is considered to be at the forefront of materials science, contributing to the wider space sciences, as well as more terrestrial adaptations. unique pockets of knowledge and research areas have formed across the UK, helping guide and mentor many of the early-stage career scientists, but access to many of the facilities can be restrictive. Unburdening the supply chain through unrestricted access to services such as short duration microgravity, opens the pathway to develop these novel materials and manufacturing processes, which is a precursor to in-orbit manufacture, and proof of concept experiments for longer duration flights. These services accelerate the development of materials leading to higher performing and advanced materials, for space, aerospace, and other terrestrial applications in civil and defence areas.

The end use of these materials developed within microgravity will ultimately lead to increased longevity and structural integrity of materials, reduce the bottleneck currently being exhibited within the supply chain, bettering the social and economic landscape through faster, more economical technological developments.

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In-situ production of thermal management structures

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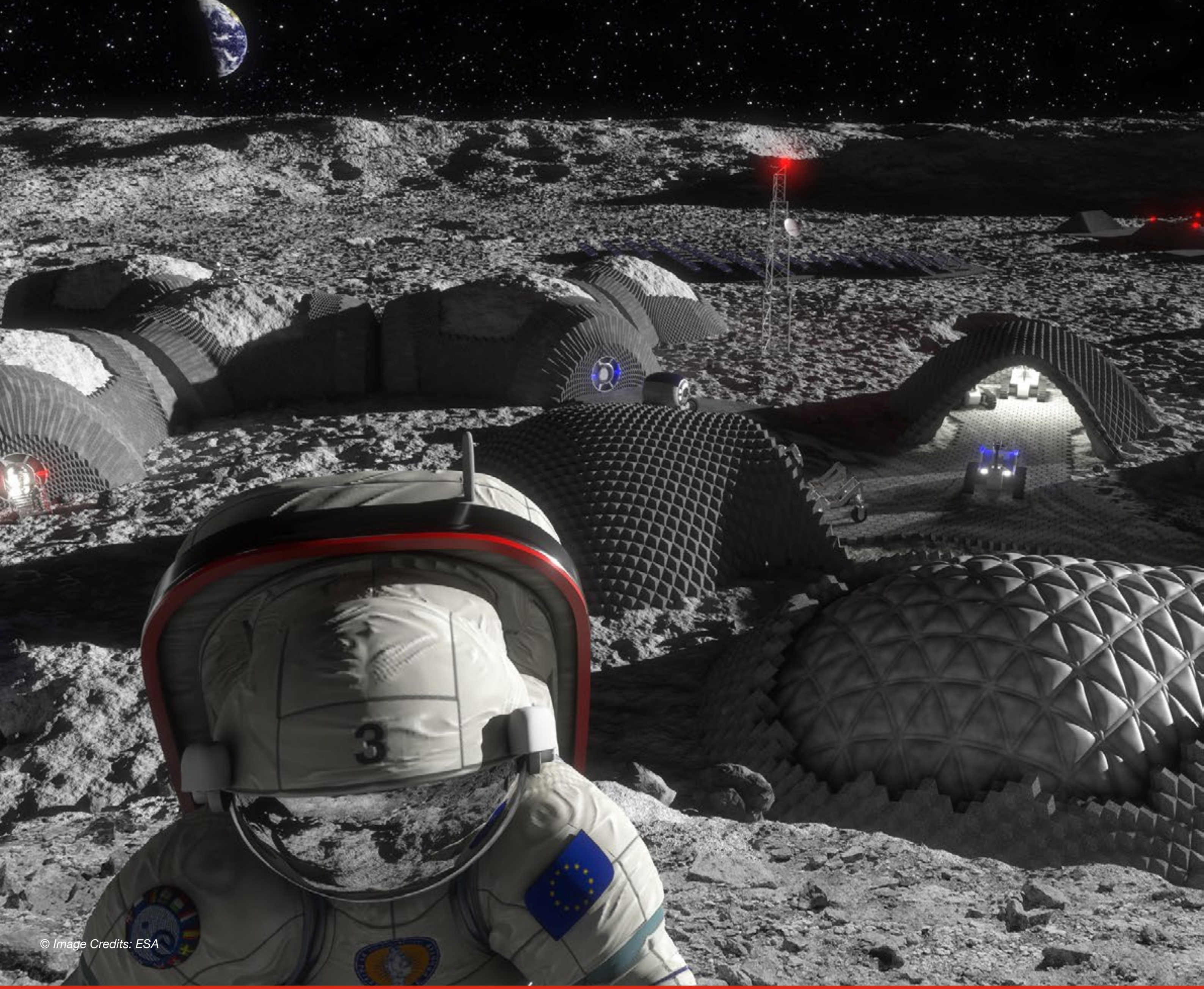

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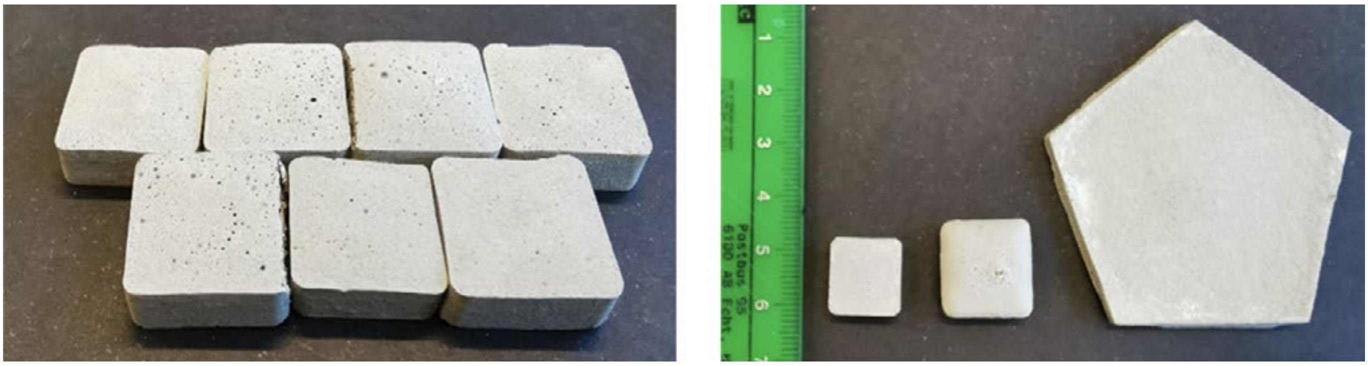

Aerogels with 20% of simulant lunar regolith tiles (left), size and shape variety of aerogels with simulant lunar regolith

Overview

Ideas such as human permanence on the Moon and Mars, water extraction from shadowed craters, oxygen production from lunar regolith, in-situ food production, and mineral extraction for metal processing have begun to transition from being purely futuristic to tangible realities. In order to enable long-term exploration, it is critical to develop structures constructed with ISRU (In-Situ Resources Utilisation) of raw materials that can shield human and robotic lunar and Martian explorers from intense radiation levels, abrupt and severe thermal gradients, and, in the case of the Moon, an absolute environmental vacuum [1]. The execution of these endeavors will necessitate the installation of power systems equipped with storage capabilities and thermal management systems that enable us to address the insufficiency (or surplus) of heat produced or absent on Mars during lunar days and seasons.

One of the main challenges comes from the lunar nights which last almost 14 Earth days on its equator, less on the lunar poles, and implying temperature drops to below -150°C which is an unacceptable value for the survival of electronics and human settlements. The Martian winters share similar harshness and robotic missions are often obliged to a period of hibernation. Aerogels using In-situ resources available on the Moon and Mars soil have been investigated in literature only recently. However, a complete econometric analysis has not been achieved for the difficulty in evaluating the processing costs and the feasibility of a closed production loop in the real Lunar and Martian environment.

Case Experience

Currently, the production of regolith-based aerogels is a research topic already ongoing in collaboration with the University of Cambridge. The research is also part of the ESA Co-Sponsored Research Agreement “Passive Protective Shields for lunar and Martian outposts”.

The research focuses on creating a passive thermal and radiation shield for surviving lunar night conditions and Martian winters [2-5]. We propose an innovative approach using pristine regolith and a freeze-drying process that exploits the Lunar and Martian conditions. The objective of the research and innovation initiative is to produce composite materials that can be constructed on-site with minimal or no Earth material input and extensive reuse of finite resources, including water [6,7]. Additionally, the utilisation of the composite material will facilitate a more direct functionalization of the distinct layers, which will initially be investigated in isolation and subsequently combined in order to ascertain their combined efficacy.

Opportunity for Research and Innovation

Impact on Space Exploration: The issue of exploration is addressed in the ESA Agenda 2025 “Make Space for Europe” by referring to the Terrae Novae Strategic roadmap. In the words of the ESA: “ESA will engage in a large robotic mission to the Moon’s surface to reinforce European exploration identity and strategic autonomy”. Following the ESA strategic roadmap, this research pathway will contribute to gains in understanding the field of thermal control of Lunar and Martian exploration systems, including robotic exploration and human settlements’ preparation. Lunar nights and Martian winter’s conditions will serve as a reference case to test new and improved composite materials whose building blocks could be mainly manufactured in situ by using local available resources.

Technology and innovation opportunity: From an ISRU standpoint, the development of new and improved materials is the driving force behind the development of novel closed-loop processing cycles that address the paucity of accessible resources in the Space environment. Water recovery and recycling from processing, energy harvesting and conversion optimization, robotic manipulation, and adaptive modelling for processing optimization will be critical areas of innovation.

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Additively manufactured Inconel 718 for high heat flux applications

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Overview

Inconel 718 is a nickel superalloy which retains exceptional strength and corrosion resistance characteristics at high temperatures. These properties make the material an excellent candidate for rocket engine combustion chamber and sub-system components. However, the material's high hardness and low thermal conductivity have posed significant challenges to conventional machining techniques, impeding its widespread adoption.

Fortunately, recent advancements in additive manufacturing have emerged as a promising solution to overcome these obstacles. Notably, the compatibility of Inconel 718 with Selective Laser Melting (SLM) has proven to be highly advantageous. This non-traditional fabrication technique enables the production of intricate part geometries and can precisely manufacture complex internal features. By leveraging these innovative additive manufacturing techniques, netshape production of complex component geometries using Inconel 718 has become attainable, revolutionizing its application in the space propulsion industry.

Case Experience

Through the InnovateUK Edge Program, the Satellite Applications Catapult has utilized its in-house SLM facilities to fabricate a variety of research and development thrust chambers utilizing Inconel 718 for propulsion organizations across the UK and Europe. The large build volume (420 x 420x 400mm) of the machine has enabled as many as 9 thrust chambers to be fabricated within a single batch, dramatically reducing manufacturing times compared to conventional methods. The thrust chambers have been specifically tailored by each organization, with many demonstrating performance across a range of propellant combinations and withstanding rigorous hot fire testing [1].

Within the broader space industry, additively manufactured Inconel has found application in several prominent rocket engine programs. Notably, SpaceX has leveraged this advanced material in their SuperDraco engines [2], integral to the Dragon Spacecraft. Similarly, RocketLab has incorporated additively manufactured Inconel into their Rutherford engines, which power the Electron rocket's first stage. These high-profile deployments exemplify the confidence and trust placed in Inconel 718 for delivering exceptional performance and reliability in critical space missions.

Opportunity for Research and Innovation

The use of additively manufactured Inconel 718 presents several exciting opportunities both in the space environment and within the wider terrestrial market.

Within the space industry, the widespread adoption of additively manufactured Inconel 718 is enabling drastic reductions in part count and production times of propulsion system components. The advantageous properties of the material allow spacecraft and launch vehicles to reduce complexity and weight, with this increased performance enabling more ambitious missions, higher payload capacities, and improved flexibility and safety. New research in the area is investigating the relationship between the manufacturing process, microstructure, and resulting mechanical and thermal properties. Challenges that need to be addressed are the optimization of the manufacturing process, assurance of material consistency, and validation of the performance under extreme conditions, which is often conducted through hot-fire testing with operationally representative thermal and stress conditions.

Extending beyond the realm of space exploration, Inconel 718 is a top candidate for several industrial applications, such as gas turbines, power generation, and high-temperature chemical processes. The improved manufacturability enabled by additive manufacturing is being spearheaded by the space industry but presents an opportunity to improve energy efficiency, reduce emissions, and enhance overall system performance within these markets. These industrial benefits translate into wider benefits such as stimulating economic growth through increased manufacturing opportunities, job creation, and the establishment of a robust supply chain.

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Picture credit: LIA Aerospace (Sourced by the authors)

Infrastructure for advanced material fabrication in space

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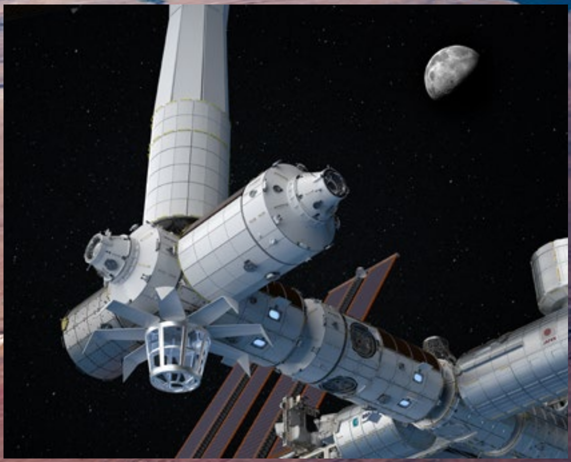

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Overview

To enable advanced material fabrication in a space environment, it is essential to establish a robust infrastructure that can host power and data-intensive capabilities. Commercial space stations will play a crucial role in providing the necessary facilities and resources to support the growth of new market segments for advanced materials in the rapidly accelerating space economy. The space industry is at an inflection point, with a landscape that now includes a growing number of commercial companies stepping in and driving activities that previously were conducted only by government agencies. A key element of in-orbit capabilities will be to design with modularity and sustainability at the forefront. This will allow for the fabrication and processing of a wide range of advanced materials like metals, polymers, composites, and biomaterials that support a wide variety of industries and applications. This adaptability will enable rapid innovation and identification of advanced materials that foster development of sustainable new markets in the expanding space economy. Together, these measures could pave the way for a robust infrastructure for advanced materials manufacturing in countries like the UK, who can leverage initiatives like the Catapult Network and the UKRI to foster international partnerships and cross-sector collaboration to enhance the growth of this sector and reinforce its position as a key player in the space economy.

Case Experience

Axiom Space is building the world's first commercial space station in low-Earth orbit to support the growing commercial, civil, and future governmental space ecosystem. Awarded exclusive use of the docking port on the International Space Station (ISS), Axiom Space is the only company with the privilege of connecting its station modules to the ISS. This arrangement will allow a seamless, cost-effective transition that will continue to facilitate discovery research and commercialization in space for the private and public sector. Subsequent modules, including a dedicated research and manufacturing facility module, AxRMF, and external payload facility will be added before the ISS is decommissioned at the end of the decade. The AxRMF will be equipped with state-of-the-art manufacturing and in-situ analytical capabilities to support the discovery, development, and scaled production of products that stand to change the paradigm of advanced materials manufacturing and foster sustainable growth of the LEO commercial space economy. Once constructed, Axiom Station will separate when the ISS is decommissioned and form the foundational infrastructure enabling a diverse economy in orbit, serving nations and private entities, researchers, product developers, manufacturers, and media. Axiom Space is currently working with customers to explore in-space production of bulk crystals and defect-free fiber optics. Initial proof-of-concept studies to be conducted on the ISS include: 1) Testing the production of larger semimetal-semiconductor crystals in microgravity, with perfectly aligned semimetal wires embedded in the semiconductor matrix. If successful in eliminating defects found in earth-made materials, our partner will have a new method for creating device-ready wafers from space-grown crystals. 2) Developing hardware to make Heavy-Metal Fluoride Glasses (HMFG or commercial name ZBLAN) in microgravity for use in advanced optical fibers and optics. Without earth's gravity, it's expected for these HMFG to have the perfect amorphous structure, eliminating defects that limit power and long-distance transmission. Additional active projects include 3D printed biomaterials and biocompatible nanomaterials.

Opportunity for Research and Innovation

The space economy is projected to grow to $1 Trillion by 2040 [1]. Axiom Space anticipates that in-space manufacturing of advanced materials in LEO will play a crucial role in enabling this growth, especially semiconductor manufacturing, energy harvesting/storage and quantum computing, among other areas yet to be defined. Axiom Station will provide a platform for true innovation, discovery, and manufacturing as a replacement to the ISS, serving the needs of industries that previously have not been traditional participants in the space industry. While supporting growth of a robust space economy, commercial infrastructure provided by Axiom Space and others stands to accelerate exploration initiatives for both private and government agencies, and secure continued US and International leadership in the space domain. Commercial space stations can also underpin technology development, on-orbit demonstration, and operationalization of capabilities in large-scale assembling of prototype space-based solar power infrastructure and other advanced orbital infrastructure for emerging applications of interest to the UK in robotics, space debris remediation and recycling, space nuclear, and in-orbit servicing and manufacturing (IOSM).

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Space-induced polymer degradation mechanisms for medical applications

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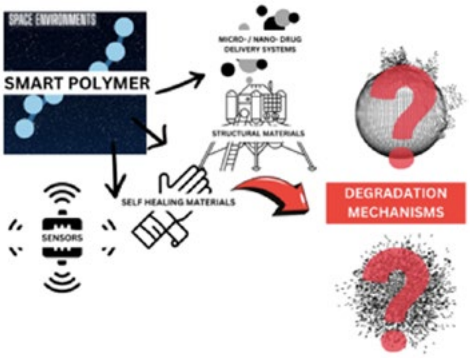
Overview

SMART polymers are stimuli-responsive, high-performance, intelligent materials that respond to changes in their environment [1]. Their adaptability has made SMART polymers an indispensable component in various fields, including medical and space systems [2,3]. SMART polymers are used in medical applications as micro- and nano-drug delivery systems and as scaffolds for tissue engineering applications [4]. In space, polymers and SMART polymers are used mainly in construction due to their favourable mechanical, thermal, electrical, and optical properties [5,6].



Spaceflight imposes multiple challenges, not only on the human body but also for materials in constructing spacecraft [7,8]. For humans, time in the space environment leads to increased exposure to radiation, as well as the effects of confinement, isolation, changes in circadian rhythm, and stress [9,10]. An additional health concern during prolonged spaceflight is increased susceptibility to infection due to altered immune systems, due to differing atmospheric climates [11]. To address this specific health concern, new formulations may be needed, which can ensure anti-infective drugs stay within a therapeutic window which may be different to those on earth. New drug delivery systems to allow controlled or prolonged release of anti-infective agents in response to stimuli experienced in space could be explored.

It is well known that polymers can undergo degradation due to irradiation but the specifics of these degradation mechanisms in extra-atmospheric conditions are relatively under explored. This creates an opportunity for the development of next-generation SMART polymers with improved and tailored properties for space environments. These next-generation SMART polymers will have multipurpose functionalities and applications in a variety of fields including medical and construction.

Case Experience

A cross-disciplinary collaboration led by Dr Bahijja Raimi-Abraham (King's College London) alongside Professor Cameron Alexander (University of Nottingham), Professor Clare Hoskins (University of Strathclyde) and SpacePharma seek to develop multipurpose next-generation SMART polymers that can resist space-induce degradation whilst maintaining their advantageous properties. Aspects of the team's work will build up on some previous NASA and ESA innovations [12-14]. SpacePharma has developed comprehensive, miniaturized lab systems equipped with sensors and readers. These systems are designed to function across various microgravity platforms, aiding research teams through all stages of microgravity experiments—from planning and preparation to execution and result analysis. The unique feature of these systems is their remote operability, allowing research teams to leverage their expertise without relying on astronauts' resources. SpacePharma technology will allow for real-time monitoring of changes in polymers generated, potentially uncovering novel degradation phenomena.

Campden BRI, an independent Research & Technology Organisation provides consultancy, training and analytical services to the food and drink industry. Their involvement was key to understanding and identifying the nutritional content of different livestock cells suitable for a nutritiously dense product.

Opportunity for Research and Innovation

The intersection of space technology and materials science, particularly in the realm of SMART polymers, presents a ripe field for innovative research. The unique environment of space provides an opportunity to study and understand polymer behaviour under extreme conditions that cannot be replicated on Earth. This knowledge can be crucial in the development of next-generation polymers with tailored properties, particularly for medical and construction applications.

The miniaturized lab systems developed by SpacePharma represent a significant innovation in the conduct of space-based research. These comprehensive systems, with their capability for remote operation, reduce the reliance on astronauts and allow researchers to leverage their expertise in a more targeted manner. The proposed experiment to study polymer degradation in real-time could uncover novel phenomena and pathways, leading to further advancements in polymer science.

In addition to understanding degradation mechanisms, there's an opportunity to innovate in the application of SMART polymers. In the medical field, for example, these polymers could be used to develop controlled or prolonged release mechanisms for many active pharmaceutical ingredients, including biologics. Such innovation could significantly improve treatment outcomes, especially in challenging environments, such as those experienced in space. Furthermore, the development of next-generation SMART polymers that can resist degradation in space environments also has significant implications for construction, particularly in the burgeoning field of space infrastructure.

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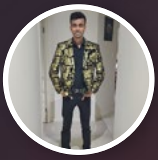
Radiant revolution: the potential of solar skin in space and on earth



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Overview

In today's world, energy is becoming an increasingly scarce resource [1]. Fossil fuels, which have been the primary source of energy for the past century, are depleting at an alarming rate, and the effects of climate change are becoming more and more pronounced. The need for a sustainable and renewable source of energy has become more critical than ever before. Space-based activities also face a significant hurdle when it comes to generating and retaining energy. The harsh environment of space and the limited resources available make it difficult to rely on traditional energy sources [2]. Therefore, it has become crucial to find novel ways to self-generate energy. One such solution is using Solar Skin material. Solar Skin is a thin, flexible material that can be applied to various surfaces, including cars, houses, spacecraft, and satellites. The material is designed to allow the surface of these items to generate their own energy using photovoltaic cells [3].

The advantages of using Solar Skin are numerous. For one, it is a renewable and sustainable source of energy that doesn't rely on fossil fuels. It is also a clean source of energy that doesn't produce any harmful emissions. Additionally, Solar Skin can be applied to a variety of surfaces, making it a versatile and flexible solution. It can also reduce energy costs over time, making it an economically viable solution [4].

Achieving successful implementation involves addressing key technical complexities. Firstly, advancing Solar Skin necessitates sophisticated materials research to create thin, lightweight, and flexible solar-active coatings. These coatings should efficiently convert sunlight into electricity, with nanomaterials like perovskite or organic photovoltaics offering potential benefits. Secondly, integrating Solar Skin into spacecraft structures requires assessing compatibility with materials such as composites or metallic alloys. This ensures mechanical integrity and thermal stability. Rigorous testing is essential to determine Solar Skin's durability in extreme conditions like space radiation, temperature changes, and micrometeoroid impacts.

Enhancing the electrical connection between Solar Skin panels and the spacecraft's power systems necessitates specialized nano-level circuitry and precise design methodologies. This involves managing electrical current flow, reducing power losses, and ensuring fault tolerance. The use of Solar Skin has significant advantages in generating sustainable and renewable energy, making it a valuable solution for both Earth and space-based activities. Its flexibility, versatility, and cost-effectiveness make it an attractive solution that could potentially revolutionize the way we generate and use energy.

Case Experience

While Solar Skin technology shows promise for sustainable energy generation, it is crucial to highlight that the authors have not conducted extensive practical research beyond conceptual studies. However, focusing on a specific use case, Solar Skin holds significant potential in the realm of space exploration, drawing inspiration from a similar concept known as the PowerMax Solar Sails.

A compelling example that demonstrates the practical application of Solar Skin-like technology is the concept of PowerMax Solar Sails developed by NASA. Solar sails utilize the pressure of sunlight to generate thrust for spacecraft propulsion. Similarly, Solar Skin could be applied to the exterior surface of a spacecraft or satellite, acting as a regenerative energy source without compromising aerodynamics or stability.

Opportunity for Research and Innovation

Research and innovation in the field of space exploration has the potential to bring about significant benefits to both terrestrial and space-based industries. By exploring the potential of Solar Skin technology in space exploration, we can advance the capabilities of space-based industries while also addressing the critical need for sustainable and renewable energy on Earth.

The economic benefits of research into Solar Skin technology are also significant. As the world moves towards sustainable and renewable energy sources, Solar Skin has the potential to become a vital component in the energy infrastructure of the future. The development of Solar Skin technology for space-based activities can lead to cost savings and energy efficiency, making it an economically viable solution for a range of industries.

The application of Solar Skin technology has the potential to create new opportunities for innovation and job creation. The development of Solar Skin technology requires the collaboration of multiple industries, from material science to aerospace engineering, creating a diverse range of employment opportunities (Bello-Ochende et al., 2020).

This involves the exploration of advanced disciplines like thermal engineering, achieved through a concentrated comprehension of the potential impact of Solar Skin coatings on spacecraft heat dissipation. Excessive heat accumulation could degrade performance or affect nearby sensitive instruments. Hence, there is a requirement to delve into thermal management strategies, encompassing the utilization of sophisticated heat dissipation materials and the incorporation of thermal control coatings.

Ultimately, it is material science, and would require the research and development of flexible material that can wrap around a subject of interest. It follows the ideology of a Solar Panel, albeit in a ‘skin-like’ deployment, enabling the aforementioned flexibility. With the development of the skin itself, it would require a miniaturization of the electrical network (so it doesn’t look bulky or inadequate from a design perspective).

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Light alloys for liquid hydrogen storage

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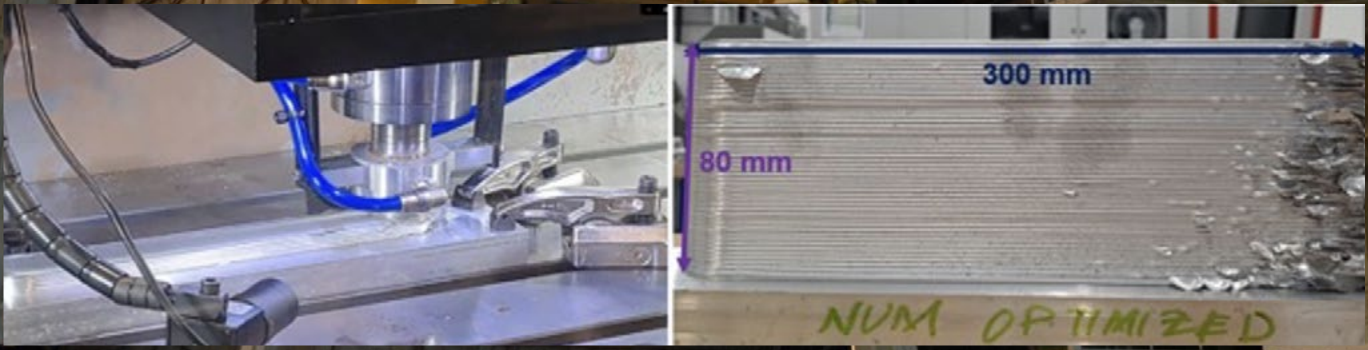

Fig. 1 An example of an Al alloy wall deposited using Solid-State Additive manufacturing

Overview

Liquid hydrogen (LH2) has great potential as a versatile and sustainable energy carrier, with applications in various industries, including aerospace, automotive, and power generation. With the increasing demand for LH2 storage and transportation in space, the density of commonly used stainless steel makes it unsuitable for aerospace applications where light weight is essential to reduce the cost. Research into high-specific-strength cryogenic materials like aluminum (Al) alloys has been advancing due to their high impact toughness and low sensitivity to hydrogen embrittlement. These features are particularly important for aerospace propellant tanks. Al Alloys used for LH2 storage tanks have been in use since 1970 [1] and have become the primary material for LH2 storage tanks in the field of rocket launching. The trend is moving towards liquid hydrogen and oxygen rockets, which will drive the demand for Al alloy LH2 storage tanks.

Case Experience

Researchers at the University of Southampton are currently developing novel light alloys and testing them at cryogenic temperatures ranging from 77K down to 20K, which is the boiling point of LH2. These projects, in collaboration with AMRC North West and Baylor University in the USA, aim to deliver defect-free light alloys with excellent hydrogen embrittlement resistance and high impact toughness at cryogenic temperatures. The author has 15 years of experience in the development of high-performance light alloys. He was awarded a full overseas PhD studentship from the University of Sheffield. In 2020, he received a UKRI Future Leaders Fellowship to design and manufacture new light alloys for the next generation of cars. Recently, his research group worked with TWI and developed bespoke light alloy wires using the one-step process CoreFlowTM. These wires can potentially be used as conductors for space applications [2,3].

Opportunity for Research and Innovation

The development of light alloys, especially Al alloys, for LH2 storage and transportation can significantly benefit space exploration by reducing the weight of spacecraft and increasing their payload capacity with no additional cost or potential risks. This allows for long-range missions and more ambitious goals. In addition, light-weighting LH2 tanks have a vast market, especially in the automotive industry for applications like hydrogen fuel cell vehicles. The widespread use of LH2 as the cleanest fuel to power next-generation vehicles and even commercial airliners will substantially reduce CO2 emissions for a sustainable society. All the creatures living on the Earth will be the beneficiaries if the rate of global warming mainly caused by greenhouse gas emissions is decreased, leading to societal benefits such as an improved living environment and sustainable biodiversity. If there is increased funding, new research directions and themes driven by the high demand for light alloys for LH2 storage and transportation will be mapped and established, such as developing new manufacturing and joining techniques (e.g. Fig. 1 shows an emerging solid-state additive manufacturing has huge potential to print defect free LH2 tanks with excellent properties), the design of alloy compositions and coatings capable of withstanding loads and impacts, and hydrogen permeation at extreme low temperatures. Moreover, a tensile test at 20 K normally costs around £500 per sample. Therefore, with increased facilities access funded by research councils or charities, new methods for inspecting and testing materials under real-world service conditions will be systematically explored, and experimental database obtained at cryogenic temperature will be established with high confidence.

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LUCIDEON – Expertise in advanced ceramics exposed to harsh environments

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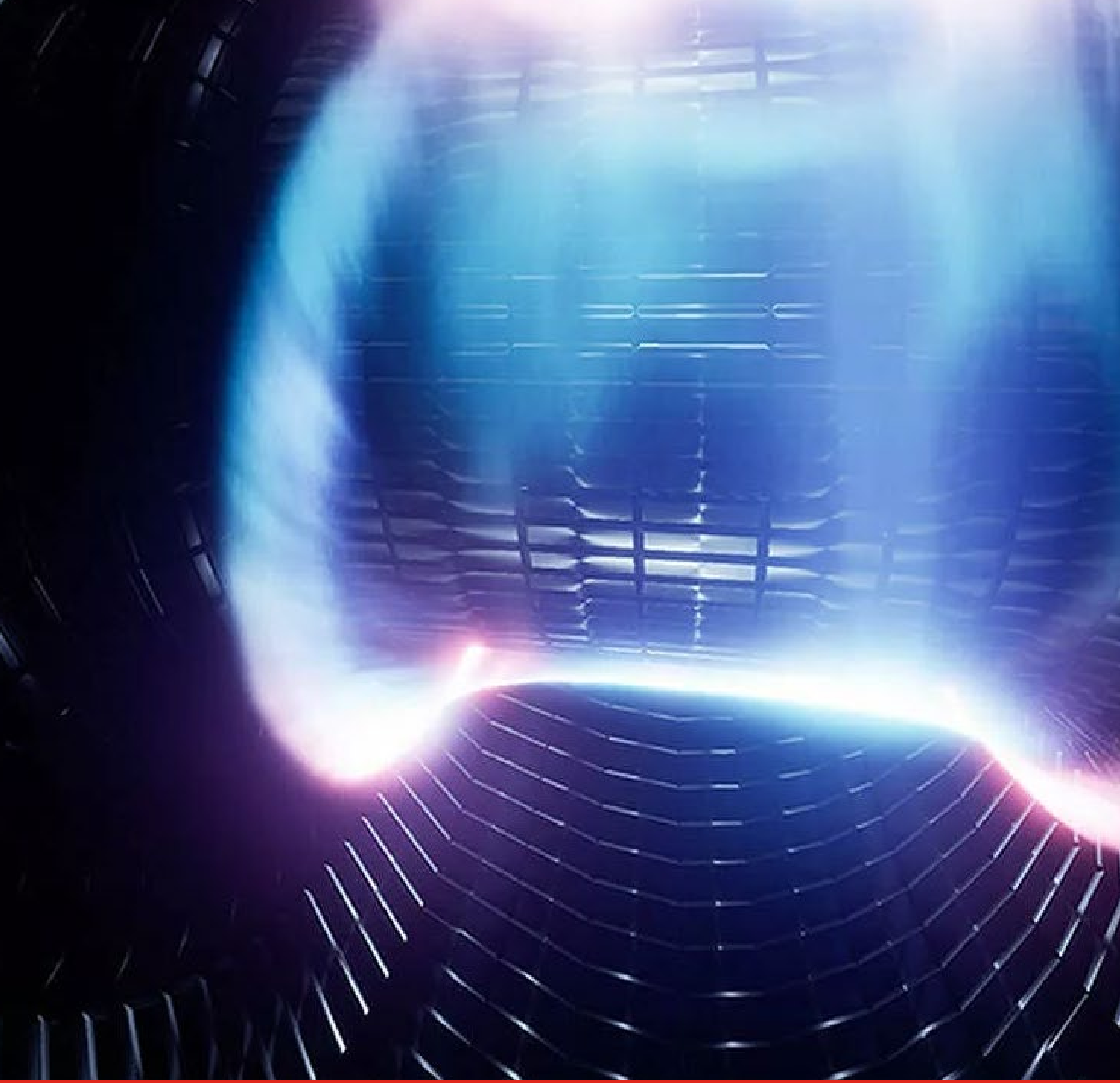

Overview

The demand for commercial space products and services has enabled the exploration of many potential development areas. Combining this demand and the reduction in cost for launches, space exploration has become realistic and achievable, revealing opportunities in deploying materials technology to overcome the remaining barriers and resulting challenges.

Lucideon is a materials development and commercialisation organisation, specialising in materials technology, processes, and testing. With expertise in advanced ceramics exposed to harsh environments, Lucideon aims to assist the space sector through the following capabilities and facilities.

Case Experience

Lucideon’s decades of experience in advanced ceramic materials give us an edge in solving materials and process-based challenges. We can identify areas where advanced ceramics should be used as replacements for metals and polymers to enhance product performance in harsh environments. Lucideon has capability in material formulation development, forming, and sintering. We can provide services to clients in need of materials development and process optimisation - working initially at pilot line scale, with a view to upscaling these processes to full manufacturing capability. This capability can be exploited across different material technologies such as Ceramic-Matrix Composites, Ultra-High Temperature Ceramics, barrier coatings, and materials joining technologies.

Furthermore, due to our material formulation expertise in ceramics, we have been able to transfer and apply this knowledge and to material challenges within the space industry. For example, Lucideon developed a deep understanding of the behaviour of regolith simulants to support and enable a broader regolith utilisation programme. An element of the Lucideon input involved the assessment of regolith physical properties such as particle size, shape, and rheology. This unique project assessed an application of highland regolith for a novel structural application and assessed the powder flow rheology to simulate and understand problems that may arise in lunar regolith handling.

Lucideon provides a range of testing characterisation services such as Molecular Organic Contamination (MOC) monitoring. A definition from the European Space Agency (ESA) for a Cleanliness and Contamination Control Plan (C&CCP) has been produced. This includes MOC monitoring, for the manufacture of appropriate hardware. Lucideon has developed and validated a cleanroom monitoring method using witness plates, capable of measuring and reporting to a limit of < 50 ng/cm2 using FTIR.

Flash Sintering (FS) applies a direct electrical field via electrodes to a material body during the sintering process. It dissipates heat directly inside the ceramic, reducing the processing time and furnace temperatures from those required by conventional sintering. It can also enable a high degree of microstructural control, which improves the performance of ceramic components. This novel process can benefit the space sector from construction applications for In-Situ Resource Utilisation (ISRU) to Space-Based Nuclear Power (SBNP) applications. For example, Lucideon is currently assessing the use of FS technology as a potential process method for manufacturing space batteries powered by Americium-241, seeking to exploit the advantage of FS vs conventional manufacturing methods.

Opportunity for Research and Innovation

Lucideon has recently been awarded £18.5 million as a significant proportion of a £42M project through the UKRI Strength In Places Fund (SIPF) that further enhances our advanced ceramic materials development and processing capabilities, specifically for pilot scale development and demonstration. The Applied Materials Research, Innovation & Commercialisation Company (AMRICC), based at Lucideon, provides these facilities, helping to bridge the gap between academia and industry. Within each step for producing advanced ceramics, we have a suite of facilities and ceramic expertise to help clients optimise their process and material technologies. For example, we have specially constructed kilns for FS, including a contactless flash sintering lab, flash sintering lab, flash bonding and hybrid sintering with functionalities that include atmosphere control, vacuum, dilatometry and “in air”. The AMRICC Centre can be utilised within the space sector to help accelerate materials development and find processing routes to enable novel technologies and meet the demand of the market.

Space-grown thermal substrates for efficient wireless communications

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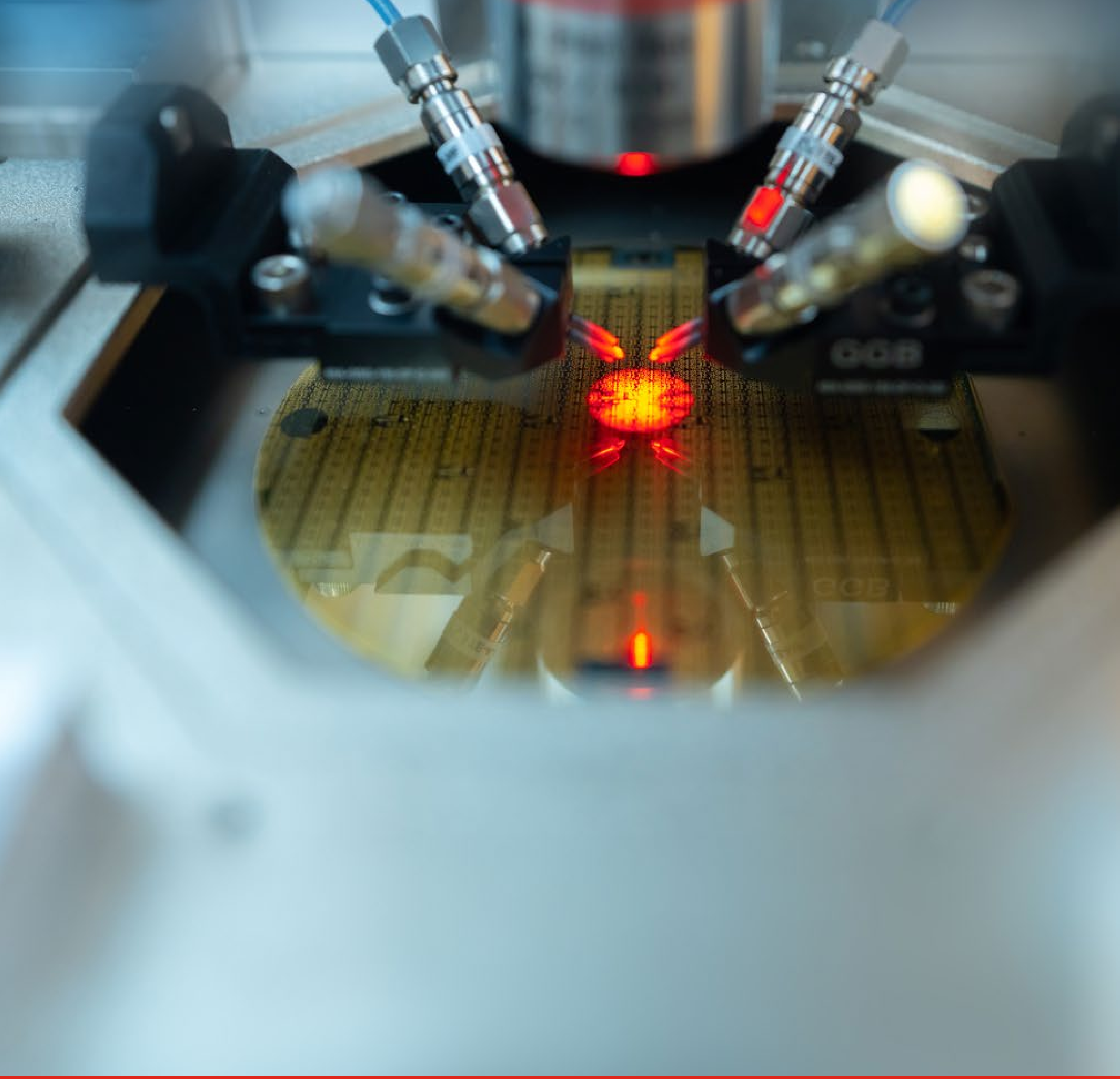

Overview

Materials grown in the microgravity and vacuum of space can show fewer defects and higher purity than terrestrially grown materials, providing superior high thermal conductivity substrates for electronic components. Energy-efficient electronics are increasingly important for telecommunication applications, as telecommunication networks account for significant electricity consumption in developed nations. Despite significant ongoing efforts to replace legacy systems and improve network efficiency, the annual growth in network data traffic results in network energy consumption increasing year on year. As higher-frequency 5G spectrum is licensed by national regulators to enable mobile capacity growth, network operators will require energy-efficient RF power amplifiers and other components at these new and more technically challenging higher frequencies. It is therefore vital that we explore new hardware technologies which can offer increased efficiencies together with improved thermal performance to limit active cooling costs.

Case Experience

The state of the art in high frequency (>28 GHz) RF power amplifiers uses gallium nitride (GaN) transistors [1] within Monolithic Microwave Integrated Circuits (MMIC) using silicon carbide (SiC) or diamond substrates [2]. GaN can achieve higher power densities than conventional narrow bandgap semiconductors, leading to higher operating channel temperatures which in turn leads to thermal degradation and reduced performance. Thermal management of high power GaN RF devices is essential and effective cooling close to the device junction itself has been shown to improve both performance and reliability. The integration of high-quality, space-grown heatsink substrates with embedded microfluidic cooling could produce unprecedented high power efficient GaN RF devices for high frequency 5G communications [3,4]. The cost of space-grown diamond substrates, integration within the MMIC and the associated cooling will initially be uneconomic as volumes will be small and the technology is new. Nevertheless, there could be an economic breakpoint in future 5G/6G use-cases where a conventional RF power amplifier cannot deliver the required high frequency power performance and energy efficiency within a compact device using conventional active cooling at an acceptable price. At first, space-grown substrates will only be appropriate for niche applications but mainstream use will follow as advanced cooling techniques and MMIC design are developed further.

Opportunity for Research and Innovation

Supporting the UK component supply chain not only provides greater supply chain resilience in an uncertain global environment but also enables us to steer innovation to gain global competitive advantage. This supply chain includes basic materials for substrates, transistor fabrication, MMIC design, packaging and system implementation.

There is clear demand for high-performance energy-efficient 5G/6G components. As academic and industrial researchers, we can characterise new technical RF front ends in practical field trials to show the operational benefits for network operators. Specifically, it is possible to measure the performance uplift in GaN Power Amplifier MMICs as a function of frequency with enhanced thermal interface materials (SiC, polycrystalline and single-crystal diamond, both terrestrial and space-grown) supported by embedded microfluidic cooling. With ambitious and innovative component design, space-grown materials can significantly reduce the energy consumption of terrestrial wireless communications whilst also delivering improved RF performance.

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4D printing 4 space

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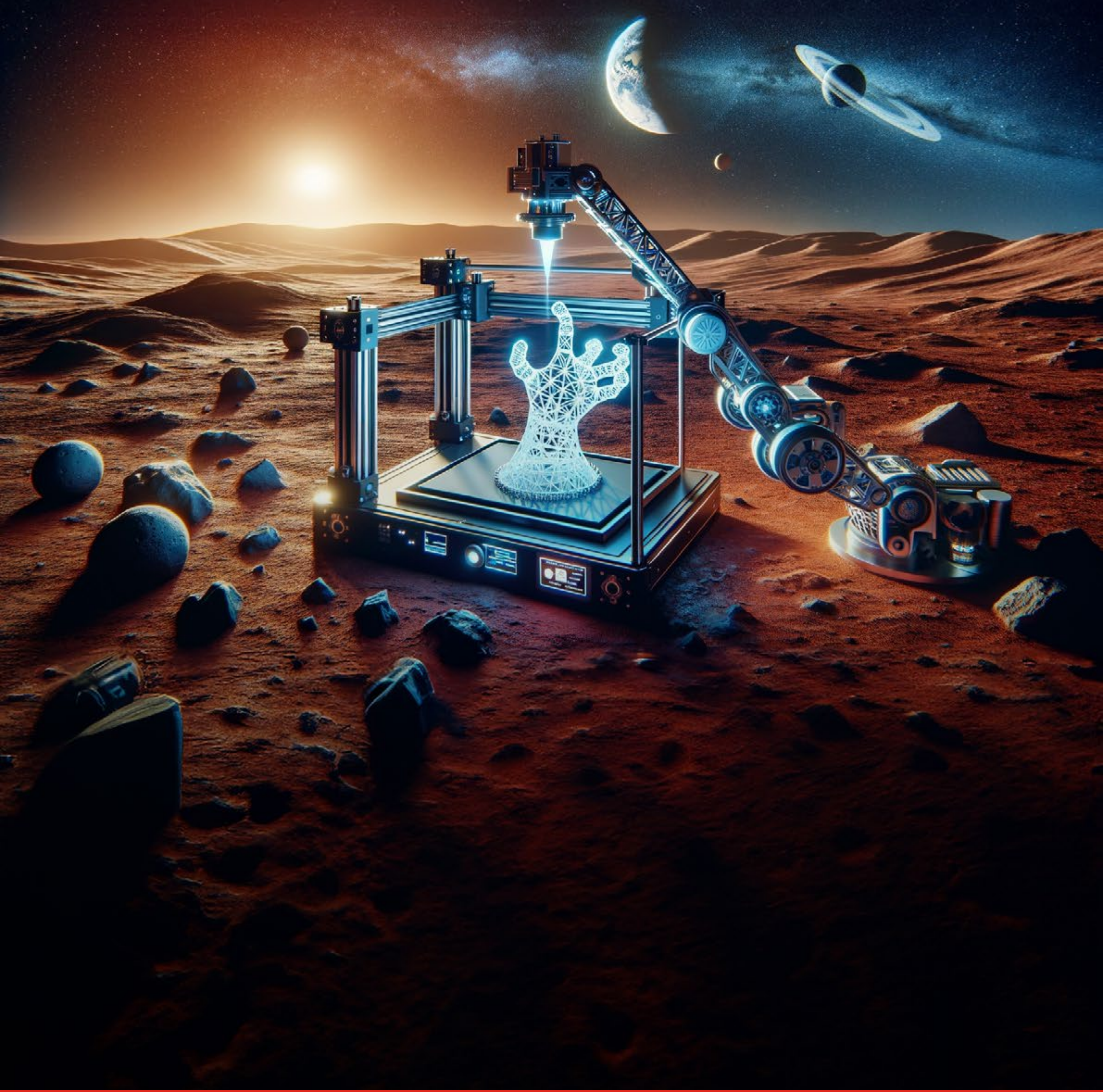

Overview

4D printing is a novel technology for creating smart structures that can change their shape/feature/properties over time in response to environmental stimuli. In the context of space exploration, 4D printing has the potential to revolutionize the way we design and manufacture astronautical devices, spacecraft, and habitats for extraterrestrial environments. By 4D printing photochromic materials, thermochromic materials, shape memory materials, and magneto-electro-mechanical materials, we can create smart structures that sense, respond, and adapt to an external stimulus or change in the environmental conditions. They are advantageous in remote locations like outer space where it is difficult to perform manipulations and multi-physics programming, and it demands a) a low level of material/energy consumption, expert interference and the need for on-orbit assembly/maintenance, b) fast on-orbit manufacturing, and c) a high level of reliability for spacecrafts and habitats.

Case Experience

Researchers in the 4D Materials & Printing Lab at Nottingham Trent University in collaboration with national and international research institutes have been elaborating shape-morphing structures by 4D printing of smart material systems for different applications including space. This comprises, for example:

- Simultaneous 4D printing and thermo-mechanical programming for creating complex 3D structures from simple 2D structures [1]. 4D printing enables programming of 2D structures during printing for an autonomous 2D-to-3D shape transformation by simply heating. This sustainable shape transformation requires lower material/energy consumption, less expert interference, and manipulations, and offers fast manufacturing and high structural strength.
- 4D printing of meta-materials and structures with zero and negative Poisson's ratio, reversible shape recovery, and energy dissipation features [2]. 4D printed meta-structures can dissipate energy via hyper-elasticity, elasto-plasticity and mechanical instability. The mechanically induced plastic deformation and dissipation processes are fully reversible by simply heating. It reduces materials wastage and the need for repair/manufacturing.
- 4D printing of magneto-electroactive shape-memory polymer composites [3], see Fig. 1. Remote controllability and quick reaction are features of 4D printed shape-morphing composite structures. They can be programmed remotely to achieve multi-stable shapes and can switch repeatedly between temporary and permanent configurations. This allows for achieving multiple desired adaptable/reconfigurable shapes in a single lightweight structure and reduces materials wastage and required effort/energy.
- 4D printing of adaptive soft robots with autonomous vibration control [4]. The 4D-printed silicone muscle integrated with carbon fibres can be activated with a low-voltage signal to develop a programmable joint with a controllable stiffness. The smart electrothermal muscle serves as a controllable mechanism for suppressing low-frequency vibrations, showcasing its adaptability and effectiveness in attenuating vibrations autonomously. These adaptive soft robots offer an excellent performance in terms of simplicity, repeatability, recovery time, and power consumption.

Fig. 1. 4D printing of magneto-electroactive shape memory polymer composites.

Opportunity for Research and Innovation

Space is a harsh unstable place and galactic cosmic rays, radiation, high-energy sources, vibrations, and temperature change can cause damage to multi-functional materials and structures, reducing their service life and capabilities. There are many opportunities for research and innovation in the field of 4D printing of sustainable space structures six of which are listed below:

- Development of new smart materials considering the impact of space to 4D print resilience, functional and sustainable space structures that can withstand harsh conditions of space and adapt to changing environmental conditions. This could result in significant cost/material/energy savings and improve sustainability of space exploration.
- Development of space-resistant semiconductor materials compatible with 4D printing to create flexible dynamic electronics for sensing, actuation, and energy storage/generation purposes.
- Development of 3D/4D printing platforms to fabricate smart space-resistant structures in micro/zero gravity and vacuum environments.
- Direct 4D printing of space-resistant components with superior properties that require no post-processing.
- Developing 3D/4D printing platforms for scaling up the physical size of structures.
- Artificial intelligence-assisted 3D/4D printing to create multi-purpose modular smart structures that can be re-used for other applications promoting a circular economy. It would offer several potential benefits, such as resource efficiency, cost-effectiveness, and versatility, maximising their utility and lifespan.

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Compound semiconductor manufacturing and use in space

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Overview

Semiconductors are the material behind all information and communication technology on Earth and in space, so underpin all aspects of modern society. Whilst organic semiconductors are sometimes used in application like displays, and widely researched for many others, inorganic semiconductors dominate, and can be subdivided into silicon (Si) and (III-V) compound semiconductors, such as GaAs or GaN. Si is currently the basis of all digital electronics and predominant in terrestrial solar cells, but as an elemental material its properties are fixed. In contrast, due to the huge materials design parameter space available to compound semiconductors by combining different elements, and their heterostructures, a vast range of applications can be addressed, often offering capability or performance advantages over Si. One example is solar cells, where use of compound semiconductors in single or multijunction format offers much greater efficiency, so is attractive for space applications, including solar power generation in space for terrestrial use [1]. High efficiency components that consume minimal energy, such as the non-volatile compound semiconductor memory ULTRARAM TM [2] are extremely attractive for space applications. On the manufacturing side the unique qualities of space such as microgravity and a naturally low-vacuum, clean environment promises a step change in semiconductor material quality for high-performance applications.

Case Experience

The author has 35 years of experience in compound semiconductor physics and devices, is (co-)inventor on several patents and patent applications related to ULTRARAM™ memory technology [2], vertical cavity surface-emitting lasers, single photon sources and novel digital logic devices. He is co-founder and Chief Scientific Officer of Quinas Technology Ltd., and within the Department of Physics he is Deputy Head of Department, Director of Research, Director of Business Engagement and Impact Champion. He and his team are actively building links between the compound semiconductor and space communities e.g., with Frazer-Nash Consultancy, CAES and Open Cosmos.

Opportunity for Research and Innovation

There are presently UK strategic priorities that provide research and innovation opportunities in space, in energy and in semiconductors. These uniquely combine in the use of compound semiconductors in space applications. The UK Semiconductor Strategy has a particular focus on compound semiconductors, which is an area of UK strength. IQE, the world's largest compound semiconductor epitaxy provider, is a key player in the world's first compound semiconductor cluster in South Wales. Wales is also the home to Space Forge [3], pioneers of space-based semiconductor epitaxy, and MicroLink Devices [4], supplier of super-lightweight high-efficiency solar cells for satellite applications. This strength in compound semiconductors is mirrored in UK Universities, e.g. Cambridge, Cardiff, Lancaster Manchester, Sheffield, UCL, Glasgow and Strathclyde, providing a rich research and innovation ecosystem that can help to build the UK space sector. An example is Quinas Technology, recently spun out of Lancaster University to commercialise ultra-efficient, non-volatile ULTRARAM™ memory technology. The memory chip market, in which the UK currently has no presence, is worth about $160 bn pa, while the electronics in space sector is worth $3bn pa, and rapidly expanding. Further academic and industrial research has the potential to generate huge terrestrial economic and environmental benefits, and opportunities for fast, efficient and non-volatile memories in space facilitating lower payloads via reduced battery and solar cell requirements and in-orbit edge computing. While the development of the technology must clearly be terrestrial, space-relevant characteristics must be considered in the design and implementation, and properties and performance validated in space to reach high technology readiness levels and commercial viability.

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Maser amplifiers: hearing the faintest space calls between the blue marble and the stars

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Overview

In 2021 approximately 1400 satellites were launched into space, many of them small volume satellite platforms. Cubesats, with a payload restricted to only 10x10x10cm, are now being seriously considered for deep-space missions [1], creating a need for ground stations capable of detecting the faint signals they will transmit to Earth. However, the challenges of communicating with faraway spacecraft are two-fold; amplifying the faint radio signals received at the ground station and amplifying what the satellite would receive from the ground station. The MASER team at Imperial College London have developed room-temperature solid-state masers, the microwave analogue of lasers, which feature exquisitely ultra-low noise amplification of these very same radio signals used in space communication. Our team has recently succeeded in miniaturising the continuous wave NV- diamond maser to a benchtop size, and so the time is ripe to bring masers out of the lab and into the industry. The project aims to exploit existing and find new maser gain media capable of operating at room temperature. These will be miniaturised as plug-and-play devices in order to create low-cost, long-range ground station communication and reduce the launch cost-per-kilogram, so that they may one day be deployed on satellites no matter how far they are from home.

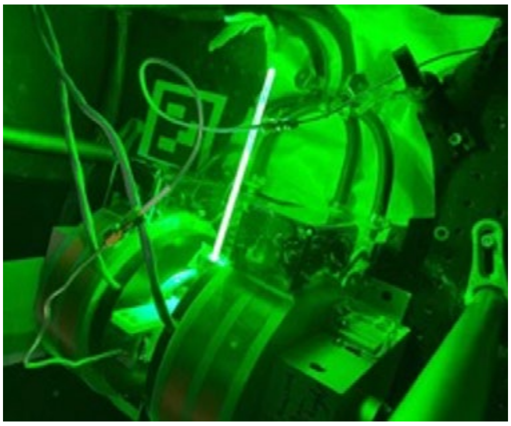

Fig 1. Excitation of a diamond MASER by green laser light. The diamond gain material is positioned inside a resonator and embedded in test tube, which is reflecting the green light.

Case Experience

Researchers in the MASER team are world experts in maser development. All three known room-temperature masers were discovered at Imperial College London [2-4]. The team has substantial hands-on experience in fabricating devices and building microwave spectrometers crucial to the investigation of paramagnetic materials such as masers. The interdisciplinary confluence of expertise in organic synthesis, optical measurements and microwave engineering with laboratories containing the necessary equipment for all three endeavours places us at the forefront of maser research.

Opportunity for Research and Innovation

The research would immediately benefit radio-astronomy telescopes, such as the Jodrell Bank array which currently uses hydrogen masers as frequency standards. The diamond maser would offer a more lightweight and much lower cost alternative, without the need for constant replenishment of hydrogen gas. Furthermore, our work would support the microwave dielectrics community who would benefit from new applications of microwave dielectric materials. Organic chemists will take an interest in the active medium that we have used for the maser, and we hope will be able to suggest other active media. Finally, room-temperature masers could act as receivers in mobile networks where the high sensitivity of maser amplifiers would extend coverage to hard-to-reach-areas while lowering the energy consumption of the networks by reducing the power at which signals must be broadcast.

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Advancing directed energy deposition techniques for extreme environments

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Overview

Directed Energy Deposition (DED) techniques are the optimal process for additive manufacturing, welding, and repair within the space environment. Using a focused energy source such as a plasma arc, laser, or electron beam, solid wire feedstock can be heated to a flow state to deposit material on a substrate, building a geometry within the microgravity environment. This method is safer and more controllable than powder based methods for zero-g, and opens up a wide range of technical alloys for construction. However, the shielding gasses used to protect the weld zone on earth from the oxygen in our air, are impractical for use in the vacuum of space. This leaves the weld vulnerable to atomic oxygen (AO) within the lower earth orbit regions, and reduces confidence in the quality of the weld and the resulting structure. For the increased interest in human exploration and the applicability of DED to constructing human rated habitats, the effect of AO on such techniques needs to be studied.

Case Experience

The author has conducted Master's level research into DED within space, specifically for constructing improved efficacy micrometeorite and orbital debris (MMOD) shielding, or Whipple shielding, on-orbit [1]. With a competent understanding of how different properties and impurities affect a weld zone on earth, they have gone on to co-author DED related concept proposals with engineers from the European Space Agency (ESA), with an idea selected by the Open Space Innovation Platform (OSIP) that built upon previous work by ESA & Airbus [2]. They have now founded their own company, Lodestar Space, to commercialise their research into robotic-enabled 3D printing of welded MMOD shielding, being backed by the ESA Business Incubation Centre and Innovate UK, while also raising a pre-seed funding round from the leading deeptech firm in Europe, to mature such in-space construction capability.

Opportunity for Research and Innovation

The UK has world-leading materials research heritage, specifically in DED related techniques at leading research at universities such as Cranfield and Imperial College London, and companies such as WAAM3D and TWI. This concentration of researchers within a close network, positions the UK best to first understand the scope of this problem, and potentially propose new alloys and additives to resist the effects of AO. This feeds into the UK's interests for the National Space Strategy, and crucially improves the understanding of how human-rated structures will fare over time under the corrosive effects of AO. This is critical for a sustained human presence in space, and will improve UK standing in collaborations with NASA and ESA.

There are also potential terrestrial benefits through researching how microgravity affects the weld zone itself, and whether metal solidification in this environment produces any enhanced microstructures that could be useful for earth. Maturing the industry's understanding of how eliminating buoyancy affects molten metal will bring valuable input for the work being undertaken by in-space alloy manufacturing companies. This has the potential to create an entire new metallurgical industry, which would allow the UK to have priority access to advanced semiconductors and high performance alloys to be brought back to earth to benefit the national interest in telecoms and computing, building upon the UK's rich history of materials innovation.

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Metal matrix composites and hypereutectic alloys for space

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Overview

Reliable, high-performing materials are necessary to meet the demands of space-based systems and components. Common challenges for space structures include mass, dimensional and thermal stability, ability to perform at both elevated and cryogenic temperatures, the ability to survive launch loads, and emissivity. Conventional polymers, ceramics and metals can struggle to meet such demanding property combinations, but composites can provide the solution. In particular, lightweight Metal Matrix Composites (MMCs) and hypereutectic alloys can meet many of these requirements simultaneously by providing exceptional specific stiffness (stiffness-to-weight ratio), controlled thermal expansion and improved damping, amongst other benefits that make them strong candidates for space applications [1].

Typically, these materials are used in high-consequence airborne applications where stability and thermal management are critical. Previous applications have included housings, chassis and frames for electronics systems, high-precision mirror substrates and structural components to support reflective optics or electro-optical systems. This chapter will review MMC compositions that are suitable for space applications, where lightweight, high stiffness and thermally stable materials are required.

Case Experience

Materion has a long history of space materials research and usage, from the early space program to the repair optics for Hubble and the Mars landers. Now recognised globally for its contributions of innovative and reliable materials technology for the harsh environment of space, Materion provides advanced materials used in numerous applications including NASA's James Webb Space Telescope.

A range of MMCs exist within Materion's portfolio based on nano-to-micron-sized ceramic particles. [2-3]. The MMC grades with the greatest degree of space heritage are:-

Figure xvi: SupremEX metal matrix composites are a durable replacement for aluminium, titanium, steel and other structural alloys and composites.

- SupremEX® 640XA MMC, 6061/SiC/40p (3 µm): High specific stiffness, strong and thermally stable making it ideal for optical and instrument assemblies.
- SupremEX® 225XE MMC, 2124/SiC/25p (3 µm): Excellent balance of mechanical properties, stiffness match to titanium, with a 36% density reduction.
- AlBeMet® AM162 MMC, Al-62wt% Be: High modulus and low-density characteristics of beryllium with the fabrication benefits of aluminium – ideal for challenging design applications.

Opportunity for Research and Innovation

Our purpose is to push the boundaries of innovation to enable breakthroughs that benefit the world. We have a team of experts and a powder metallurgy facility in the UK, dedicated to the manufacture and development of MMCs and hypereutectic alloys. Expansion of the collaboration between our UK-based team of materials experts and end users within the space industry will enable improved design, function and longevity of mission-critical components. This will in turn provide the UK with more resilient space systems capable of extended missions to advance our knowledge of the universe. Furthermore, increased market feedback can drive focused research of new and novel materials specifically designed to address key challenges of next-generation spacecraft.

Most recently, we have developed a series of hypereutectic aluminium-silicon alloys, namely AyontEX™. These Al-Si alloys have tailored thermal expansion and lower density than conventional Al alloys to address the growing challenge of thermal management in space. AyontEX™ 17 alloy matches the CTE of copper alloys (17 ppm/°C) making it an ideal, lightweight material for use in avionics applications that require reliability in thermal cycling. AyontEX™ 13 alloy matches the CTE of nickel alloys (13 ppm/°C) making it ideal for reflective optics and instrument assemblies where a CTE match to nickel plating or other coatings is needed to provide good thermal stability over broad operating temperature ranges [4-6].

Adoption of new and novel high-performance materials in space, such as AyontEX™ alloys, can be limited due to the barriers posed by sometimes conservative heritage-based design approaches, resulting in lengthy and often ambiguous qualification processes and approval routes. Additional in-space testing, as early in the design cycle as possible, would result in faster verification of new materials. This in turn would provide engineers with greater design freedom enabled by the benefits provided by high-performance materials.

Many applications for MMCs and hypereutectic alloys are dual use in nature, and thus increased adoption within space will provide spill-over benefits into industries such as aerospace, defence, semiconductor and high-performance automotive. The key societal benefits from producing high reliability, lightweight components are strongly aligned to weight and fuel savings, as well as increased longevity and capability of mission-critical components and therefore the spacecraft itself.

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Designing inorganic/organic hybrid resin matrices for extreme environments

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Overview

Polymer-based carbon fibre-reinforced polymer (CFRP) composites offer low weight and outstanding mechanical properties, which make them promising candidates in space applications. However, the particularly harsh conditions place exacting demands on the materials. Atomic oxygen erosion plays a leading role in the degradation of polymer based composite materials, especially in low Earth orbit (LEO), which can severely limit composite durability. Since 2017, within two PhD projects, the University of Bristol has been developing new nanocomposite formulations of both cyanate ester and benzoxazine resins, one of which has been patented. With funding from the UK Space agency (UKSA), and in collaboration with the National Composites Centre, the technology readiness level (TRL) of these blends has been raised to TRL 5 / 6 through the manufacturing and testing of large (500 mm x 500 mm x 3 mm) panels and these are soon to be evaluated in space.

Case Experience

Researchers in the Bristol Composites Institute, University of Bristol, are currently conducting two UKSA-funded composite development projects with the European Space Agency (ESA). In AO-2020-EMA (Q1, 2024), four nanocomposite CFRP specimens designed and manufactured in Bristol will be exposed on the Bartolomeo platform of the International Space Station for up to 18 months, while monitoring mass loss. In AO-2022-IBPER (2024-2025), the same team will explore the potential of the nanocomposites to offer low mass radiation shields by performing beam experiments in the high energy particle collider at the GSI/Helmholtz facility in Darmstadt to simulate the effects of cosmic radiation on CFRP panels. While ongoing projects in this field concentrate on self-healing nanocomposite matrices and in-orbit manufacturing methods (3D printing of CF reinforced thermoplastics) these are terrestrially based and the opportunity to carry out experiments in a microgravity environment would be valuable to explore the potential effects on healing mechanisms or polymer morphology to aid materials design.

Opportunity for Research and Innovation

We have a thriving community of materials scientists in the UK, some of whom are already actively engaged in space-related projects. Today, UK scientists continue to shape the future of spaceflight by providing expert input to new ESA materials research roadmaps, developing materials and processing technologies to allow ESA and other agencies to extend the reach and ambition of the space and space analogue missions, and providing critical mentorship to young and early-career scientists interested in pursuing work in this area. There is clear downstream terrestrial benefit of work being conducted by UK scientists focused on space as materials under development have the potential for use in established applications. Many of the materials are dual use in nature and will have terrestrial applications in defence and high-performance aerospace, etc. While the use of these materials will lead to increased longevity and greater structural integrity and yield more resilient spacecraft capable of longer space exploration missions. The need to make changes to the chemical structures will generate new avenues of scientific research, while improvements in processing methods may open new pathways to e.g. in orbit manufacturing. The societal benefits from producing stronger, lightweight materials are allied to weight and fuel savings, and simplified manufacturing and joining processes.

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Advanced materials development for hypersonic vehicles

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Overview

Around the world, there is an increasing appreciation of the strategic advantages and commercial opportunities associated with very high-speed flight and its role in facilitating sustainable access to space. Designing spacecraft to achieve such high speeds requires a detailed understanding of the challenging field of hypersonic aerothermodynamics and associated specialist materials and structures, which must withstand extreme thermal loads. Experimental aircraft such as NASA's rocket-powered X-15 [1], scramjet-powered X-43A [2] and Boeing's unmanned, air-breathing X-51A WaveRider [3] have pushed the boundaries of what is possible for vehicles with conventional (mainly metallic) airframes. To continue flying faster, higher, and for longer, future hypersonic aircraft and spacecraft require a step-change in the way aerothermal loads are managed through novel, radically different approaches to airframe design and the development and utilisation of advanced new materials and surface treatments that minimise the need for complex (heavy and inefficient) active cooling systems.

Case Experience

The assembled research team uniquely combines the breadth of disciplinary expertise necessary to conceptualise, design, manufacture, test and analyse the effectiveness of new advanced materials for hypersonic applications. Dr Li has rich experience in material and composites development, especially in metal alloys, ceramics and their composites including material manufacturing, characterisation, and nanoparticle dispersion [4-5]. She runs a well-equipped lab at Imperial with extensive manufacturing facilities including high temperature furnaces with stirring and ultrasonication under different inert atmospheres and rolling and hot pressing. Dr Rigas has expertise in modelling and control of transitional and turbulent flows and interrogating the dynamics of fundamental flows using hydrodynamic stability theory and high fidelity experimental/simulation data [6-7]. Dr Bruce leads Imperial's high-speed experimental aerodynamics group, using Imperial's supersonic and hypersonic wind tunnels to explore fundamental aspects of high-speed aerothermodynamics [7-8].

Opportunity for Research and Innovation

This research aims to develop a new class of aerodynamically smooth metallic/ceramic composite material that has been shown (via theoretical research at Imperial) to offer a novel and highly tunable capability to passively control aerothermal loads to spacecraft via the suppression of hypersonic boundary layer transition [7]. Further research and development are urgently needed to design and manufacture a real-life sample prototype, of the new material which can be tested in a representative aerothermal environment and assess its efficacy in managing thermal loads. The material manufacturing and processing challenges are significant and will require specialist equipment and expertise to overcome the practical challenges of realising a working prototype that performs in high-speed, high-temperature wind tunnel tests. Successful demonstration of a prototype will pave the way for further development of the material concept utilising modelling-guided experimental design and optimisation, as well as the potential addition of nanomaterials and nanocomposites to maintain thermal performance with reduced weight and improved robustness.

Further development of the concept in the form of a spaceflight-qualified prototype would enable the robustness of the design in a real space environment to be assessed. The efficacy of the concept is expected to be highly sensitive to very small imperfections or surface tolerances. While these can be carefully monitored and mitigated as necessary in ground-based tests, the ability of a prototype to withstand the rigours of a real mission including structural (vibrational) loading during launch and cyclic variations in thermal load during orbital or sub-orbital atmospheric flight at high-altitude, will be the true test of the concept's potential for adoption in a real spacecraft or any high-performance aerodynamic system where thermal management is important. Finally, the ability to make high-precision measurements of a material's surface in-space will be essential to assess the system, as it is unlikely to survive atmospheric re-entry and return to the Earth's surface for inspection.

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Wide bandgap transistors for electronics in space

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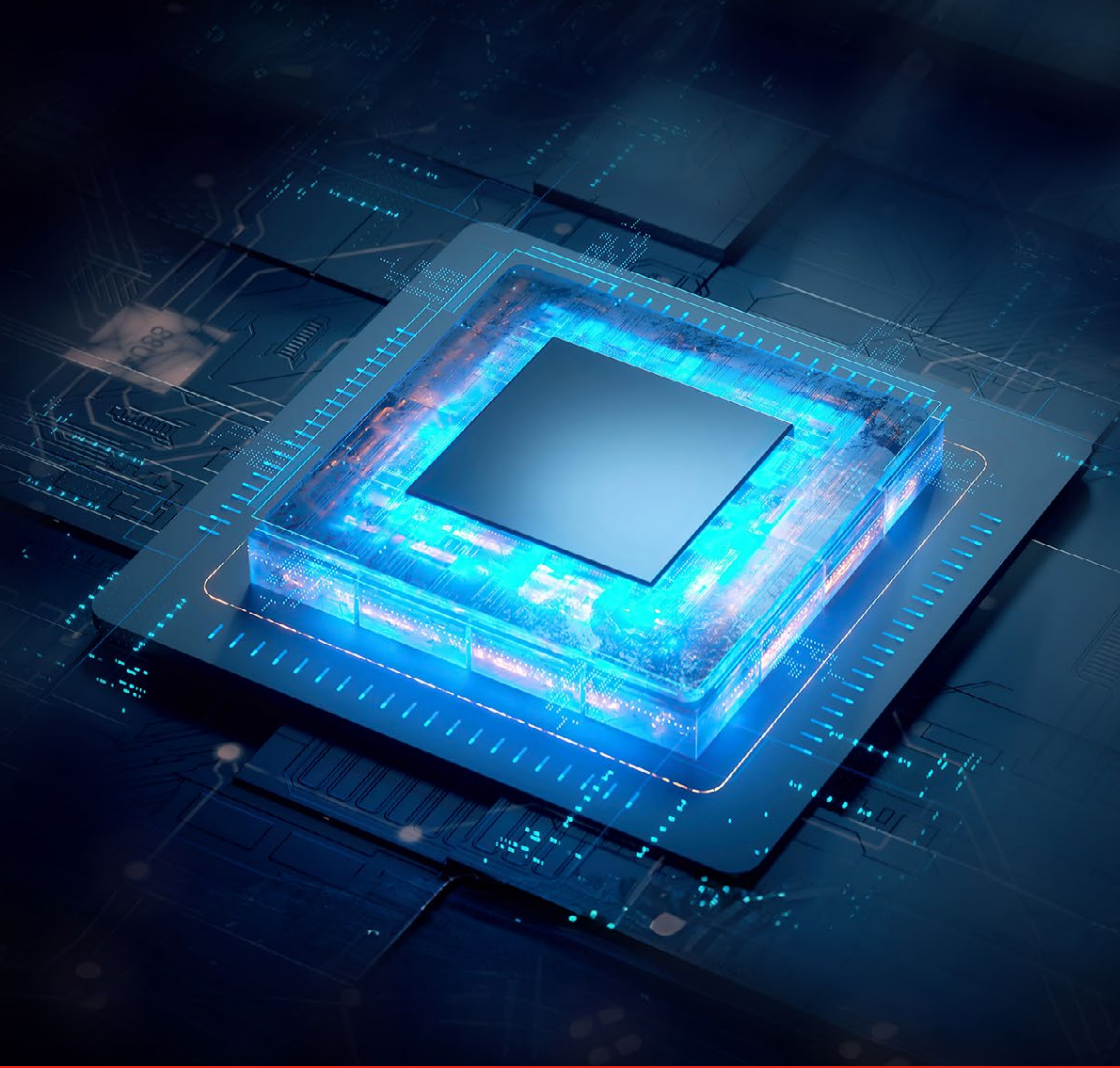

Overview

Transistors are tiny electronic devices that control the current flow through circuits. The invention of the semiconductor-based transistor, approximately 75 years ago [1], marks the beginning of modern electronics. Until recently, silicon (Si), technologically the most mature semiconductor, was used for transistors for almost all applications. For all semiconductors, bandgap (Eg) is an important parameter. Specifically, it is the energy required to elevate an electron from the valence energy band to the conduction energy band, where it can conduct current. Si has a moderate bandgap, and semiconductors with wider bandgaps are superior candidates for space-based electronics. However, to achieve the true potential of wide bandgap (WBG) semiconductor-based transistors in space, considerable improvement of all the involved material technologies is still required.

Case Experience

Presently, in terrestrial high-frequency communication and electrical power conversion, materials like silicon carbide (SiC) and gallium nitride (GaN) are gradually replacing silicon. This is due to their advantageous intrinsic properties, such as higher channel conductivity, electron saturation velocity and tolerance of higher breakdown electric fields. Incidentally, SiC and GaN are WBG semiconductors with bandgaps three times more than Si (note materials such as gallium oxide (Ga2O3) and diamond have even larger Eg). Wider bandgap materials are generally more capable of functioning in high-temperature hazardous environments. A wider bandgap also ensures a higher threshold for defect-creation from high-energy radiation particles encountered continuously in radiation belts or intermittently in solar events. In addition to the benefits for which they are already desired in terrestrial applications, these reliability benefits of WBG semiconductors could be crucial for long-term unmonitored operations in specific space-based applications. For instance, from interstellar probes to the constellation of low-earth orbit satellites providing global internet coverage, the entire data-link to ground receivers is wireless. In such communications, with SiC or GaN transistors, the higher-efficiency of signal amplification can lower the power demand and the capability to operate at higher frequencies can increase the data bandwidth. They also waste less electrical energy as heat. This reduces cooling system requirements and, in turn, payload, providing competitive cost advantages to new ventures. WBG transistors can also play an essential role in power electronics in space. E.g., their high-voltage handling capability can aid in realising the high-power management and distribution systems necessary for fully electric propulsion [2] that may reduce conventional propellant usage by ten times.

Opportunity for Research and Innovation

Several R&D opportunities exist in this field. E.g., WBG-based transistors comprise thin layers of single-crystalline semiconductors, often with unintentional atomic-scale defects. Understanding the electrical activity of these defects and their evolution in space environments is critical. Furthermore, besides the semiconductor, metal electrodes and insulating dielectrics are part of the transistor, and their reliability needs thorough scrutiny. Investigations are also required to identify device designs with better radiation immunity. Hence, there is a need to solve materials challenges in semiconductor growth and characterisation, device physics, atomistic modelling, layout design, fabrication, electrical characterisation, and packaging. So far, the USA and Japan have dominated investigations targeting space-based electronics. However, UK academia has a strong history in several WBG semiconductors, with activities led by Bristol, Cambridge, Sheffield, Strathclyde, Glasgow, Cardiff, and other universities. Also, as the recent 'National Semiconductor Strategy [3] roadmap pointed out, know-how for semiconductor design and high-throughput manufacturing already exists in companies clustered throughout the UK. Hence, as the race-to-space intensifies, strategically coordinated industry-academia efforts towards developing space-qualified WBG transistors could place the UK as a global leader in this upcoming semiconductor value chain.

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3D printing for fast and secure satellite communications

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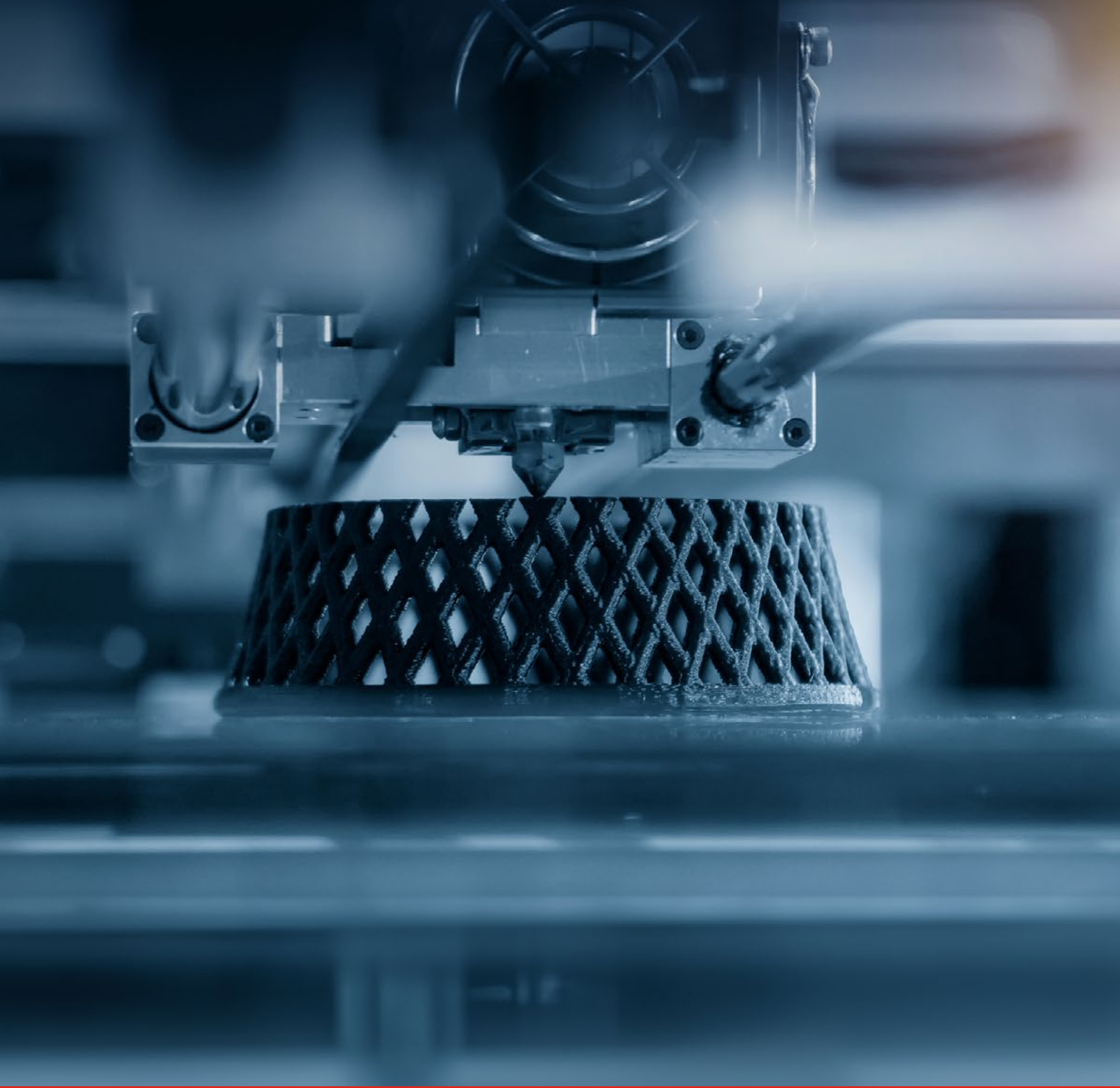

Overview

Additive manufacturing (AM) technology is capable of creating new shapes that were not possible with traditional fabrication methods. AM offers a third degree of freedom to RF (Radio Frequency) Engineers, allowing them to move from 2D metallized shapes to 3D structures to achieve isotropic and anisotropic electromagnetic properties in a material, introducing new novel innovation in the field of wireless communications, electromagnetic sensing, and material research. Several new RF applications such as dielectric lenses, reflectarrays, polarization converters, etc. have been developed using 3D-printing. They are very useful for satellites, as 3D printed devices such as lenses and reflectarrays can be used to produce highly directive electromagnetic beams that can establish a secure network irrespective of the orientation of the receiver and/or satellite. They can replace large dish antennas to reduce their size and weight. After several proof-of-concepts in the literature, extensive research is being conducted to achieve higher TRL and implement new AM based RF elements for future space programs. AM techniques are suitable for fast prototyping; however, a great deal of interest is being shown in exploring mass production methods with AM-based methodologies.

Case Experience

Researchers at Loughborough University have been working on additive manufacturing techniques for RF applications with the support of industrial partners including Satellite Applications Catapult, Her Majesty's Govt Communications Center, BAE Systems, Airbus, Defense Science & Technology Laboratory and National Space Center. This includes synthesizing 3D printed metamaterials, graded index lenses, beamforming antennas, and anisotropic materials for satellites. The group has extensive RF measurement facilities up to 67 GHz, and material characterizing facilities which can be used to better understand 3D-printing techniques and materials from an electromagnetics perspective. The author (Prof Whittow) is a Professor of Radiofrequency Materials at Loughborough University. He is a Named Investigator on research grants focusing on new materials and AM for RF applications in telecommunications, sensing, and space. Some of the notable works from Loughborough University's Wireless Communication Research Group on this subject [1-4].

Opportunity for Research and Innovation

AM has proven to be effective for fast prototyping and producing extremely efficient RF system such as antennas, graded-index lenses, reflectarrays, etc. AM allows for lightweight structures which are highly beneficial for space applications. For instance, a 3D printed lens can increase the effective aperture of the antenna while maintaining a small form-factor. It can also allow for directive beams, hence, boosting communication links between satellites and ground stations. AM has several economic and societal benefits. Fast prototyping with AM will allow for new technology to reach the market in a short period of time. It can allow for more bespoke properties in a material for both space and terrestrial applications without the delays caused by traditional manufacturing processes.

A new degree of freedom introduced by AM allows for a whole new set of opportunities for RF and mechanical engineers. Although AM allows us to alter the properties of a material with new shapes, it is important to understand the mechanical limitations of such 3D structures and their stability over time and as a function of temperature, and vibration frequency etc. clustered throughout the UK. Hence, as the race-to-space intensifies, strategically coordinated industry-academia efforts towards developing space-qualified WBG transistors could place the UK as a global leader in this upcoming semiconductor value chain.

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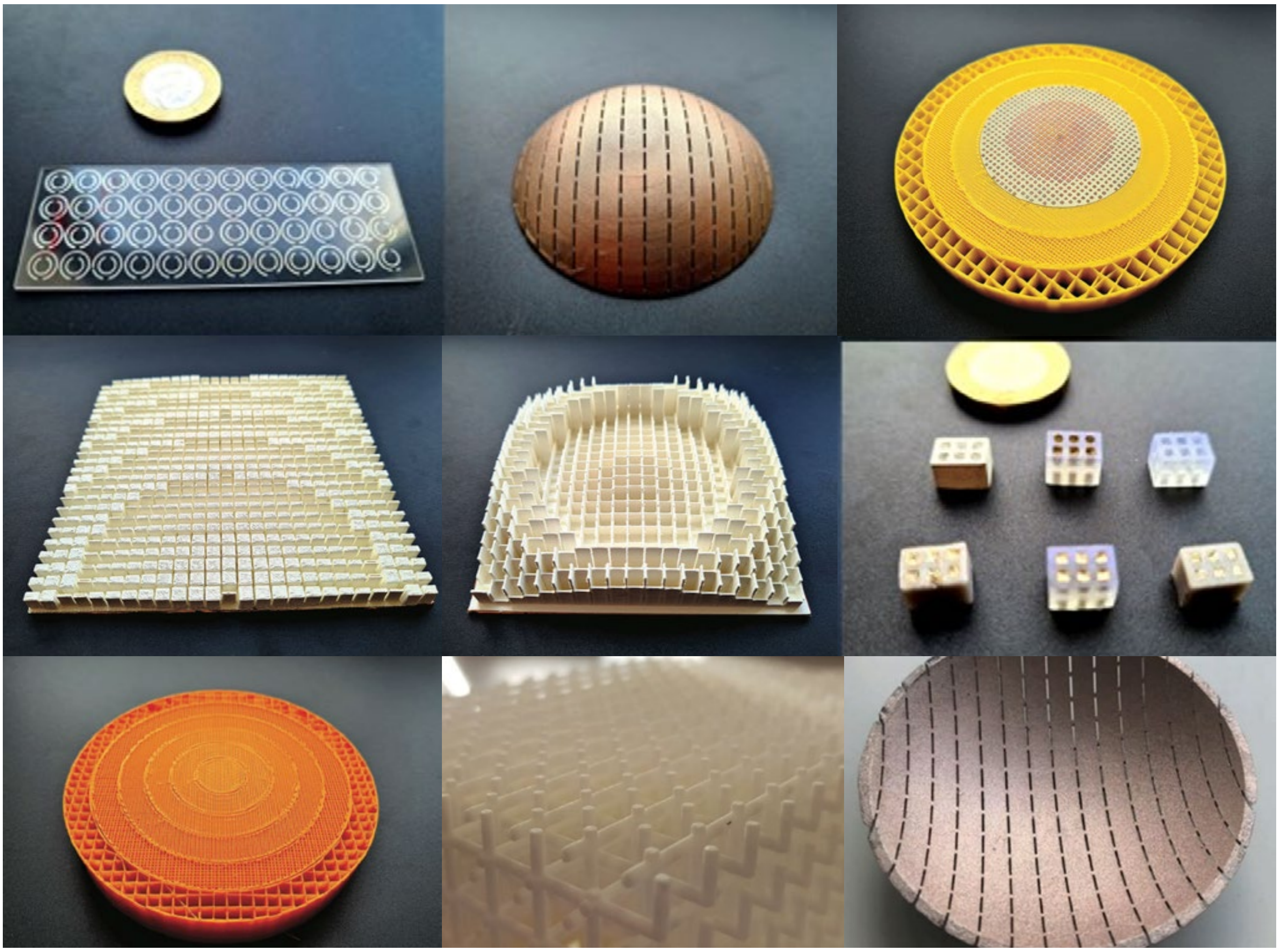

Fig. 1: Different 3D printed RF devices (frequency selective surfaces, dielectric lens, reflectarrays and artificial capacitor) at Loughborough University.

2D materials for space applications

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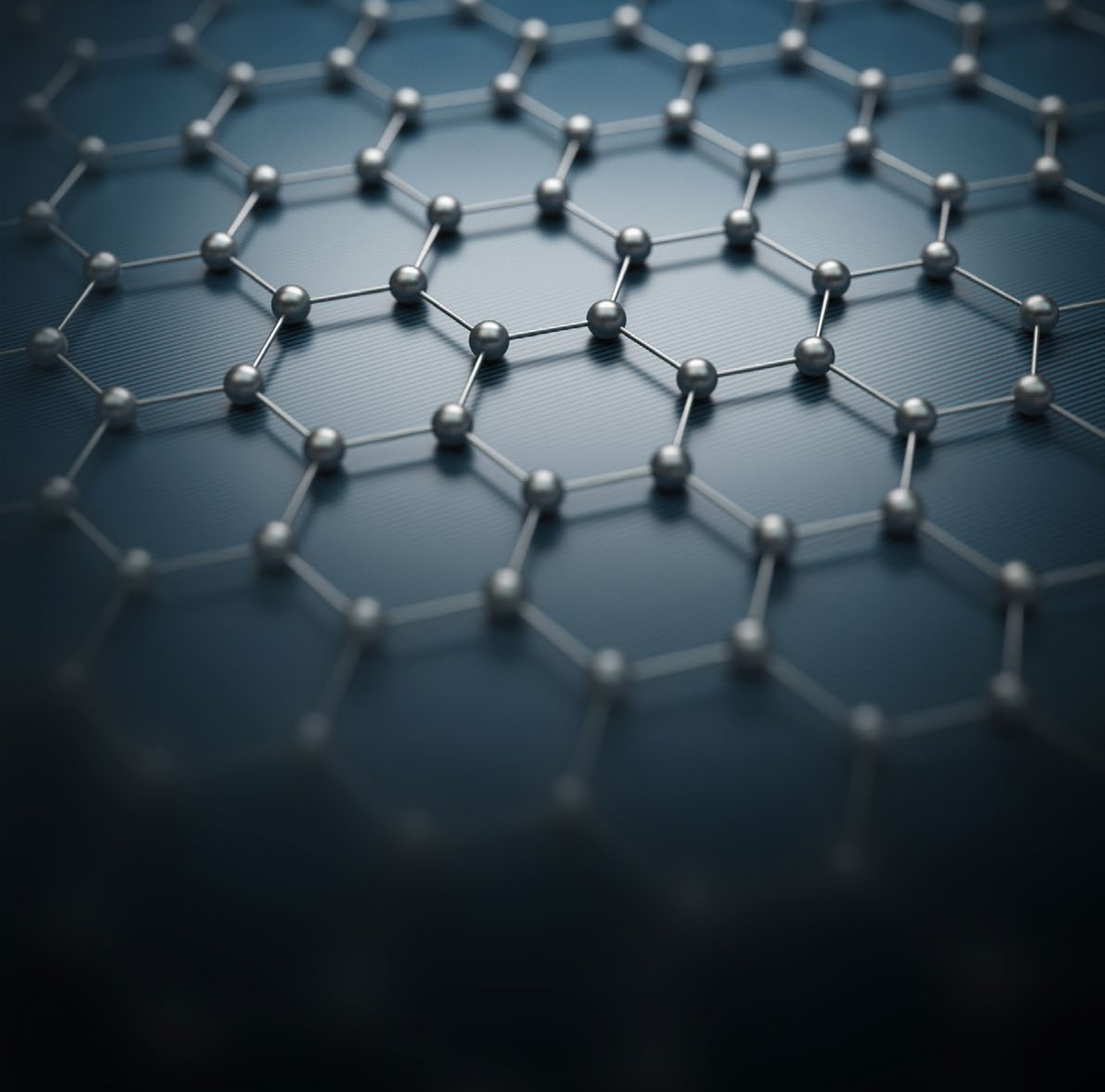

Overview

2D materials also known as graphene and related materials (GRMs) are a relatively new class of materials with versatile properties and use cases in a range of applications [1]. From being theoretically the strongest material with highest thermal conductivity to the recent advances representing potential for room temperature superconductivity this class of materials are on the right track to solve some of the persistent challenges humanity is facing [2]. Our vision of graphene and 2D materials-based technologies for solving some of the most pressing space challenges (e.g., radiation protection, thermal management, direct component development by printing, and coating in space) is to be cross-cutting i.e., solve challenges in space and find use cases on earth. It is, therefore, pertinent to develop the materials and components from this class of materials for space application to achieve the desired properties, which aren't achievable with any existing materials. GRMs have already proven to be useful both theoretically and experimentally in a plethora of Space applications including but not limited to propulsion by laser [3] and charge dissipation in space [4] among many others. For example, GRM enhanced LHPs demonstrate performance improvement in ground and as well as microgravity conditions hence can be employed for earth-based thermal management applications such as transportation and electronics [5].

Case Experience

We have been working on GRMs for space applications including but not limited to thermal management and printing and deposition in space, wound healing in space and moon regolith slippage during rover maneuvers. The first suspension/ink of graphene for printing and deposition in space was prepared using the Hydrofluoroether (HFE) based solvent, which is a space safe solvent [6]. The suspension was produced using a proprietary method of producing GRMs using high pressure homogenization (HPH). In this method GRMs can be produced with close to a 100% yield. GRMs including graphene, hexagonal boron nitride (hBN) and molybdenum disulfide (MoS2) suspended in HFE were investigated for their deposition using controlled droplet deposition on a silicon nitride substrate both on earth and space conditions. Sounding rocket platforms were used to test the deposition mechanism in microgravity conditions using Swedish Space Corporation and European Space Agency's collaboratively launched MASER14 in 2018 and MASER15 IN 2022. Some of these results are still under investigation. We have also developed graphene based LHP evaporators, which were tested in multiple parabolic flights and promising results demonstrating at least an order of magnitude enhancement in evaporation rate compared to the state-of-the-art steel and nickel-based evaporators. Additionally, we have also deployed GRM/polymer based additively manufactured composites on the wheels of Mohammad Bin Rashid Space Center's (MBRSC) moon rover, Rashid Rover I, launched recently via Hakuto-R 1 lander.

Opportunity for Research and Innovation

AThe field of GRMs for space applications is fairly under explored. We were arguably the first team in the world to test graphene and related materials for the first time in microgravity conditions utilizing platforms such as sounding rockets and parabolic flights. In our opinion Space economy goes together with the advanced materials (e.g., GRMs) developments and innovations. We are investigating applications in space for GRMs, we would expect the science & technology developed here to gradually inform applications areas. A technology built to fit the hostile environment of space can also find applications on earth. With GRMs we intend to perform such cross-cutting research, which solves challenges in space and on earth simultaneously. Thus, our work on producing GRMs suitable for space applications can also open new avenues of research areas for earth-based applications. With the current and foreseen developments in GRMs, we believe the challenges in Space, which can be solved with them include but are not limited to thermal management, electrical energy transmission, protection against galactic and cosmic radiations, communication, photonic propulsion systems, energy generation and conversion, in-situ resource utilization etc.

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Metamaterials for space

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Overview

A metamaterial is a 3D structure (a metasurface is a 2D structure confined to a plane) with a response or function that is impossible to achieve with any individual constituent material. The response/function results from the ensemble effects of designed and engineered elements (“Meta-atoms”). The response or function may be electromagnetic (photonic, RF & microwave, THz etc), acoustic (audio, ultrasonic, vibrational), magnetic, structural and thermal. The potential application of metamaterials in space is broad, covering domains from manipulation of electromagnetic signals through to control of spacecraft structures.

Case Experience

The UK Metamaterials Network was funded by the EPSRC to develop the network of people in academia, industry and government, working in metamaterials in the UK, such that it can have a positive impact on prosperity. To aid in this, the network formed three challenge areas in 2022, one of these is metamaterials for space. In line with the aim of the network, the challenge is tasked with developing an environment through which the UK metamaterials community can engage with and contribute to advancing this priority area through adoption of metamaterials related technology. Interaction of academics and stakeholders within the network have identified two themes which align to UK, European and other space agency goals, such as supporting space science and Earth observation, making access to space sustainable, safe and easy and providing a resilient and fair-for-all communication infrastructure. The first theme is Spacecraft Performance, which is further sub-divided into Communication, Propulsion, Power generation, Impact protection, Structural response, and Thermal control. The second theme is Observation and Sensing, which includes all aspects of observation and sensing associated with space applications, including observation of the near and far space environment, observation of the Earth from Space and spacecraft operational sensing.

Opportunity for Research and Innovation

There has already been substantial work on the use of metamaterials in antennas for non-space based applications, including commercial products. The relative maturity of some of this technology and the general characteristics of metamaterials solutions, makes this an obvious area in which metamaterials could be applied to address some of the challenges with space applications, such as weight, size, deployability, steering and weak signal strengths. Mechanical, acoustic and elastic metamaterials also have significant potential for application. A notable characteristic is the ability of lightweight and deployable metamaterials structures to provide high levels of vibration/sound reduction and impact protection, two key areas for space application, including future manned missions. Developments in mechanisms for propulsion and power generation, partially driven by an interest in interplanetary human exploration and other missions, place strong requirements on the use of advanced materials, for which metamaterials are well placed to provide potential solutions. As an example, solar sails need to cover a large area when unfolded. This requires very thin and light materials to be used, whilst also maintaining the required optical reflection or diffraction characteristics. They can also require significant heat dissipation, particularly if powered by lasers, which is problematic in space where radiation is the main source of heat dissipation. Most metamaterials research has so far been confined to research labs and base materials are selected to either suit the manufacturing process, or to provide the designed for performance. The suitability of the base materials for specific applications is often not considered. There is an opportunity to explore what performance can be achieved using metamaterials manufactured with existing space certified materials, or to validate performance optimised metamaterials in a space environment.

Regolith biocomposites for extraterrestrial construction

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Overview

Without a protective atmosphere or geomagnetic field, bullet-like meteors and exposure to space radiation will pose a deadly thereat to the future inhabitants of Lunar and Martian colonies. To mitigate these risks, future habitats will need meters-thick walls and ceilings fabricated from resources available on site – a concept known as in situ resource utilization (ISRU). Although several technology concepts for the generation of off-world construction materials have been proposed, most have significant drawbacks such as extremely high energy or water use, complex processing, or the need to be situated near rare mineral deposits. An alternative option is to use biopolymers as binders for extraterrestrial regolith to produce concrete-like biocomposite materials. The primary advantage of this approach is that biopolymers are produced under the mild conditions compatible with life, and any crewed habitat will have the systems needed to sustain life anyway.

Case Experience

Researchers at the Future Biomanufacturing Research Hub, University of Manchester, are pioneering the development of high-performance biocomposites for extraterrestrial construction. The author recently discovered that a common protein obtainable from human blood plasma (human serum albumin), when combined with a substance obtainable from human urine (urea), can serve an effective binder for both Lunar and Martian regolith – producing materials with compressive strengths as high as 39.7 MPa (Megapascals), a value that exceeds the strength of ordinary concrete. However, since it is neither ethical nor wise to farm human astronauts for construction materials, the researchers sought to “cut out the middle man” by employing plant-derived biopolymers instead. They discovered that ordinary potato starch could be employed in a similar manner, producing materials with compressive strengths as high as 91 MPa – a value that exceeds some definitions of high-strength concrete.

Opportunity for Research and Innovation

Given than concrete accounts for about 8% of global greenhouse gas emissions, there is a clear terrestrial benefit to developing relatively sustainable bio-based alternatives to established construction materials. The author has recently founded a start-up company, DeakinBio, which is developing similar bio-based materials as sustainable alternatives to ceramic tiles. According to an independent LCA, their materials have a 94% lower carbon footprint compared to ordinary ceramic tiles by circumventing the need for high-temperature kiln firing. Space exploration has a strong track record of spearheading advanced technologies, so further funding in this area could have substantial trickle-down benefits on Earth through the development of next-generation advanced material technologies that contribute to a sustainable, circular economy. Going forward, the researchers plan explore new bio-based material concepts for off-world construction, coupled with autonomous space-based fabrication techniques (e.g., additive manufacturing), before applying the findings to spearhead the development of sustainable construction technologies on Earth.

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New methods for the transport and management of lunar regolith

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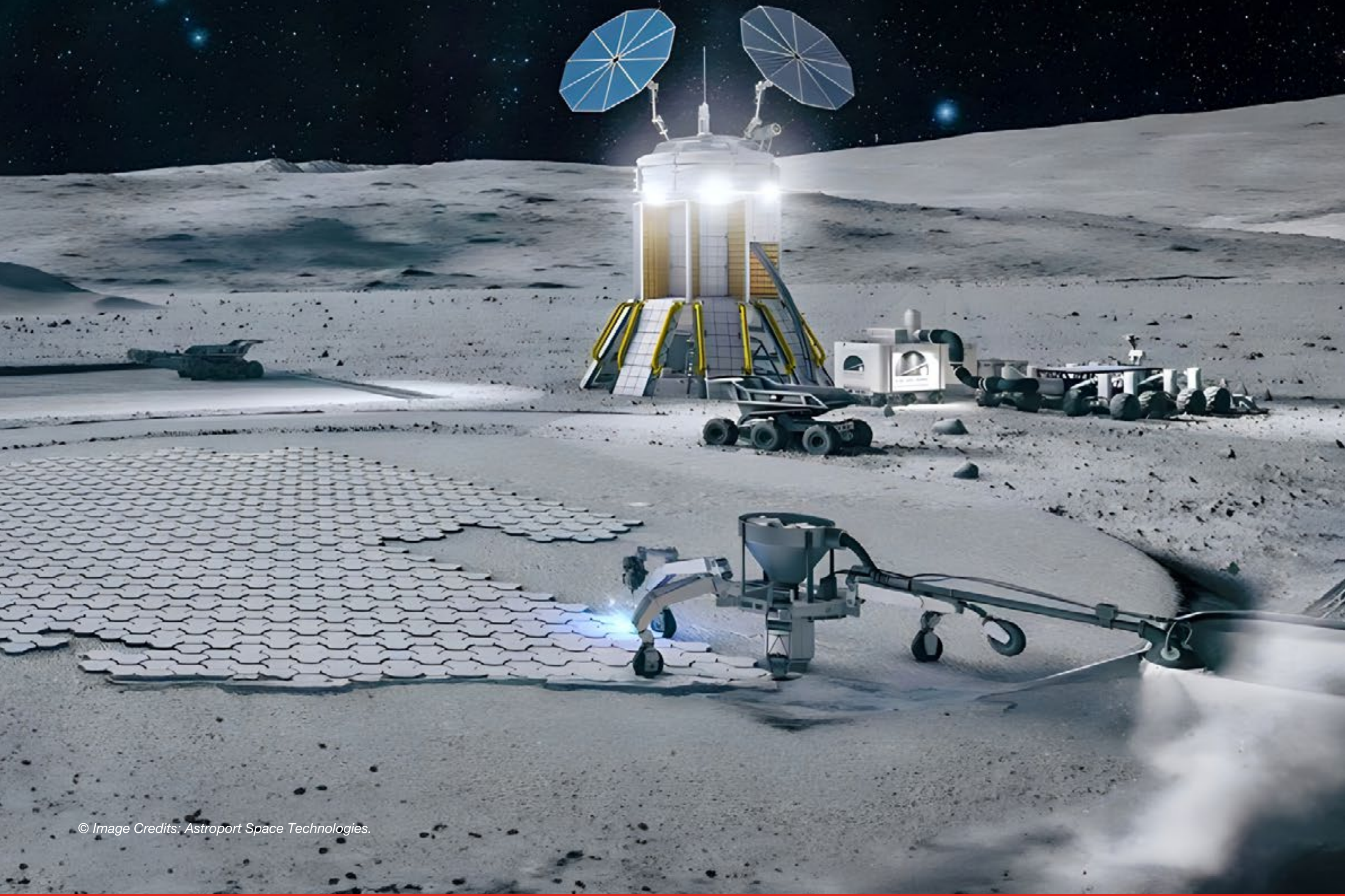

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Overview

In the field of space exploration, it is essential to assemble and transport particles for various applications, for example transporting lunar and Martian soil (typically regolith), for mining, to study geological aspects and establish habitats on the Moon or Mars. The ability to synthesize complex materials directly in space or build specific structures on the surface of other planets is one the main challenges to be addressed in such a context. In this regard, the utilization of lunar regolith is being explored with regard to several potential applications, e.g., as feedstock for 3D printing and even as a solid-support substrate for plant growth, a source for extraction of essential plant-growth nutrients, a substrate for microbial populations in the degradation of wastes, a source of O_2 and H_2, which may be used to manufacture water [1-3]. However, the lunar and Martian soils are difficult to handle, because they are made of abrasive and reactive materials. Regardless of its intended use, the use of lunar regolith is hindered by its intrinsic nature, which makes its management (transfer from the surface of the Moon inside 'containers' or transport inside 'pipes') relatively difficult. Lunar regolith is characterized by very strong electrostatic effects and internal friction, which strongly limit its 'flowability'.

Case Experience

The author is collaborating with the European Space Agency (ESA) in the framework of an OSIP project entitled "Vibrations as a novel tool for particle self-assembly and regolith vibro-fluidization in space environments". OSIP is the Open Space Innovation Platform that the European Space Agency ESA launched in 2019 to better serve the emerging needs of the modern space sector. With this project, novel particle-control strategies based on "vibrations" are being explored at the University of Strathclyde. In microgravity, vibrations can be used as an alternate means to control the dynamics of solid particles dispersed in a liquid forcing them to self-organize and form specific three-dimensional complex structures (which can be used as backbones for special alloys or other materials) [4]. In the presence of a gravitational field such as that on the surface of Moon, there is potential to use vibrations to force regolith (which is characterized by strong internal inter-particle friction) to behave as a 'fluid' [5] thereby making its transportation and utilization in the context of several applications much easier. Researchers at the University of Strathclyde are combining theoretical, numerical and experimental work to study in detail the ability of vibrations with different amplitudes, frequency and direction to induce "liquefaction" of regolith-type particles (simulants) for different levels of gravity. The behaviour of lunar regolith is being assessed considering various geometries or configurations, i.e. pipes (with square or circular cross section and different constant transverse size) under different inclinations and "hoppers" (ducts with converging walls) with various sizes of the outlet sections.

Opportunity for Research and Innovation

Moon is the closest available target for the definition and testing of new technologies that make use of locally available (extra-terrestrial) resources for the production of consumables for life support systems, propellant, and/or feedstock for 3D printing. Lunar regolith is the most abundant material on the Moon and it could be used for the development of manned installations and many other applications. Most of its surface is covered with this substance, namely, a mixture of fine dust and rocky debris produced by meteor impacts, which displays many similarities with analogous materials available on asteroids and other rocky planets. There is therefore strong interest in this material and its potential exploitation for the colonization of Moon and the definition of new technologies for the exploration and exploitation of even more distant sites. In such a context, the present project targets the elaboration of a new regolith control strategy relying on the combined use of different mechanical stimuli.

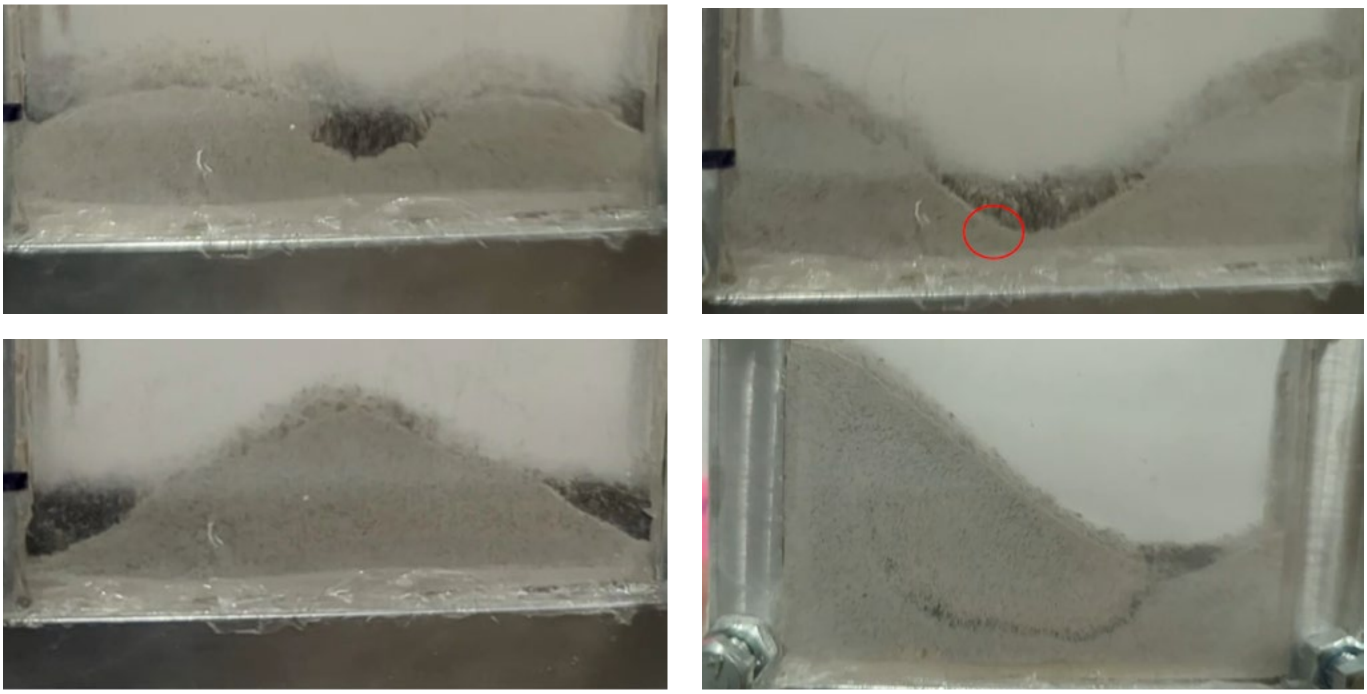

Figure: Snapshots of various convective states enabled in a layer of lunar regolith (simulant) with initial constant depth when it is subjected to vertical vibrations (Note: black particles with larger size tend to separate from particles having a smaller size and accumulate in the regions where the thickness of the material becomes smaller as a result of the liquefaction process).

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