Composites for UK strategic advantage: Granular level insights into enabling technologies for Ceramic Matrix Composites & Metal Matrix Composites

DSIT-IfM Joint Stakeholder Workshop Technical Report

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Project Partner
UK Department for Science, Innovation & Technology (DSIT)

Acknowledgements
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Disclaimer

The views expressed in this report do not imply the expression of any opinion on the part of the UK Government, the UK Department for Science, Innovation & Technology (DSIT) or contributing organisations.

Parts of the report have been removed due to commercial sensitivities.

Executive Summary

Ceramic matrix composites (CMCs) and metal matrix composites (MMCs) outperform traditional materials across a combination of performance characteristics with a significant promise in enabling multiple high growth industrial sectors. Their increasing relevance aligns with the *UK Industrial Strategy*, which positions advanced materials as central to future productivity and economic growth. This led to a joint workshop hosted by the Institute for Manufacturing, University of Cambridge, and the UK Department for Science, Innovation & Technology in London on 20 January 2026.

The workshop convened UK stakeholders from industry, academia, research technology organisations, and government to explore future opportunities and barriers in CMCs and MMCs. The workshop led to identifying priority use cases, key technologies and capabilities, their cross-cutting nature, value chain bottlenecks, and key organisations required for developing and scaling these materials, in the context of growing national interest in advanced materials.

This report summarises key workshop findings and technical details. It also describes the workshop approach, relying on a framework to guide more systematic discussions, in detail and reflects on key learnings for future workshops or similar evidence gathering exercises. The report also reviews the relevant literature on CMCs and MMCs providing further insights into their growth potential, key application areas, manufacturing processes, and barriers (see Appendix B).

Across the workshop, there was general agreement that although CMCs and MMCs currently serve niche markets, they outperform traditional materials across a combination of performance characteristics and offer significant potential to enable multiple high-growth industrial sectors; sectors in which the UK already has strong industry presence. A shared view emerged that the UK has the potential to lead across CMC and MMC supply chains at the European or wider level in the next 5-10 years as identified through the different use cases explored during the workshop. The use cases helped to showcase that many value chain capabilities already exist in the UK, including a number of capabilities in which the UK leads. Several cross-cutting insights however highlighted that future potential will depend on demand signals, ecosystem convening, capital investment, scale-up capacity, enabling technologies and skills.

More specifically, participants identified a set of use cases with strong UK potential within a 10-year horizon, concentrated in civil aerospace, defence, and nuclear fission and fusion, including aero-engine hot-section components, defence propulsion and airframe structures, and nuclear thermal-management parts. Different composite families were associated with distinct roles: oxide-oxide (Ox/Ox) CMCs for near- to mid-term thermal-protection components around 1000 °C, silicon carbide-silicon carbide (SiC/SiC) CMCs for higher-duty or irradiation-exposed environments, and aluminium- and titanium-based MMCs for high-load, thermally managed defence and aerospace applications. Each use case is described in detail in Section 5.

Participants emphasised that sustained demand signals from original equipment manufacturers and government procurement are essential, supported by clear component requirements, structured pull-through programmes, demonstrator funding, capital investment in manufacturing infrastructure and pilot facilities to raise manufacturing and supply chain readiness and give confidence to end users. In line with this, the need for developing, improving and standardizing manufacturing routes was highlighted as an essential step across all use cases.

Early development of design allowables, standardising test and evaluation methods, and improving simulation and design tools, and alignment with certification bodies could establish industrial access and UK leadership. Participants also highlighted the importance of other enabling capabilities including expanded domestic skills pipelines at the research, technical and manufacturing level, automation and enhanced supply chain resilience. Key findings are further detailed in Section 2.

The workshop also strongly validated the analytical approach taken to first select use cases and standardize terminology around related technologies and capabilities, followed by additional questions, which were answered in relation to the standardised terminology. For example, key UK actors were identified in relation to the technological capabilities that they have or could have in the future. This standardised terminology of technologies and capabilities could be further used to more systematically gather evidence if further analysis was required.

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Contributing organisations

3M UK Ltd

Alkegen Ltd

Advanced Manufacturing Research Centre (AMRC)

AMRICC Centre

Archer Technicoat Ltd

AWE Ltd

Carbon Three Sixty Ltd

Composites UK

Cristex Ltd

Cross Manufacturing Company Ltd

Composite Test & Evaluation Ltd

Defence Science & Technology Laboratory (Dstl)

High Value Manufacturing Catapult (HVMC)

High Temperature Material Systems Ltd

Imperial College London

LAYRR Ltd

Lucideon Ltd

Materion UK Ltd

MBDA Ltd

Manufacturing Technology Centre (MTC)

National Composites Centre (NCC)

Rolls Royce Ltd

Royce Discovery Centre

SHD Composites Ltd

Slingsby Advanced Composites Ltd

Swansea University

TiSiCs Ltd

The Welding Institute (TWI)

UK Atomic Energy Authority (UK AEA)

UK Department for Business & Trade

UK Department for Science, Innovation & Technology

University of Birmingham

University of Cambridge

Zircotec Ltd

1 Context

The UK's focus on advanced materials is strongly shaped by the *UK Industrial Strategy Advanced Manufacturing Sector Plan* (2025)[1], which positions advanced manufacturing as one of the eight growth driving sectors – with advanced materials as one of the key frontier industries – central to productivity, competitiveness and long-term economic growth. With this as a driver, a joint workshop on ceramic matrix composites (CMCs) and metal matrix composites (MMCs) was hosted by the Institute for Manufacturing, University of Cambridge, and the UK Department for Science, Innovation & Technology in London on 20 January 2026.

The workshop brought together a variety of UK CMC and MMC stakeholders from the private sector, including suppliers, manufacturers, and original equipment manufacturers (OEMs), academia, research technology organisations (RTOs) and the UK Government.

The workshop aimed to reveal future opportunities and barriers for innovation leadership, economic growth and national resilience in CMCs and MMCs. Its focus was on characterizing technologies, capabilities, and key organisations that may be needed to develop and scale these materials and technologies, while mitigating value chain risks and blockers.

CMCs and MMCs were selected for several reasons in addition to heightened policy interest. Although they remain niche materials with relatively modest market potential compared to other emerging fields, they are projected to grow steadily over time.[2] CMCs and MMCs outperform traditional materials across a combination of performance characteristics such as strength-to-weight ratio, durability, high temperature resistance, etc. They also show significant promise in enabling multiple high-growth industrial sectors, including dual-use applications. Furthermore, CMCs and MMCs are at a relatively immature stage of manufacturing readiness as evidenced by the absence of an industrial product manufacturing base beyond niche and low volume uses.

At the same time, as presented in Appendix B, a review of existing evidence highlights a number of key challenges including limited viable business cases beyond high-cost low volume uses, supply chain bottlenecks for critical materials, need for improved manufacturing processes, automation, simulation, testing and data, etc.[3] Understanding

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[1] UK Government (2025). Advanced Manufacturing Sector Plan.

[2] Market.us (2025a). Ceramic Matrix Composites Market.; Market.us (2025b). Metal Matrix Composites Market.

[3] See Section 2.3 for review of: Shrivastava et al. (2024); Karadimas & Salonitis (2023); NASA (2024); NCC (2025); HVMC (2025); Pooja et al. (2025); Mussatto et al. (2020); National Composites Network (2006).

these challenges at a more granular level can help to identify future opportunities and barriers to achieve innovation leadership.

1.1 Policy context and existing evidence base

As part of the *UK Industrial Strategy Advanced Manufacturing Sector Plan*[4], materials innovation is increasingly recognised as a cross-cutting enabler across advanced manufacturing sectors such as aerospace, but also clean energy industries, life sciences, defence, and digital technologies.

Several other key UK initiatives – including the National Materials Innovation Programme, funding for testing and verification capabilities, the Defence Materials Centre of Excellence, the National Composite Centre (NCC) open access carbon fibre innovation facility – all highlight the importance of materials innovation of which advanced composites play a significant part.

Recent UK strategy and evidence on composite materials includes:

- **The Sir Henry Royce Institute *National Materials Innovation Strategy* (2025)**[5]
  Cross-sector UK materials strategy developed in an effort to build national consensus around key areas of focus and speed up material development cycles and unlock untapped potential in the UK.
  Composites are within the "Structural Innovations – Materials for sustainable structural systems" theme focusing on sustainability and supply chain resilience but not specifically focused on CMCs or MMCs.

- **The High Value Manufacturing Catapult (HVMC) *Composites Manufacturing Roadmap* (2025)**[6]
  Composites manufacturing roadmap identifying key industry challenges, technology capabilities, and the HVMC's developments.
  Coverage is cross-composites rather than CMC or MMC-specific.

- **The NCC *Technology Strategy* (2025)**[7]
  CMC strategy identifying and prioritising the key technology and capability challenges with a specific focus on three sectors: aerospace, defence and energy.

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[4] UK Government (2025). Advanced Manufacturing Sector Plan.
[5] Henry Royce Institute (2025). National Materials Innovation Strategy.
[6] HVMC (2025). Composites Manufacturing.
[7] NCC (2025). Technology Strategy.

The NCC technology portfolio is grouped into the 4 categories of advanced materials, processes, products and growth initiatives.

Earlier strategies and evidence also provide valuable foundations:

- **The Aerospace Technology Institute (ATI) FlyZero *Novel Composites and Composite Aerostructures* position paper (2021)**
  This position paper reviews key technology developments that may have the potential to aid the design and manufacture of zero carbon emission aircraft with a key focus on fibre reinforced polymer composites (PMCs), nanomaterials, other additives, novel textile forms, etc.

- **The Lucintel UK Composites Industry Competitiveness and Opportunities report (2020)**[8]
  The report investigated the UK composites supply chain and opportunities across key industries, focusing on PMCs.

- **The National Physical Laboratory (NPL) review of composites regulatory infrastructure (2019)**[9]
  The study identified regulatory barriers preventing the adoption of composite materials, in particular fibre reinforced PMCs.

- **The ATI *Composite Material Applications in Aerospace* report (2018)**[10]
  The document is the result of a consultation across the Aerospace sector to identify the priority technologies needed for composite material exploitation, as well as the priority product areas for which composites are of interest across aircraft, structures, systems and propulsion components. Coverage is cross-composites rather than CMC or MMC-specific.

- **The Composite Leadership Forum *UK Composites Strategy* (2016)**[11]
  This is a widely referenced strategy document based on market predictions and focused, predominantly, on polymer matrix composites (PMCs).

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[8] Lucintel (2020). UK Composites Industry Competitiveness and Opportunities.
[9] NPL (2019). Increasing UK Competitiveness by Enhancing the Composite Materials Regulatory Infrastructure.
[10] ATI (2018). Insight: Composite Material Applications in Aerospace.
[11] Composites Leadership Forum (2016). The 2016 UK Composites Strategy.

- **The National Composites Network Technology Roadmap for the Metal-Matrix Composites Industry (2006)** [12]
  An early activity to develop a UK MMC-specific roadmap.

- **Library of reports on composite materials at Composites UK (trade association for the UK composites industry)**[13]

- **Academic research**

Together, these initiatives, strategies, and evidence illustrate substantial and growing interest and potential in advanced materials. To date, studies on fibre reinforced composites have been concentrated (in the main) on fibre reinforced polymer matrix composites. Much less attention has been given toto CMCs and MMCs.

1.2 Workshop aim and objectives

The workshop was aimed at revealing future opportunities and barriers for innovation leadership in CMCs and MMCs. The focus was on characterizing enabling technologies, capabilities, and key organisations that may be required to develop and scale these materials and technologies, while mitigating value chain risks and blockers.

Key objectives:

- Pilot *the Technology Strata Framework* [14] which provides a common basis for distinguishing technological entities that enables:
  - Developing a common language
  - Ensuring attention to a full variety of technologies, at an appropriate level of granularity
- Consider priorities and perspectives of all stakeholders, including OEMs, small medium enterprises, suppliers, vendors, research technology organisations, academia, etc.
- Provide an enriched evidence base to inform the composites innovation community and policymakers

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[12] National Composites Network (2006). Technology Roadmap for the Metal-Matrix Composites Industry.
[13] Composites UK (2026). Library.
[14] Döme et al. (2023). Technology Strata: A Framework Distinguishing Between Technologies.

2 Key findings

2.1 Cross-cutting findings

Use cases identified deployable products within 10-year reach, focusing predominantly on civil aerospace, defence, nuclear fission and fusion applications. These included products that include aero-engine hardware (exhaust cones/cylinders, heat shields, shrouds, seals), defence propulsion and airframe hot-structures, and nuclear fusion and fission thermal components.

Oxide-oxide (Ox/Ox) CMCs were viewed as near- to mid-term options for thermal-protection and secondary hot section parts at ~1000 °C where oxidation resistance and cost matter. Silicon carbide-silicon carbide (SiC/SiC) CMCs were associated with higher-duty or irradiation-exposed roles (nuclear fusion and fission components, primary hot section aero components) where load, temperature, or neutron tolerance exceed Ox/Ox performance envelopes.

Metal matrix composites, such as SiC-reinforced aluminium and titanium-based MMCs, were also highlighted as important materials for specific high-load, thermally-managed defence and aerospace components, where MMCs can offer the right balance of strength, stiffness retention at temperature, and manufacturability.

Primes/OEMs and government procurement are essential for catalysing demand and convening the UK ecosystem. The importance of clear demand-pull and operational requirements (temperature, environment, duty cycle, component life, inspection regime) was highlighted. Participants noted that such clarity could strengthen confidence across supply chains and allow material properties and performance needs to be defined earlier, avoiding reformulation cycles and enabling supplier investment in standardised fibres, slurries and manufacturing routes.

Participants emphasised structured pull-through programmes that tie research and development (R&D) to funded demonstrators and qualification paths, rather than ad-hoc projects. Collaboration on R&D, product development and process development with end users was suggested (design-for-manufacture, mounting, joins, non-destructive evaluation (NDE) acceptance, standardisation, etc.) to shorten technology development cycles and manufacturing scale-up. Consistency and long-term direction, demand and funding were a recurring theme.

France was cited as an example of where sustained government and industry demand (civil, defence, nuclear) helped to create a connected CMC supply chain.

Capital investment in manufacturing scale-up, capacity, and competence could help raise manufacturing and supply chain readiness and give confidence to end users. High entry costs for core production infrastructure such as prepreg (pre-impregnation) lines, specialised forming equipment, and controlled-environment manufacturing spaces were repeatedly noted. Across Ox/Ox, SiC/SiC, and MMC-adjacent processes, participants highlighted, for example, the need for additional hot isostatic presses (HIPs), increased HIP turnaround capacity in the long-term, and access to pilot-scale manufacturing lines to bridge lab-scale developments to industrial throughput. To accelerate product qualification, stakeholders also identified the importance of funding demonstration environments – including test rigs, pilot plants, and sub-component demonstrators – which are essential for validating designs, maturing processes, and de-risking adoption for OEMs and government customers. There is a need for pilot production facilities to raise manufacturing readiness levels and give end users confidence that products can be made reproducibly and economically.

Improving and scaling-up manufacturing routes. There are multiple processing routes each with their distinct advantages and disadvantages. There is a need to better understand, develop, down select and standardise processing routes based on required material properties and cost/performance needs, which need to be specified early on. This demands materials science understanding (rheology, densification, shrinkage, interphases) tied to design tools, standards, and testing so processes can be rapidly scaled without losing quality. Mapping potential scenarios of manufacturing routes could help this process.

Early development of design allowables and alignment with certification bodies (such as the Civil Aviation Authority or equivalent authorities) could establish industrial access and UK leadership. Securing regulatory approval ahead of international competitors was seen as a source of first-mover advantage; the country that generates the accepted allowables effectively becomes the default supplier, while those who wait for third-party approvals must later replicate the full qualification effort and attempt to displace an established incumbent.

Standardised test methods, acceptance criteria and non-destructive testing and evaluation (NDT/NDE) procedures, all supported by shared, quality-controlled datasets covering materials, process windows and defect-performance relationships were highlighted as potential areas where the UK could lead. Participants noted that pre-competitive characterisation and coordinated testing strategies would reduce duplicated effort and accelerate supplier qualification. Formalising progressive test pyramids in collaboration with aerospace and energy certification bodies was seen as essential to avoid "one-off" demonstrations that cannot be certified, scaled or industrialised.

Design tools, simulation capabilities and data are at an immature state and need to be developed and verified in order to satisfy various certification bodies. Participants stressed the need for process–structure–property models coupled to performance simulation (thermal, oxidation, creep, thermal-shock, vibro-acoustic, etc.) so design values flow from measured data into allowables and design allowables handbooks. Toolchains should support test-pyramid planning (from coupons, through sub-element and element, to system) and link to manufacturing data to accelerate allowables and configuration control. More generally, this will require significant investment and could be addressed through the creation of joint industry projects with academia and RTOs.

Conventional structural design approaches cannot be readily applied to evaluate CMCs. Strength is governed by the influence of defects, and this requires stochastic/probabilistic design methods rather than normally distributed material strength-based methods. Thus, there is a need to ensure that designers have the requisite skills and the associate niche modelling tools to support the product life cycle of CMCs.

Mechanisation of hand processes followed by automation will secure industrial leadership for reproducibility, economics and capacity. Lay-up and deposition processes such as automated tape laying (ATL) and automated fibre placement (AFP) will become increasingly relevant where stable oxide preforms or unidirectional tapes are available. Additive manufacturing methods, including metal binder jetting, were also highlighted as emerging automated routes for complex geometries.

Skills as one of the key enablers. It was suggested that a two-track skills plan could work well: (1) upskilling the current workforce in R&D, engineering, operation, and production and (2) expanding education pathways (short courses, apprenticeships, university degree modules, doctoral students); both designed and delivered with industry. Retention hinges on competitive salaries and visible career paths from lab to line to certification. Access to demonstration environments (testbeds, burner rigs, altitude rigs, nuclear-relevant labs) must be part of training so skills map to real qualification needs. Practical skills and hands-on craft training will help secure industrial capability and capacity for growing the industry.

The workshop also enabled understanding the importance of supply chains in relation to fibres and precursor materials but also in a wider context.

2.2 Other potential use case applications identified

A number of use case applications that were not explored in detail in this workshop were also identified.

Defence	Aerospace	Space	Energy	Automotive	Industry	Other
[Section removed]	Ox/Ox exhaust mixers	Thermal protection systems (Carbon/SiC, UHT CMCs, SiC/SiC)	Fusion core blanket components, <1000degC, corrosion, radiation, high specification	Brakes	Radiant burner tubes for steel processing and heat treatment	CMC for implants
	Aero engine hot section shrouds combustion chamber	Heat shields for thermal applications	Fusion out of core pipework, 500-1000°C, corrosion, lower specification (SiC/SiC)	Carbon/SiC automotive brakes	SiC/SiC for ethylene cracking reactor tubes/coils	Geo ceramic matrix composites (low cost)
	Brakes	High alumina fibre for heat shield tiles (spacecrafts)	Fission (small modular reactors (SMRs)) - accident tolerant fuel tubes, perhaps not UK?	Ox/Ox for electric vehicle (EV) battery enclosures		High alumina fibre and/or paper for MMC components
	SiC/SiC aero engine components	UHT CMC rocket nozzles	Fission molten salt reactors (MSRs)	Ox/Ox for Formula 1 applications		Ox/Ox heat shields

Defence	Aerospace	Space	Energy	Automotive	Industry	Other
	Al/Al2O3 Struts, Wheels, Actuators		MMC for fusion (neutron shielding)			Electromagnetic interface shield
	Ox/Ox single use exhaust		SiC/SiC for nuclear fission fuel casing			
			SiC/SiC breeder blankets for nuclear fusion			

3 Workshop

This workshop delivered insights into priority use cases, key technologies and capabilities, their cross-cutting nature, value chain bottlenecks and key actors and capabilities required for developing and scaling CMCs and MMCs, as intended.

It strongly validated the analytical approach taken to first select use cases and standardize terminology around related technologies and capabilities, followed by additional questions, which were answered in relation to the standardised terminology. For example, key UK actors were identified in relation to the technological capabilities that they have or could have in the future. Furthermore, the standardised terminology of technologies and capabilities could be supplemented, for example, by benchmarking, SWOT analysis, roadmapping, etc. if future evidence needs are required.

The workshop was guided by *the Technology Strata Framework*[15] with an aim to provide a common basis for distinguishing technological entities and ensure that attention to full variety of technologies at the right level of granularity was paid (see Figure 1). Once the framework was populated with technological entities, it was then used to guide further discussions.

The questions guiding the workshop included:

1. What are some **exemplar use cases** (CMC/MMC composite material with concrete functionality, performance and application) with high UK potential?
2. By focusing on a single exemplar use case, how would you describe the **development trajectory of the material/ product** (starting from its underpinning scientific principles, through integration with other materials and technologies, all the way to final product)?
3. By focusing on the same single exemplar use case, **what innovation 'toolbox' technologies** are needed now, in the next 5 and 10 years to support the development and scaling of this material/product?
4. By focusing on the same single exemplar use case, are there any **other required capabilities/ enablers** (e.g., workforce, finance, standards, routines, facilities, etc.) that are needed now, in the next 5 and 10 years?
5. What technologies and other capabilities/ enablers are **cross-cutting** across composites (CMCs, MMCs but also PMCs) and application sectors? Or are any of the technologies and capabilities highly specialised?

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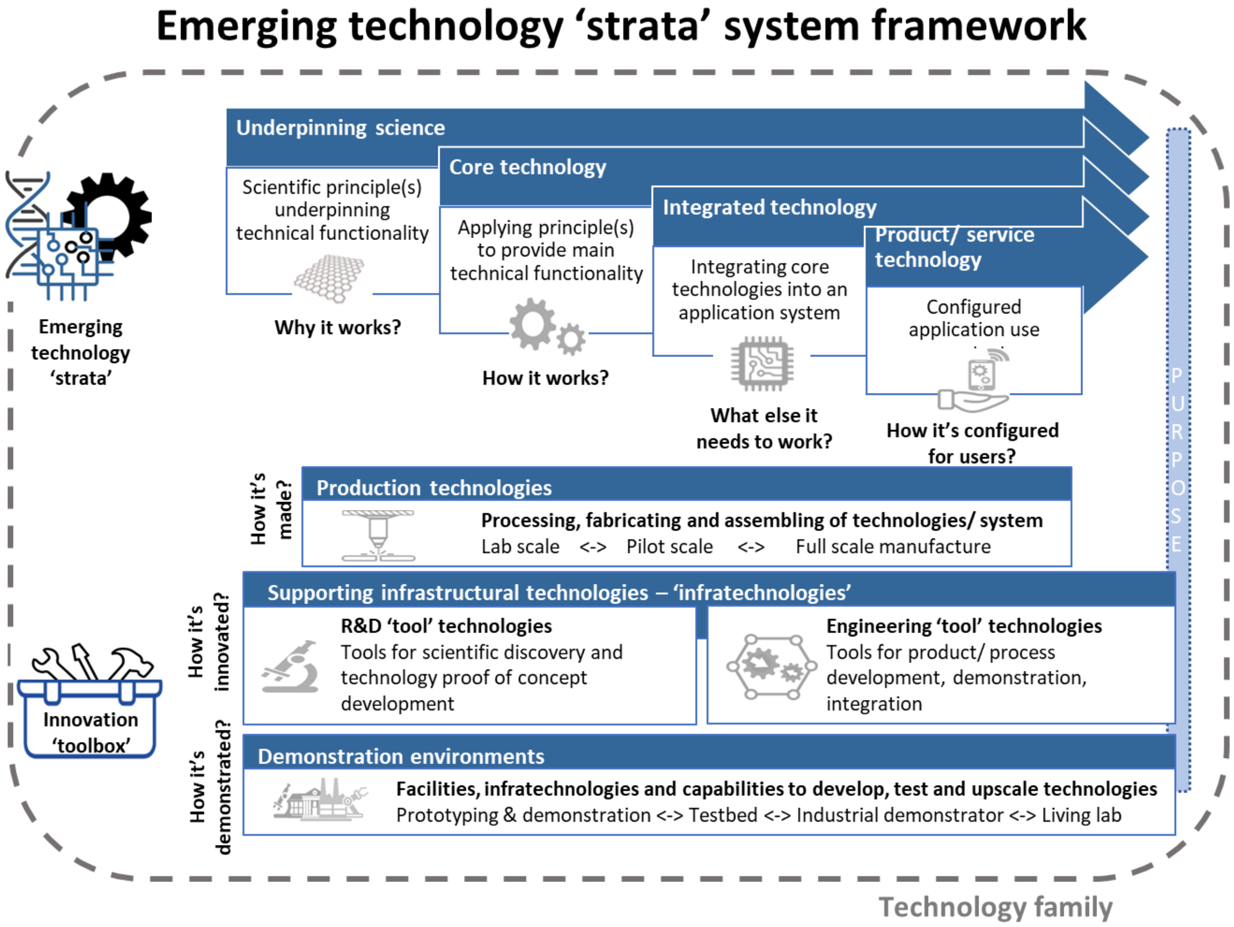
[15] Döme et al. (2023). Technology Strata: A Framework Distinguishing Between Technologies.

6. Who are the **key actors and firms** in the value chain with relevant, current or future, capabilities? What are the, current or future, **value chain bottlenecks and risks** in the wider ecosystem?

Figure 1 Emerging Technology Strata Framework that enables distinguishing between technological entities. Source: Döme et al. (2023).



3.1 Framework guiding the workshop

As shown in Figure 2, *the Technology Strata Framework*[16] was used to develop a common language around an exemplar use case and ensure attention is paid to a full variety of technologies at the right level of granularity. A template representing the framework was provided at each table.

One of the main points, and first steps, was to identify and select one exemplar use case per table to narrow down further discussions. This step is necessary to enable more targeted discussions as innovation pathways from science through materials/ technologies to products can be better explored and forecasted when a clear application domain is provided. This then enables identifying key enablers and barriers along the innovation pathway, the aim of the workshop.

More specifically, CMC/MMC composite materials with concrete functionality, performance and application with high potential for the UK were identified. Based on collective agreement at each table, one exemplar use case was selected with the key selection criteria being high potential for the UK.

3.2 Workshop facilitation

The step-by-step guide to the facilitation is provided below:

Step 1: Individually identify exemplar use cases (composite material with concrete functionality/ performance and application) with highest UK potential, write on green post-it notes (5 mins)

Step 2: Choose 1 exemplar use case per table, map out technology according to the boxes on the template, use template directly (15 mins)

Step 3a: Map out enabling ‘toolbox’ technologies, thinking about 1-2 yrs, 5 yrs, 10 yrs, use template directly (45 mins)

Step 3b: Identify any other required capabilities/ enablers (e.g., workforce, finance, standards, routines, facilities, etc.), use yellow post-it notes (15 mins)

What technologies and other capabilities/ enablers are cross-cutting across composites (CMCs, MMCs but also PMCs) and application sectors? Or are any of the technologies and capabilities highly specialised? (40 mins)

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[16] Ibid.

Step 4: Visit other tables and identify cross-cutting or highly specialised enabling technologies and capabilities (both across composites and across application sectors)

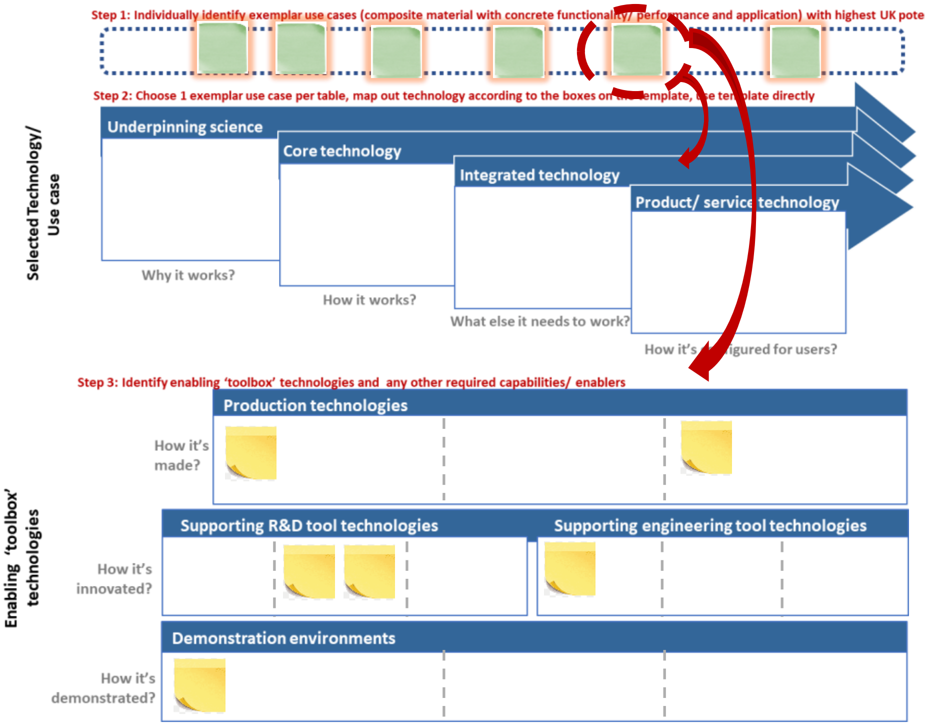
Step 5: Report back to your table and add notes on template, use pink post-it notes

Who are the key actors and firms in the value chain with relevant, current or future, capabilities? What are the, current or future, value chain bottlenecks and risks in the wider ecosystem? (40 mins)

Step 6: Identify key actors and firms with relevant capabilities, use blue post-it notes

Step 7: Identify value chain risks, use orange post-it notes on template

Figure 2 Workshop template used, divided into top (step 1 & 2) and bottom (step 3) in practice.



3.3 Reflections and learnings for future

In general, workshops and other evidence gathering exercises benefit significantly from being designed with clarity in terms of their main objective and structured to support the broader sequence of analysis, whether it concerns early scoping, deep dive benchmarking, supply chain mapping, strategy setting, etc. This ensures each workshop or analytical activity efficiently advances overall thinking, rather than duplicates effort or generates insights that cannot be connected to downstream evidence.

The workshop methodology proposed here could be considered as one of the initial/ early steps of analysis helping to standardise terminology related to the main technologies and capabilities in question enabling more systematic follow-on discussions, with a clear application sector in mind.

This workshop delivered insights into priority use cases, key technologies and capabilities, their cross-cutting nature, value chain bottlenecks and key actors and capabilities required for developing and scaling CMCs and MMCs, as intended.

The workshop strongly validated the analytical approach taken to first select use cases – more specifically, concrete composite material with concrete application – and standardize terminology around key technologies and capabilities, followed by additional questions, which were answered in relation to the standardised terminology. Generally, this enabled more systematic discussions as basics of the technology have been laid out and follow on discussions specified which aspect of the technologies/capabilities they are referring to.

If desired in next round of analysis or evidence gathering, the standardised terminology of technologies and capabilities could be supplemented, for example, by benchmarking, SWOT analysis, roadmapping, etc. if future evidence needs are required.

A post-workshop survey was sent to the participants. Main observations and feedback are provided below, but as already implied, their relevance is highly dependent on the key questions and sequence of the analytical process.

- Selection of one exemplar use case per table helped to focus follow-on discussions.
- The template enabled focused and productive discussions.
- The template helped to surface issues and insights that might otherwise have been missed.
- Workshop instructions and template prompts and instructions were easy to understand, but the level of detail on the template could be expanded.
- Advance explanation of the full template (top and bottom at the same time) could provide more clarity in terms of the relationship between technology, product, and use case, as well as how information should flow through the different parts of the template. Making these distinctions explicit at the outset would likely streamline future exercises and ensure more consistent inputs across groups.

- Sharing information and structure of workshop in advance of the workshop was suggested to help participants better prepare and organise ideas.

Composite-specific points:

- The template was useful for composite-specific discussions.
- Diving deeper into and exploring limitations and scenarios of different production technologies was suggested, which could be a potential next step building on current findings.
- Exploring challenges and opportunities for the UK, including UK's capabilities, technology needs with examples, market size, routes to market and industrial growth was suggested to understand where investment and support is needed. This could be a potential next step building on current findings, for example using roadmapping.

4 Use cases in detail

Seven use case were selected and explored by participants:

4.1 Silicon carbide fibre reinforced titanium alloy matrix composites (SiC/Ti) for landing gear structures, actuators, and robotics

4.2 Particulate reinforced aluminium alloy matrix composites for structural aerospace components

4.3 Carbon fibre reinforced silicon carbide composites (C/SiC) for thermal protection systems and leading-edge structures

4.4 Alumina-based oxide–oxide ceramic matrix composites (Ox/Ox) for exhaust cones and cylinders in aero engines (and defence applications)

4.5 Alumina-based oxide-oxide ceramic matrix composites (Ox/Ox) for heat shields in aerospace applications

4.6 Silicon carbide fibre reinforced silicon carbide matrix composites (SiC/SiC) for jet engines and other aero components (static parts)

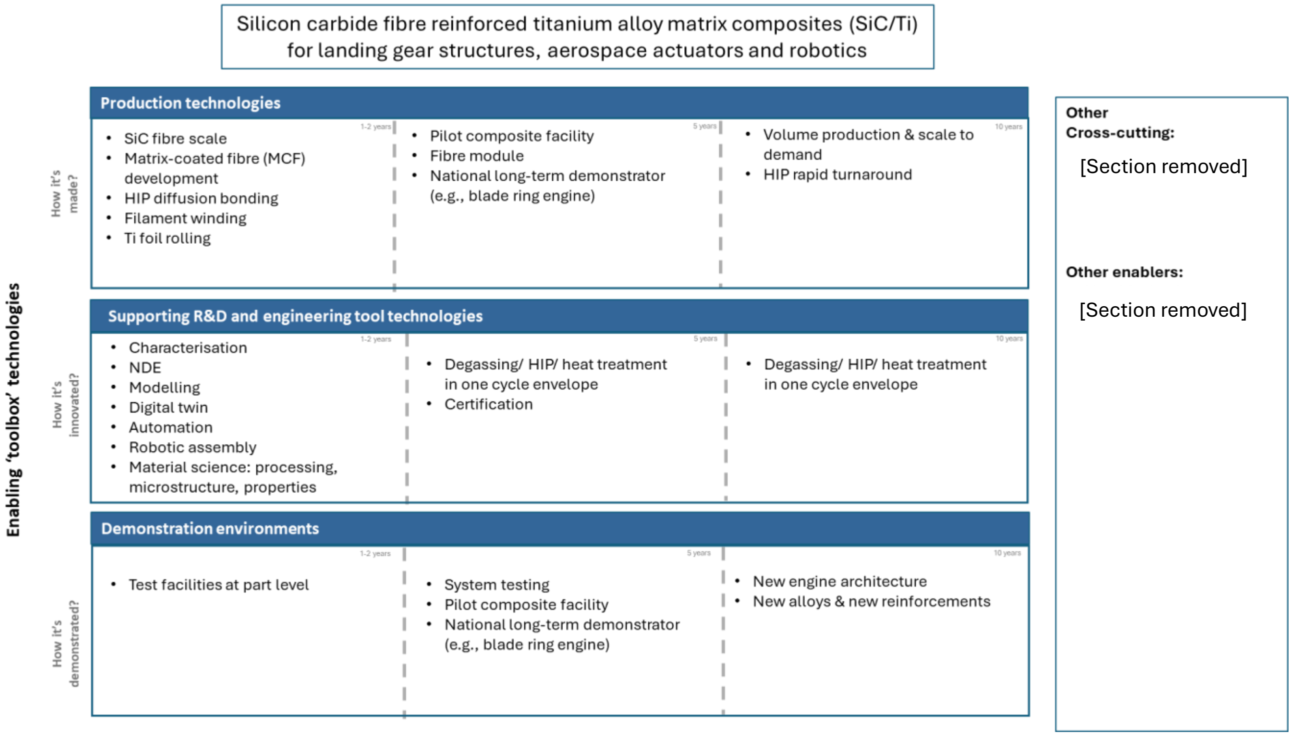
4.7 Silicon carbide fibre reinforced silicon carbide matrix composites (SiC/SiC) for nuclear fusion and fission

4.1 USE CASE: Silicon carbide fibre reinforced titanium alloy matrix composites (SiC/Ti) for landing gear structures, actuators, and robotics

Continuous silicon carbide (SiC) fibre reinforced titanium (Ti) matrix composites were selected by participants as these systems offer high specific stiffness and strength, excellent fatigue and creep resistance, and temperature capability well above monolithic Ti.

Participants suggested that SiC/Ti composites are attractive for **landing gear structures in single-aisle and twin-aisle aircraft**, including components such as **sidestays, brake rods, and main fittings**, as they are able to reduce mass while maintaining stiffness and load-carrying capability. These characteristics also suit **aerospace (hydraulic and electric) actuator components**, enabling lighter actuator rods, torque links, and structural links that meet stringent deflection and durability requirements under high cyclic loading. The 10-year target is flight use on next generation single aisles, with 5–6-year target being flight parts to twin aisle landing gear applications from UK pilot plants.

The elevated temperature stability and stiffness-to-weight ratio of SiC/Ti were suggested to support applications in **engine structures** and selected **airframe structures**, where weight savings, rigidity, and thermal performance are essential. The same stiffness-to-weight advantages translate directly into **robotics**, enabling lightweight robotic arms, end-effectors, and high-duty mechanisms with improved speed, reduced inertia, and higher positional precision.



Silicon carbide fibre reinforced titanium alloy matrix composites (SiC/Ti) for landing gear structures, aerospace actuators and robotics

Enabling 'toolbox' technologies

	1-2 years	5 years	10 years
Production technologies			
How it's made?	• SiC fibre scale • Matrix-coated fibre (MCF) development • HIP diffusion bonding • Filament winding • Ti foil rolling	• Pilot composite facility • Fibre module • National long-term demonstrator (e.g., blade ring engine)	• Volume production & scale to demand • HIP rapid turnaround
Supporting R&D and engineering tool technologies			
How it's innovated?	• Characterisation • NDE • Modelling • Digital twin • Automation • Robotic assembly • Material science: processing, microstructure, properties	• Degassing/ HIP/ heat treatment in one cycle envelope • Certification	• Degassing/ HIP/ heat treatment in one cycle envelope
Demonstration environments			
How it's demonstrated?	• Test facilities at part level	• System testing • Pilot composite facility • National long-term demonstrator (e.g., blade ring engine)	• New engine architecture • New alloys & new reinforcements

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

4.1.1 Production technologies

[Section removed]

4.1.2 R&D and engineering tool technologies

[Section removed]

4.1.3 Demonstration environments

[Section removed]

4.1.4 Other enabling capabilities

[Section removed]

4.1.5 Value chain considerations

[Section removed]

4.1.6 Cross-cutting technologies and capabilities

[Section removed]

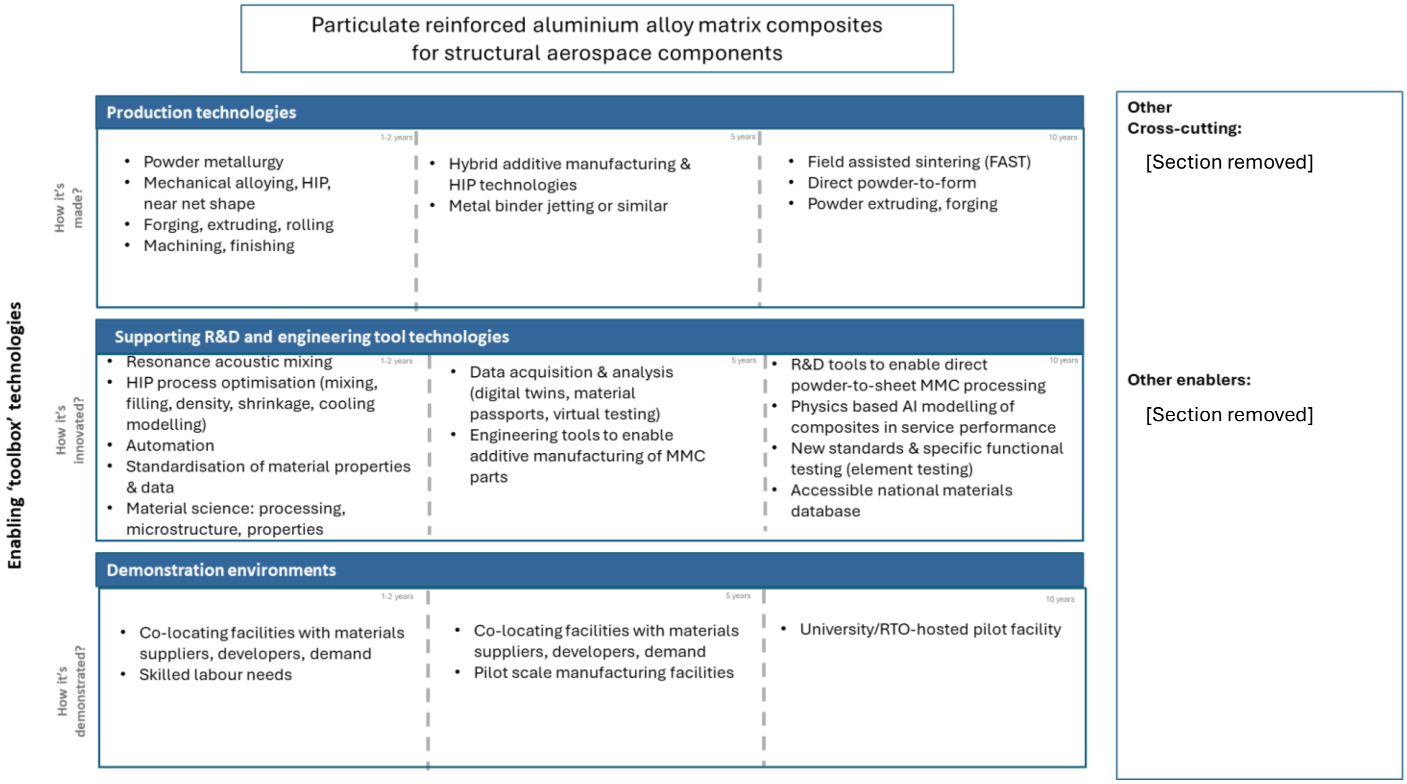
4.1.7 Key actors mentioned (non-exhaustive)

[Section removed]

4.2 USE CASE: Particulate reinforced aluminium alloy matrix composites for structural aerospace components

Particulate reinforced aluminium (Al) alloy matrix composites (MMC) were selected by participants as they offer high strength-to-weight and stiffness-to-weight ratios, while behaving similarly in all directions (isotropic), relative to other types of materials.

Participants suggested that applications could follow a pathway from space and defence, through rotorcraft, and finally to commercial aerospace applications. Space and defence are viewed as initial application domains where high-performance requirements can justify high cost, manufacturing complexity, and technical risk. The technology could then be applied in rotorcraft, where demanding cyclic loads and stiffness requirements benefit from performance gains, while still allowing a relatively high cost–performance trade-off. Ultimately, participants suggested that these more mature and validated technologies might progress for commercial aerospace development, where stringent certification, damage tolerance, large production volumes, and life-cycle cost considerations significantly constrain adoption. An initial use case for a flight qualified aircraft part already exists opening opportunities for greater adoption.



Particulate reinforced aluminium alloy matrix composites
for structural aerospace components

Enabling 'toolbox' technologies

	1-2 years	5 years	10 years
Production technologies How it's made?	• Powder metallurgy • Mechanical alloying, HIP, near net shape • Forging, extruding, rolling • Machining, finishing	• Hybrid additive manufacturing & HIP technologies • Metal binder jetting or similar	• Field assisted sintering (FAST) • Direct powder-to-form • Powder extruding, forging
Supporting R&D and engineering tool technologies How it's innovated?	• Resonance acoustic mixing • HIP process optimisation (mixing, filling, density, shrinkage, cooling modelling) • Automation • Standardisation of material properties & data • Material science: processing, microstructure, properties	• Data acquisition & analysis (digital twins, material passports, virtual testing) • Engineering tools to enable additive manufacturing of MMC parts	• R&D tools to enable direct powder-to-sheet MMC processing • Physics based AI modelling of composites in service performance • New standards & specific functional testing (element testing) • Accessible national materials database
Demonstration environments How it's demonstrated?	• Co-locating facilities with materials suppliers, developers, demand • Skilled labour needs	• Co-locating facilities with materials suppliers, developers, demand • Pilot scale manufacturing facilities	• University/RTO-hosted pilot facility

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

4.2.1 Production technologies

[Section removed]

4.2.2 R&D and engineering tool technologies

[Section removed]

4.2.3 Demonstration environments

[Section removed]

4.2.4 Other enabling capabilities

[Section removed]

4.2.5 Value chain considerations

[Section removed]

4.2.6 Cross-cutting technologies and capabilities

[Section removed]

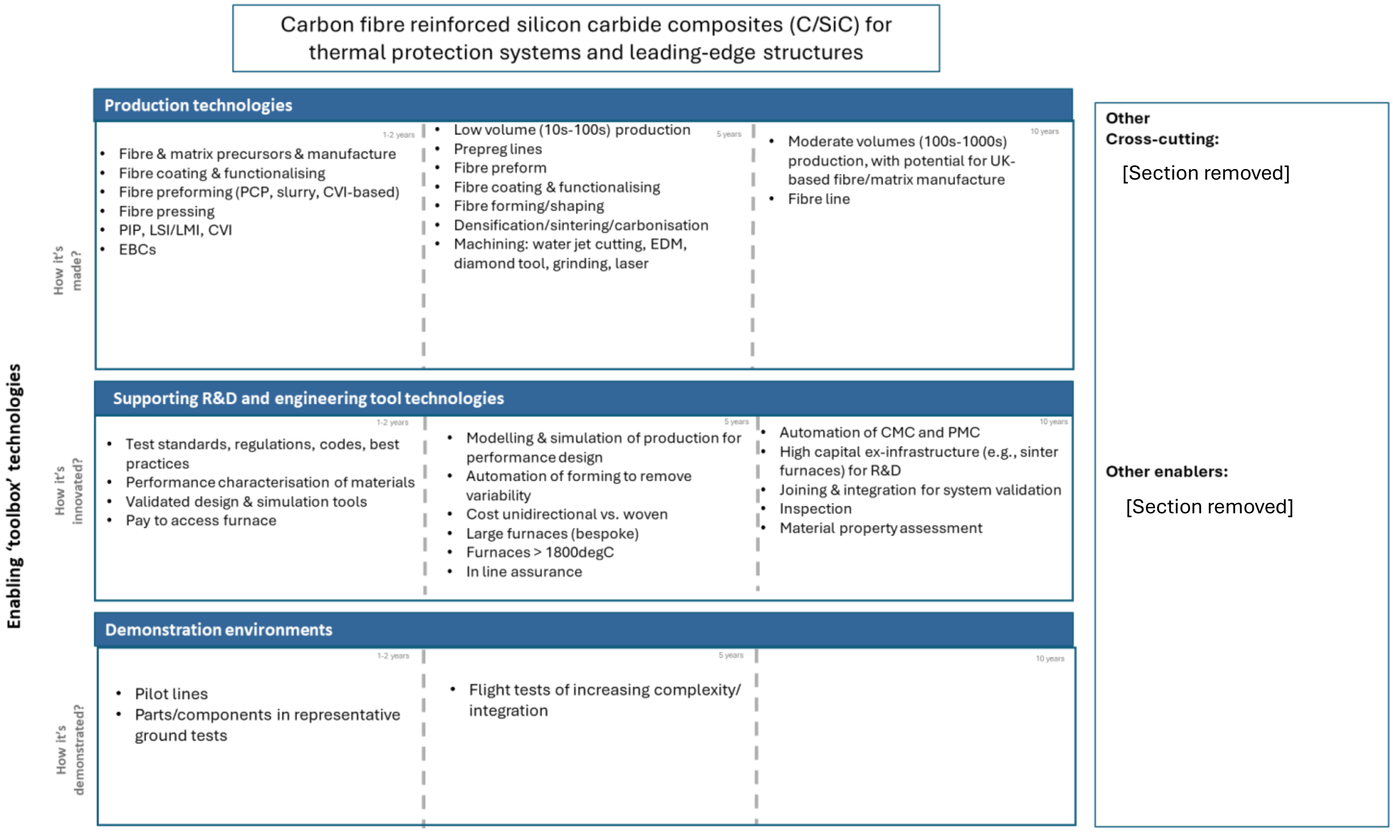
4.2.7 Key actors mentioned (non-exhaustive)

[Section removed]

4.3 USE CASE: Carbon fibre reinforced silicon carbide composites (C/SiC) for thermal protection systems and leading-edge structures

In carbon (C) fibre reinforced silicon carbide (SiC) ceramic matrix composites, carbon fibres provide high tensile strength and damage tolerance, while the SiC matrix delivers high temperature capability, oxidation resistance, and structural stability. C/SiC composites were selected as their properties make them suitable for harsh, high-enthalpy aerothermal environments where metals and polymer composites cannot survive.

Participants suggest key applications to include **missiles and rocket propulsion** as C/SiC components tolerate sustained high heat flux and rapid thermal cycling, supporting uses such as control fins, nose cones, exhaust flaps, and internal hot-gas structures. For **ballistic and armour protection**, the material's stiffness and hardness contribute to lightweight protection systems with improved multi-hit resistance compared to monolithic ceramics.



Carbon fibre reinforced silicon carbide composites (C/SiC) for thermal protection systems and leading-edge structures

Enabling 'toolbox' technologies

	1-2 years	5 years	10 years
Production technologies (How it's made?)	• Fibre & matrix precursors & manufacture • Fibre coating & functionalising • Fibre preforming (PCP, slurry, CVI-based) • Fibre pressing • PIP, LSI/LMI, CVI • EBCs	• Low volume (10s-100s) production • Prepreg lines • Fibre preform • Fibre coating & functionalising • Fibre forming/shaping • Densification/sintering/carbonisation • Machining: water jet cutting, EDM, diamond tool, grinding, laser	• Moderate volumes (100s-1000s) production, with potential for UK-based fibre/matrix manufacture • Fibre line
Supporting R&D and engineering tool technologies (How it's innovated?)	• Test standards, regulations, codes, best practices • Performance characterisation of materials • Validated design & simulation tools • Pay to access furnace	• Modelling & simulation of production for performance design • Automation of forming to remove variability • Cost unidirectional vs. woven • Large furnaces (bespoke) • Furnaces > 1800degC • In line assurance	• Automation of CMC and PMC • High capital ex-infrastructure (e.g., sinter furnaces) for R&D • Joining & integration for system validation • Inspection • Material property assessment
Demonstration environments (How it's demonstrated?)	• Pilot lines • Parts/components in representative ground tests	• Flight tests of increasing complexity/ integration	

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

4.3.1 Production technologies

[Section removed]

4.3.2 R&D and engineering tool technologies

[Section removed]

4.3.3 Demonstration environments

[Section removed]

4.3.4 Enabling capabilities

[Section removed]

4.3.5 Value chain considerations

[Section removed]

4.3.6 Cross-cutting technologies and capabilities

[Section removed]

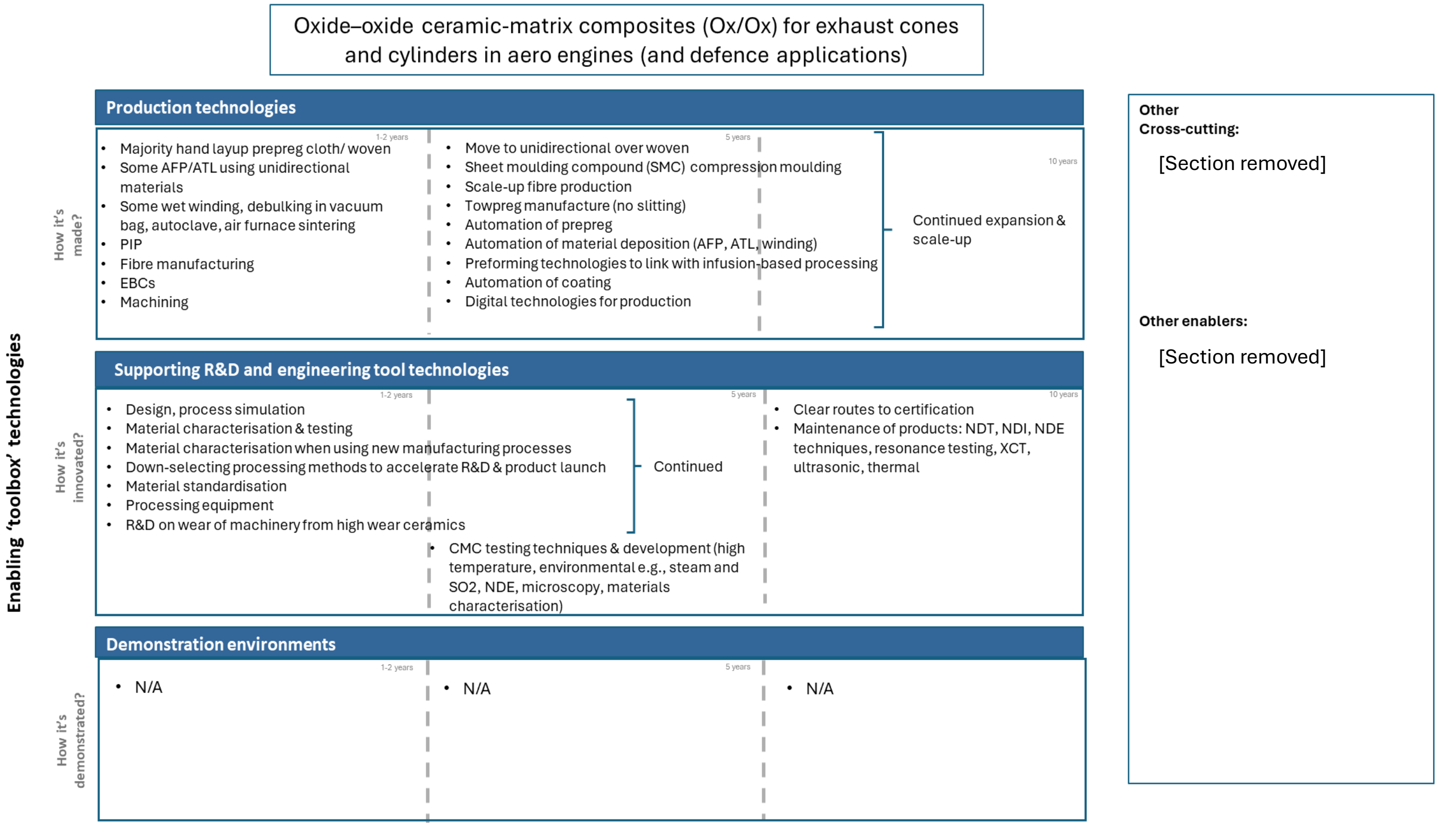
4.3.7 Key actors mentioned (non-exhaustive)

[Section removed]

4.4 USE CASE: Alumina-based oxide-oxide ceramic matrix composites (Ox/Ox) for exhaust cones and cylinders in aero engines (and defence applications)

Oxide–oxide ceramic-matrix composites (Ox/Ox) are all-oxide material systems in which oxide fibres are embedded within an oxide ceramic matrix. They are inherently resistant to oxidation and thermal degradation, and typically operate at around 1000 °C, while remain significantly lighter than metal alloys and maintain stability under rapid thermal cycling.

Participants selected Ox/Ox as a strong candidate material for **exhaust cones and cylinders in aero engines and defence applications in the long term**, where components must tolerate sustained exposure to hot, oxygen-rich exhaust streams, vibration, and intermittent thermal shocks. The combination of thermal robustness, lower density, and environmental durability makes Ox/Ox well-suited for these demanding rear-end engine environments. Ox/Ox CMCs also presents near-term opportunities beyond aerospace. These include **EV battery enclosures, F1 and drone applications.**



Oxide–oxide ceramic-matrix composites (Ox/Ox) for exhaust cones and cylinders in aero engines (and defence applications)

Enabling 'toolbox' technologies

Production technologies

How it's made?

1-2 years

- Majority hand layup prepreg cloth/ woven
- Some AFP/ATL using unidirectional materials
- Some wet winding, debulking in vacuum bag, autoclave, air furnace sintering
- PIP
- Fibre manufacturing
- EBCs
- Machining

5 years

- Move to unidirectional over woven
- Sheet moulding compound (SMC) compression moulding
- Scale-up fibre production
- Towpreg manufacture (no slitting)
- Automation of prepreg
- Automation of material deposition (AFP, ATL, winding)
- Preforming technologies to link with infusion-based processing
- Automation of coating
- Digital technologies for production

10 years

Continued expansion & scale-up

Supporting R&D and engineering tool technologies

How it's innovated?

1-2 years

- Design, process simulation
- Material characterisation & testing
- Material characterisation when using new manufacturing processes
- Down-selecting processing methods to accelerate R&D & product launch
- Material standardisation
- Processing equipment
- R&D on wear of machinery from high wear ceramics

Continued

5 years

- CMC testing techniques & development (high temperature, environmental e.g., steam and SO2, NDE, microscopy, materials characterisation)

10 years

- Clear routes to certification
- Maintenance of products: NDT, NDI, NDE techniques, resonance testing, XCT, ultrasonic, thermal

Demonstration environments

How it's demonstrated?

1-2 years

- N/A

5 years

- N/A

10 years

- N/A

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

4.4.1 Production technologies

[Section removed]

4.4.2 R&D tool & engineering tool technologies

[Section removed]

4.4.3 Demonstration environments

[Section removed]

4.4.4 Enabling capabilities

[Section removed]

4.4.5 Value chain considerations

[Section removed]

4.4.6 Cross-cutting technologies and capabilities

[Section removed]

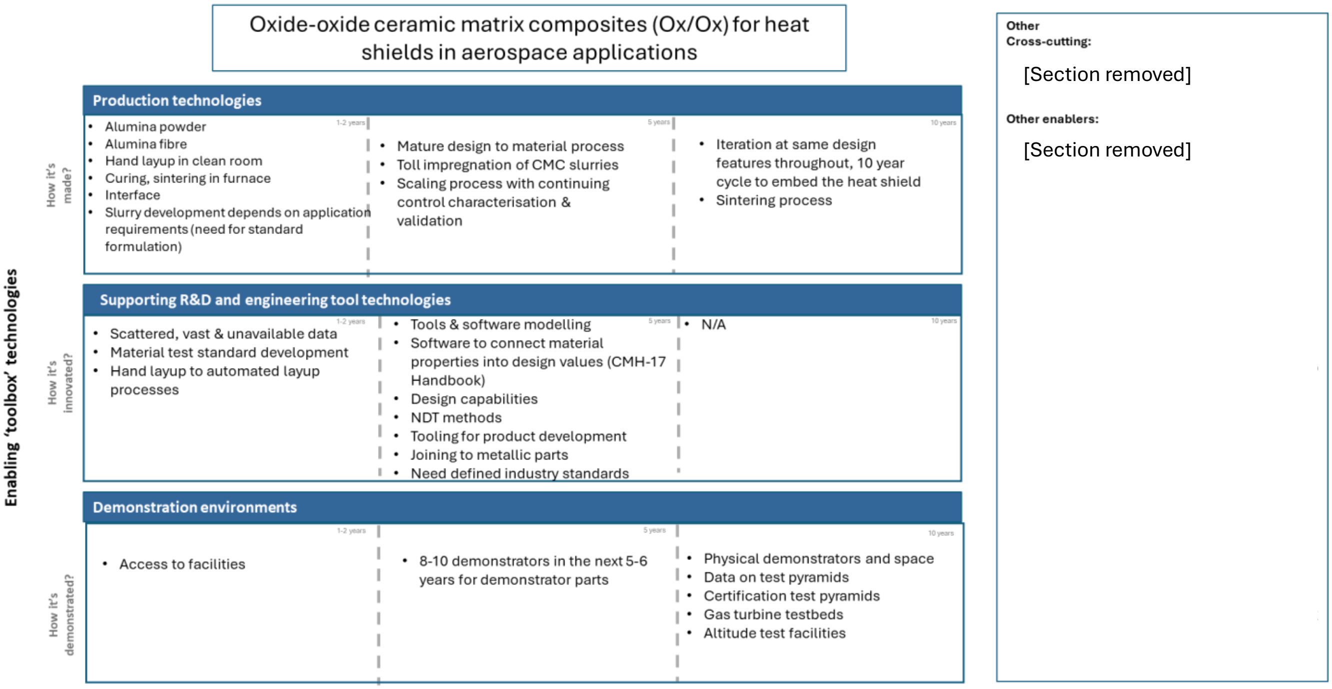
4.4.7 Key actors mentioned (non-exhaustive)

[Section removed]

4.5 USE CASE: Alumina-based oxide-oxide ceramic matrix composites (Ox/Ox) for heat shields in aerospace applications

Oxide–oxide ceramic-matrix composites (Ox/Ox) were selected as they provide a lightweight, oxidation-resistant solution for thermal protection and high-temperature structural applications across **aerospace, propulsion, energy, and industrial sectors**. Their ability to retain mechanical integrity and environmental stability at ~1000 °C makes them attractive for components that experience continuous heat flux, thermal cycling, and oxidising environments but do not require the extreme strength of SiC/SiC or C/SiC systems.

Participants identified Ox/Ox as particularly relevant **for heat-shielding and secondary hot-section components in jet engines, including heat shields, nozzle exhaust structures, turbine seal segments, and certain nozzle guide vane (NGV) or blade-adjacent insulating components** where thermal protection, oxidation resistance, and weight savings are prioritised over peak load-bearing performance. In addition, Ox/Ox was noted as suitable for aircraft brake thermal barriers and high-temperature seal components where stable high-temperature behaviour and manufacturability are key. The material also has potential relevance for aerospace nose cones and thermal-protection elements for high-speed vehicles, provided mechanical loadings remain moderate and oxidation resistance is most important.



Oxide-oxide ceramic matrix composites (Ox/Ox) for heat shields in aerospace applications

Enabling 'toolbox' technologies		1-2 years	5 years	10 years
Production technologies	How it's made?	Alumina powder Alumina fibre Hand layup in clean room Curing, sintering in furnace Interface Slurry development depends on application requirements (need for standard formulation)	Mature design to material process Toll impregnation of CMC slurries Scaling process with continuing control characterisation & validation	Iteration at same design features throughout, 10 year cycle to embed the heat shield Sintering process
Supporting R&D and engineering tool technologies	How it's innovated?	Scattered, vast & unavailable data Material test standard development Hand layup to automated layup processes	Tools & software modelling Software to connect material properties into design values (CMH-17 Handbook) Design capabilities NDT methods Tooling for product development Joining to metallic parts Need defined industry standards	N/A
Demonstration environments	How it's demonstrated?	Access to facilities	8-10 demonstrators in the next 5-6 years for demonstrator parts	Physical demonstrators and space Data on test pyramids Certification test pyramids Gas turbine testbeds Altitude test facilities

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

4.5.1 Production technologies

[Section removed]

4.5.2 R&D tool and engineering tool technologies

[Section removed]

4.5.3 Demonstration environments

[Section removed]

4.5.4 Enabling capabilities

[Section removed]

4.5.5 Value chain considerations

[Section removed]

4.5.6 Cross-cutting technologies and capabilities

[Section removed]

4.5.7 Key actors mentioned (non-exhaustive)

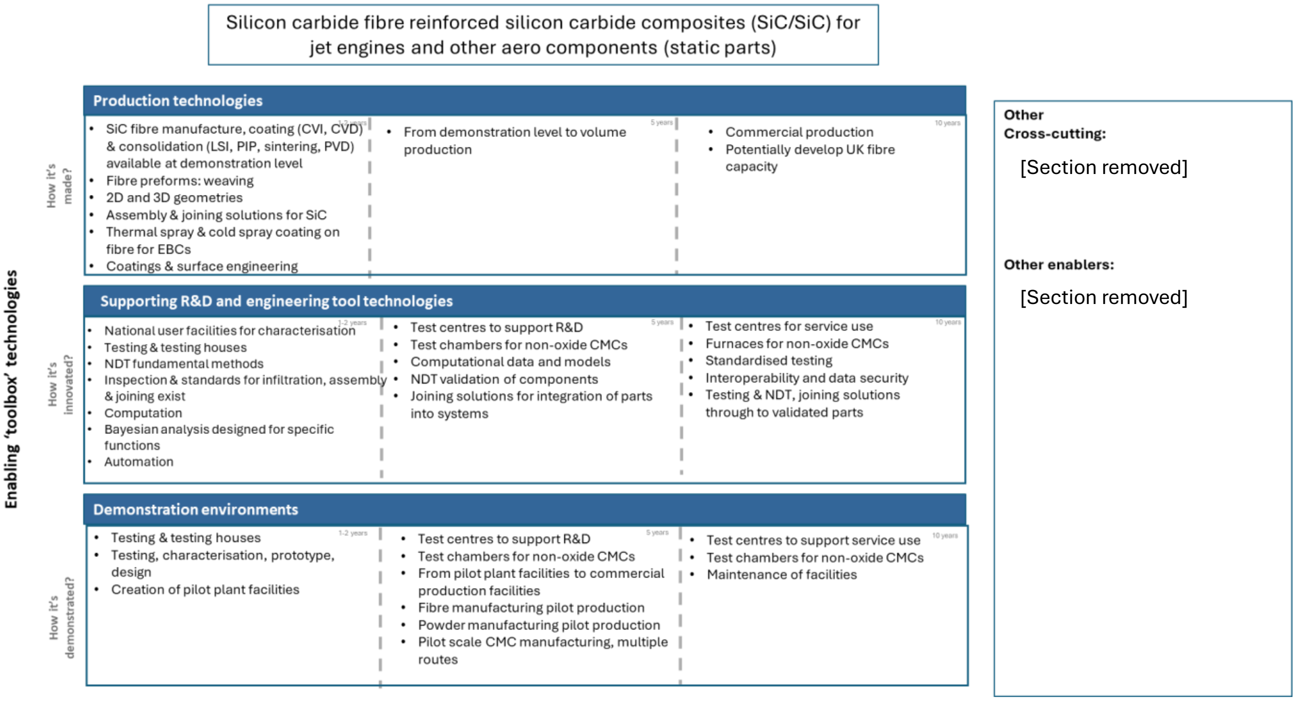
[Section removed]

4.6 USE CASE: Silicon carbide fibre reinforced silicon carbide matrix composites (SiC/SiC) for jet engines and other aero components (static parts)

Silicon carbide (SiC) fibre reinforced silicon carbide matrix composites for aero engine components were selected as a use case for their high temperature resistance (compared to metals), lower weight (one-third to one-half that of metals) reducing fuel consumption, and their resistance to stress, oxidation, and radiation. Compared with monolithic ceramics, SiC/SiC also offers improved toughness, providing adequate damage tolerance for demanding aerospace environments.

These combined properties make SiC/SiC particularly well suited to **jet engine static components**, where materials must sustain extreme heat, oxidation, and cyclic loading. Typical applications include combustor liners, shrouds, exhaust mixers, vanes, thermal shielding, and afterburner components, where replacing superalloys enables higher engine temperatures, efficiency gains, and weight reduction.

Beyond engines, SiC/SiC is attractive for **airframe and propulsion-adjacent structures** exposed to high thermal flux—such as thermal protection panels, fairings, heat shields, nozzle liners, and hot-gas path components in both civil and defence aerospace platforms. Continued advances in fibre quality, coating technologies, joining methods, and inspection could eventually support **migration into selected rotary components**, broadening its role in next-generation turbine architectures.



Silicon carbide fibre reinforced silicon carbide composites (SiC/SiC) for jet engines and other aero components (static parts)

Enabling 'toolbox' technologies

	1-2 years	5 years	10 years
Production technologies			
How it's made?	• SiC fibre manufacture, coating (CVI, CVD) & consolidation (LSI, PIP, sintering, PVD) available at demonstration level • Fibre preforms: weaving • 2D and 3D geometries • Assembly & joining solutions for SiC • Thermal spray & cold spray coating on fibre for EBCs • Coatings & surface engineering	• From demonstration level to volume production	• Commercial production • Potentially develop UK fibre capacity
Supporting R&D and engineering tool technologies			
How it's innovated?	• National user facilities for characterisation • Testing & testing houses • NDT fundamental methods • Inspection & standards for infiltration, assembly & joining exist • Computation • Bayesian analysis designed for specific functions • Automation	• Test centres to support R&D • Test chambers for non-oxide CMCs • Computational data and models • NDT validation of components • Joining solutions for integration of parts into systems	• Test centres for service use • Furnaces for non-oxide CMCs • Standardised testing • Interoperability and data security • Testing & NDT, joining solutions through to validated parts
Demonstration environments			
How it's demonstrated?	• Testing & testing houses • Testing, characterisation, prototype, design • Creation of pilot plant facilities	• Test centres to support R&D • Test chambers for non-oxide CMCs • From pilot plant facilities to commercial production facilities • Fibre manufacturing pilot production • Powder manufacturing pilot production • Pilot scale CMC manufacturing, multiple routes	• Test centres to support service use • Test chambers for non-oxide CMCs • Maintenance of facilities

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

4.6.1 Production technologies

[Section removed]

4.6.2 R&D tool and engineering tool technologies

[Section removed]

4.6.3 Demonstration environments

[Section removed]

4.6.4 Enabling capabilities

[Section removed]

4.6.5 Value chain considerations

[Section removed]

4.6.6 Cross-cutting technologies and capabilities

[Section removed]

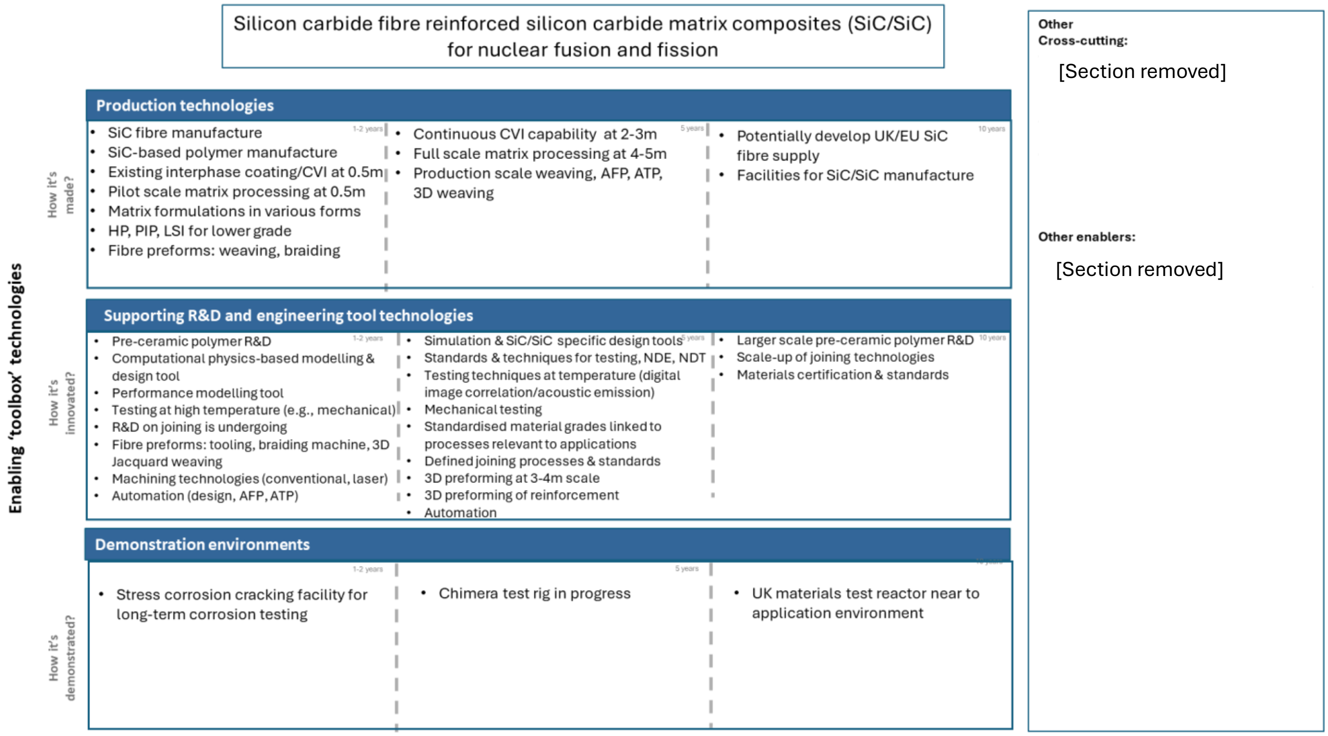
4.6.7 Key actors mentioned (non-exhaustive)

[Section removed]

4.7 USE CASE: Silicon carbide fibre reinforced silicon carbide matrix composites (SiC/SiC) for nuclear fusion and fission

Silicon carbide (SiC) fibre reinforced silicon carbide matrix composites for nuclear fusion and fission were selected due to their suitability for extreme operating environments requiring high-temperature stability, irradiation and corrosion resistance, low hydrogen permeation, controlled neutron interaction, and long-term mechanical integrity. Generally, nuclear applications have more stringent quality criteria in terms of impurities and contamination due to their operating environment.

The final product and service technologies identified were manufactured SiC/SiC CMC components for nuclear fission and fusion systems, including **fission accident-tolerant fuel (ATF) cladding tubes and channel boxes, manifolds, multi-metre (at least 4 metres) molten salt reactor (MSR) tubes, and fusion breeder blanket structures.** SiC/SiC CMCs for nuclear fusion and fission are believed to be on a path from pilot-scale components (~0.5 m) to full-scale, reactor-relevant parts (4–5 m) within a decade.



Silicon carbide fibre reinforced silicon carbide matrix composites (SiC/SiC) for nuclear fusion and fission

Enabling 'toolbox' technologies

	1-2 years	5 years	10 years
Production technologies How it's made?	SiC fibre manufacture SiC-based polymer manufacture Existing interphase coating/CVI at 0.5m Pilot scale matrix processing at 0.5m Matrix formulations in various forms HP, PIP, LSI for lower grade Fibre preforms: weaving, braiding	Continuous CVI capability at 2-3m Full scale matrix processing at 4-5m Production scale weaving, AFP, ATP, 3D weaving	Potentially develop UK/EU SiC fibre supply Facilities for SiC/SiC manufacture
Supporting R&D and engineering tool technologies How it's innovated?	Pre-ceramic polymer R&D Computational physics-based modelling & design tool Performance modelling tool Testing at high temperature (e.g., mechanical) R&D on joining is undergoing Fibre preforms: tooling, braiding machine, 3D Jacquard weaving Machining technologies (conventional, laser) Automation (design, AFP, ATP)	Simulation & SiC/SiC specific design tools Standards & techniques for testing, NDE, NDT Testing techniques at temperature (digital image correlation/acoustic emission) Mechanical testing Standardised material grades linked to processes relevant to applications Defined joining processes & standards 3D preforming at 3-4m scale 3D preforming of reinforcement Automation	Larger scale pre-ceramic polymer R&D Scale-up of joining technologies Materials certification & standards
Demonstration environments How it's demonstrated?	Stress corrosion cracking facility for long-term corrosion testing	Chimera test rig in progress	UK materials test reactor near to application environment

Other Cross-cutting:

[Section removed]

Other enablers:

[Section removed]

Current UK strengths include domestic fibre coating and CVI (ATL UK), and matrix formulation development capabilities at the 0.5m scale. ATL UK is in fact the sole supplier of fibre coating globally for many end uses. There are established weaving/forming houses and active design/testing actors in the UK who can build relevant capabilities needed for the medium and long-term. However, the UK relies heavily on internationally sourced inputs, in particular, SiC fibres are predominantly imported, alongside certain pre-ceramic polymers and precursor materials.

4.7.1 Production technologies

[Section removed]

4.7.2 R&D tool and engineering tool technologies

[Section removed]

4.7.3 Demonstration environments

[Section removed]

4.7.4 Enabling capabilities

[Section removed]

4.7.5 Value chain considerations

[Section removed]

4.7.6 Cross-cutting technologies and capabilities

[Section removed]

4.7.7 Key actors mentioned (non-exhaustive)

[Section removed]

5 Appendix A: Abbreviations

AE	Acoustic emissions
AFP	Automated fibre placement
AFRC	Advanced Forming Research Centre, University of Strathclyde
ATI	Aerospace Technology Institute
ATL	Automated tape laying
CAGR	Compound annual growth rate
CMC	Ceramic matrix composite
CTE	Coefficient of thermal expansion
CVD	Chemical vapour deposition
CVI	Chemical vapour infiltration
DIC	Digital image correlation
EBC	Environmental barrier coating
HIP	Hot isostatic pressing
HP	Hot pressing
LMI	Liquid melt infiltration
LSI	Liquid silicon infiltration
MCF	Matrix-coated fibre
MMC	Metal matrix composite
MSR	Molten salt reactor
NDE	Non-destructive evaluation
NDI	Non-destructive inspection
NDT	Non-destructive testing
NGV	Nosel guide veins
NPL	National Physical Laboratory

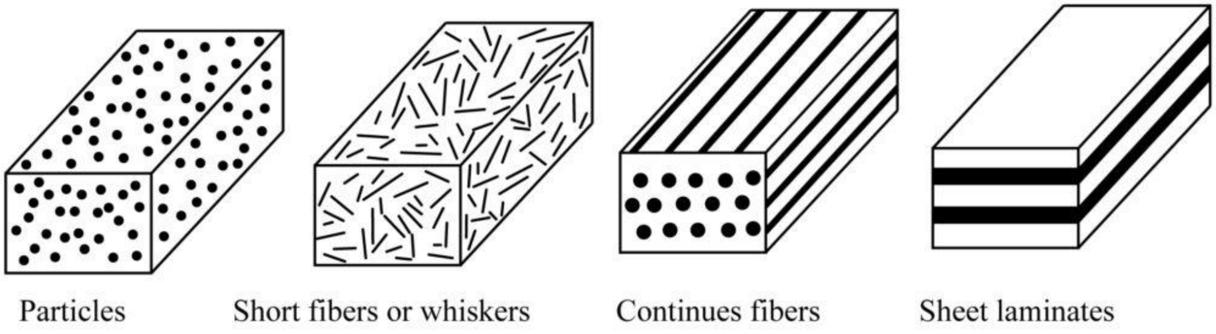
OEM	Original equipment manufacturer
PIP	Polymer infiltration and pyrolysis
PMC	Polymer matrix composites
PVD	Physical vapour deposition
RTM	Resin transfer moulding
RTO	Research technology organisation
R&D	Research and development
SMC	Sheet moulding compound
SME	Small medium enterprise
SMR	Small modular reactors
SQEP	Suitably qualified and experienced personnel
TRL	Technology readiness level
UHT	Ultra-high temperature

6 Appendix B: Literature review: Background to CMCs and MMCs

Composite materials are engineered systems made by combining two or more distinct materials so that the resulting material exhibits improved performance characteristics that none of the individual constituents could provide on their own. These characteristics include better strength-to-weight ratio, improved durability, high temperature resistance, added functionality, more freedom and precision in design configurations, etc.

Composites are made up by combining two key constituents with the most common forms as illustrated in Figure 3. Particulate or fibre reinforcements are utilised in CMCs and MMCs, with the highest structural performance accruing from continuous fibre reinforcement, *embedded within a matrix material that binds the structure together.*

Figure 3 Common architecture of reinforced composites.



There are three major categories of composite matrices – polymer matrix, metal matrix, and ceramic matrix – alongside the broad classes of reinforcements (e.g., carbon, silicon carbide (SiC), alumina (Al_2O_3), aramid, natural fibres) commonly used to tailor mechanical, thermal, and chemical properties.[17] The matrix-fibre combination is therefore central to composite performance and classification.

6.1.1 CMCs

Ceramic matrix composites (CMCs) are created by embedding **ceramic or carbon fibres within a ceramic matrix** (such as oxides, carbides, nitrides) to offer high temperature

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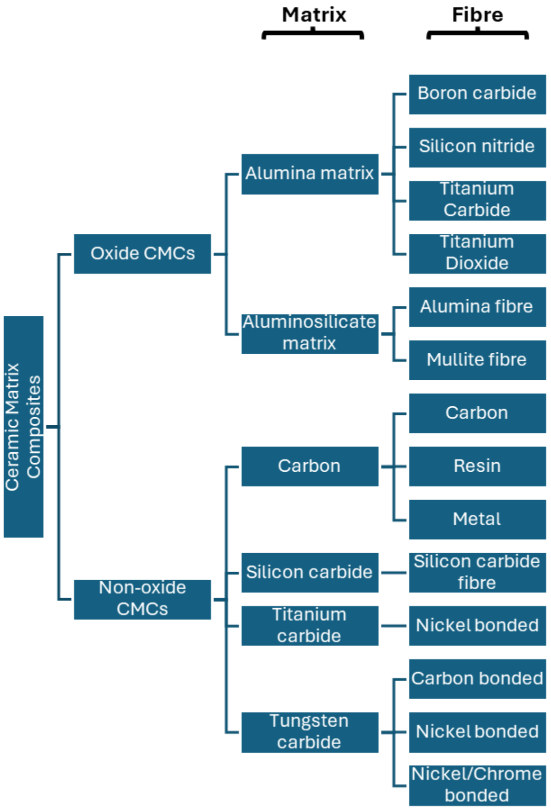
[17] ATI (2018). Insight: Composite Material Applications in Aerospace.

resistance, low weight, high strength and toughness, making them suitable for harsh environments.

Figure 4 provides a more detailed breakdown of CMC types, distinguishing between oxide CMCs and non-oxide CMCs.[18] [19] There is a broad design space within CMCs, where both the ceramic chemistry and fibre-matrix bonding approaches can be adapted to achieve specific high-temperature, structural, or chemical-resistance requirements.

Figure 4 CMC classification. Source: Shrivastava et al. (2024); Karadimas & Salonitis (2023).



6.1.2 MMCs

Metal matrix composites (MMCs) utilise a **matrix** consisting of a continuous monolithic metal or alloy that holds the structure together, while the **reinforcement** consists of ceramic

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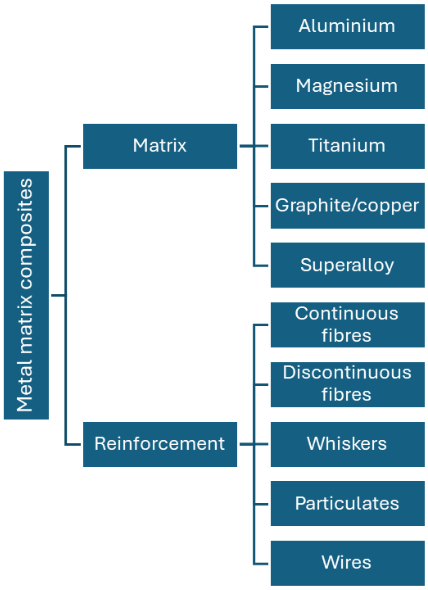
[18] Shrivastava et al. (2024). Ceramic Matrix Composites: Classifications, Manufacturing, Properties, and Applications.

[19] Karadimas & Salonitis (2023). Ceramic Matrix Composites for Aero Engine Applications - A Review.

or metallic materials added to improve mechanical and physical properties (see Figure 5 for summary).

Figure 5 MMC classification. Source: Musatto et al. (2020).



Common MMC Matrix Types

The matrix material is typically chosen based on the desired weight, temperature resistance, and conductivity of the final composite.

- **Aluminium (Al) and its Alloys**: The most widely used matrix due to its low density, high thermal conductivity, and ease of processing. Popular alloys include 6061, 7075, and 2024.
- **Magnesium (Mg) Alloys**: Used for ultra-lightweight applications as magnesium is approximately two-thirds the density of aluminium. It is common in aerospace and automotive sectors despite its lower corrosion resistance.
- **Titanium (Ti) Alloys**: Preferred for high-temperature applications (e.g., jet engines) because they offer superior strength and stiffness compared to superalloys at half the weight.
- **Copper (Cu)**: Used primarily in electrical and thermal management applications due to its high conductivity.
- **Nickel (Ni) and Cobalt (Co)**: Employed for extreme high-temperature environments where lighter metals would fail.

6.1.3 Reinforcement Types

Reinforcements are classified by their **geometry** (morphology), which determines whether the resulting material is isotropic (properties same in all directions) or anisotropic:

- **Particulates**: Small, roughly equal-axed particles (typically >1 µm) like **Silicon Carbide (SiC)** or **Alumina (Al_2O_3)**. They are the most common and least expensive, providing isotropic property improvements.
- **Whiskers**: Tiny, needle-like single crystals with a high aspect ratio. They offer higher strength than particles but are more expensive and can pose health risks during handling.
- **Continuous Fibers**: Long, thin filaments (e.g., carbon, boron, SiC) that run through the entire component. They provide the highest strength and stiffness in the direction of the fibers (anisotropic) but are the most expensive to manufacture.
- **Discontinuous/Short Fibers**: Chopped fibres or filaments that provide intermediate property improvements between particles and continuous fibres.

Common Reinforcement Materials

Material	Type	Primary Benefit
Silicon Carbide (SiC)	Ceramic	High hardness, wear resistance, and stiffness
Alumina (Al_2O_3)	Ceramic	Excellent compressive strength and thermal stability
Boron	Ceramic/Fiber	High specific stiffness; often used in aerospace
Carbon/Graphite	Carbon	Low density, high thermal conductivity, and self-lubricating properties
Titanium Diboride (TiB_2)	Ceramic	High hardness and good wettability in molten aluminum

Nano and hybrid reinforcements are seeing increased usage in niche applications.[20]

6.2 Growth potential and application domains

As the following sections will show, market predictions for both CMC and MMC point to significant global growth due to applications spanning aerospace, automotive, energy, defence, hypersonics, space, biomedical devices, and advanced engineering systems.

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[20] Mussatto et al. (2020). Advanced Production Routes for Metal Matrix Composites.

The next sections will outline CMC and MMC 1) market growth potential and application domains, 2) manufacturing processes, and 3) barriers identified across prior roadmapping and other analyses.

Figure 6 presents projected **global market growth for CMCs between 2023 and 2033**. The market is shown to increase from USD 6.8 billion in 2023 to USD 18.8 billion by 2033, representing a compound annual growth rate (CAGR) of 10.7%. The figure also highlights growth across key CMC product categories—oxides, silicon carbide, carbon, and other ceramic systems—all showing steady increase with silicon carbide making up the largest share.[21]

Figure 6 Global CMC market growth predictions. Source: Market.us (2025a).

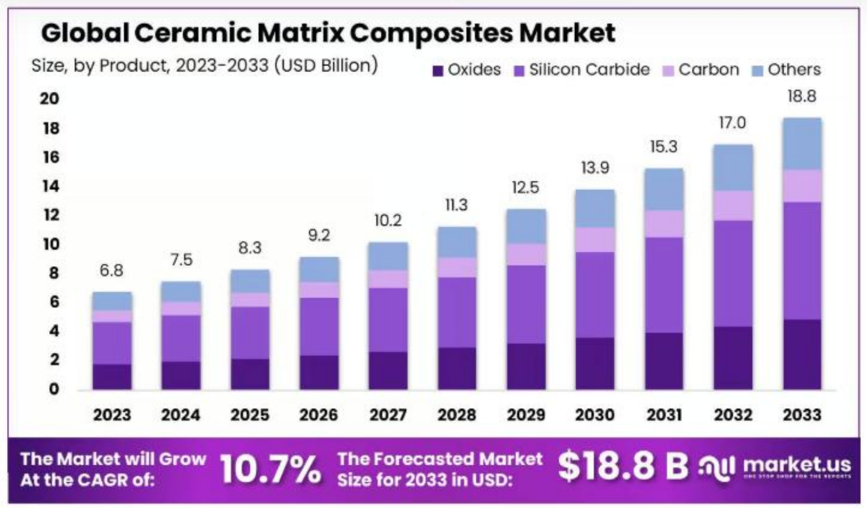

Figure 7 shows the **projected global market growth for MMCs from 2024 to 2034**. The sector is forecast to expand from USD 525.9 million in 2024 to USD 1,124.9 million by 2034, corresponding to a CAGR of 7.9%. Several matrix categories—aluminium MMCs, magnesium MMCs, copper MMCs, superalloy MMCs, and other metal-based composites—are all reflected in the growth trend. Aluminium MMCs appears to make up the largest shares across the forecast period.[22] Although the market is smaller than that of CMCs, the projected doubling in value signals robust and sustained global uptake.

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[21] Market.us (2025a). Ceramic Matrix Composites Market.

[22] Market.us (2025b). Metal Matrix Composites Market.

Figure 7 Global MMC market growth predictions. Source: Market.us (2025b).

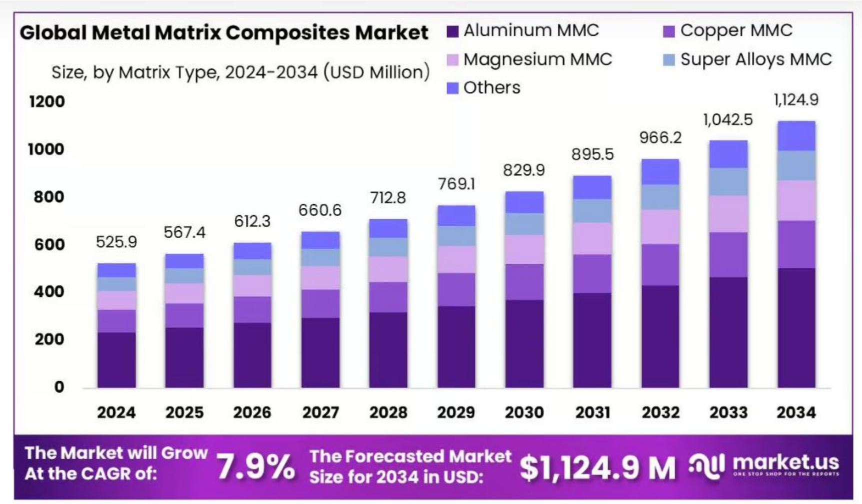

Figure 8 synthesises **the application sectors for CMCs** identified across the literature with some concrete examples.[23] Across these domains, the common driver is the need for high-temperature capability, oxidation/chemical resistance, reduced weight and high strength, all attributes consistently associated with CMCs in the literature and reflected in the breadth of sectors shown in Figure 6.

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[23] Shrivastava et al. (2024); Karadimas & Salonitis (2023); ATI (2019); NASA (2024).

Figure 8 CMC application sectors. Source: Shrivastava et al. (2024); Karadimas & Salonitis (2023); ATI (2018); NASA (2024).

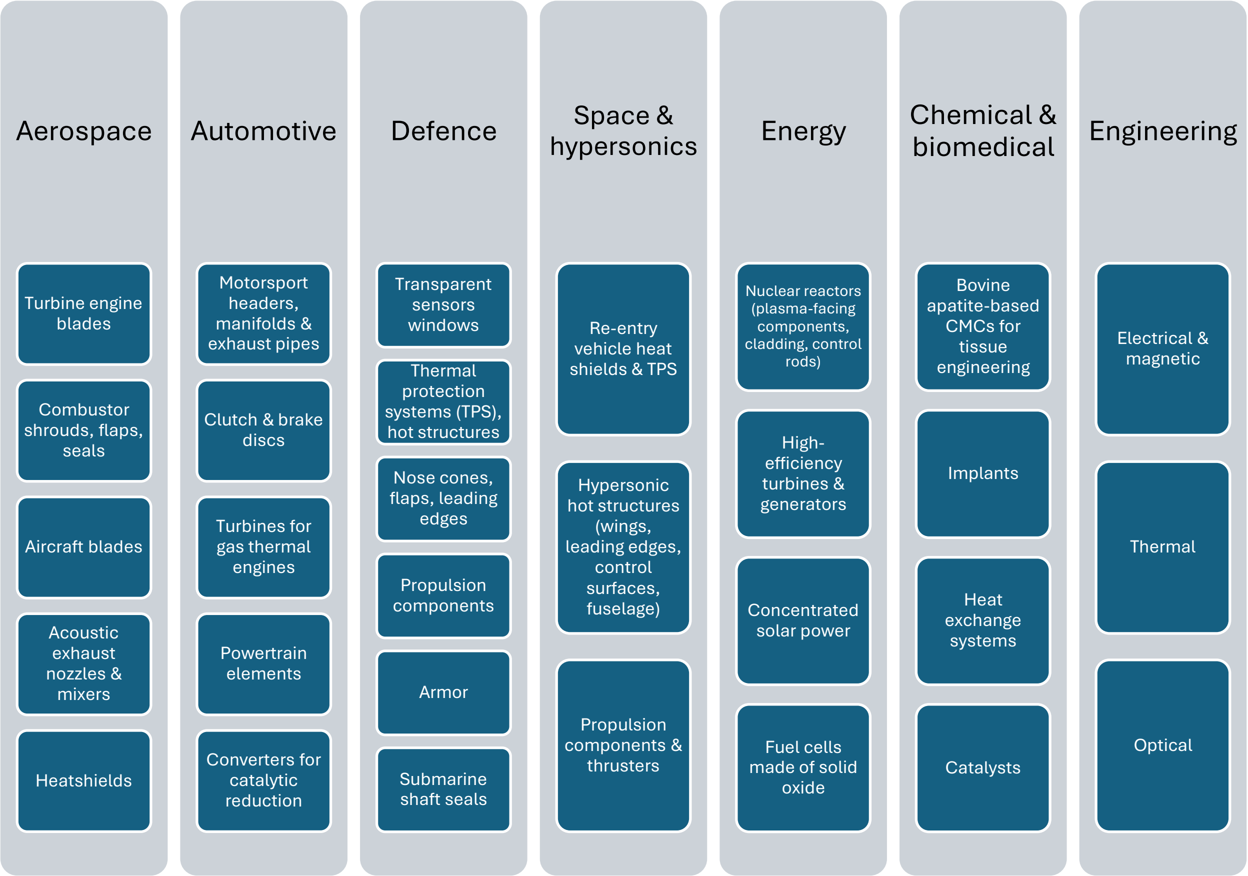
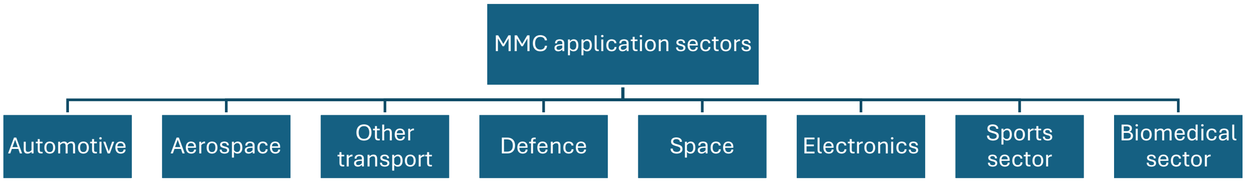


Figure 9 summarises the broad **application sectors for MMCs** identified in prior studies and reviews. The applications highlighted align with widely reported MMC advantages, such as improved wear resistance, enhanced mechanical strength, and superior thermal performance, all attributes that support their use in high-performance structural, electronic, and mechanical components.

Figure 9 MMC application sectors. Source: Musatto et al. (2020).



6.3 Manufacturing processes

6.3.1 CMCs

The **value chain for CMCs** proceeds from fibre production and preform fabrication through matrix infiltration/ impregnation, then drying/ thermal processing, and finally post-processing (machining, coating, and quality evaluation), as presented in Figure 10.

Matrix infiltration/ impregnation is an important step in establishing pore closure, fibre/ matrix interfacial condition, and, ultimately, mechanical and thermal performance. There is a number of routes to achieve this step including polymer infiltration and pyrolysis (PIP), reactive melt infiltration (RMI)/ liquid silicon infiltration (LSI), chemical vapour infiltration (CVI), electrophoretic deposition (EPD), spark plasma sintering (SPS), directed-energy deposition (DED), and laser-based fabrication. However, route differs substantially in cost, cycle time, resulting porosity, suitability for complex geometries, energy intensity, etc. For example:[24]

- Chemical vapor infiltration (CVI) process: A gaseous precursor (like methyltrichlorosilane for SiC) is introduced into a reactor containing a fibre preform. The gas decomposes, depositing a solid ceramic matrix layer-by-layer on the fibres. Its key advantage is that it produces high-purity matrices with excellent high-temperature mechanical properties, while its disadvantage is that the process is generally very slow (can take weeks) and often leaves 10–15% residual porosity.
- Melt infiltration is faster and lower-cost, enabling near-net-shape fabrication, but it is energy-intensive due to high process temperature, and it can also pose risks of fibre damage.
- Methods like PIP are relatively accessible and compatible with existing composite preform technologies but require many infiltration–pyrolysis cycles and generally produce higher residual porosity. Furthermore, polymer-derived ceramics tend to be largely amorphous after pyrolysis and may undergo crystallization or other phase transformations at elevated temperatures, which can introduce additional microstructural instability.
- Sintering is cost-effective but mainly suited for oxide CMCs, tends to produce higher porosity levels, and is generally ideal for weak matrix systems with not interphase required.

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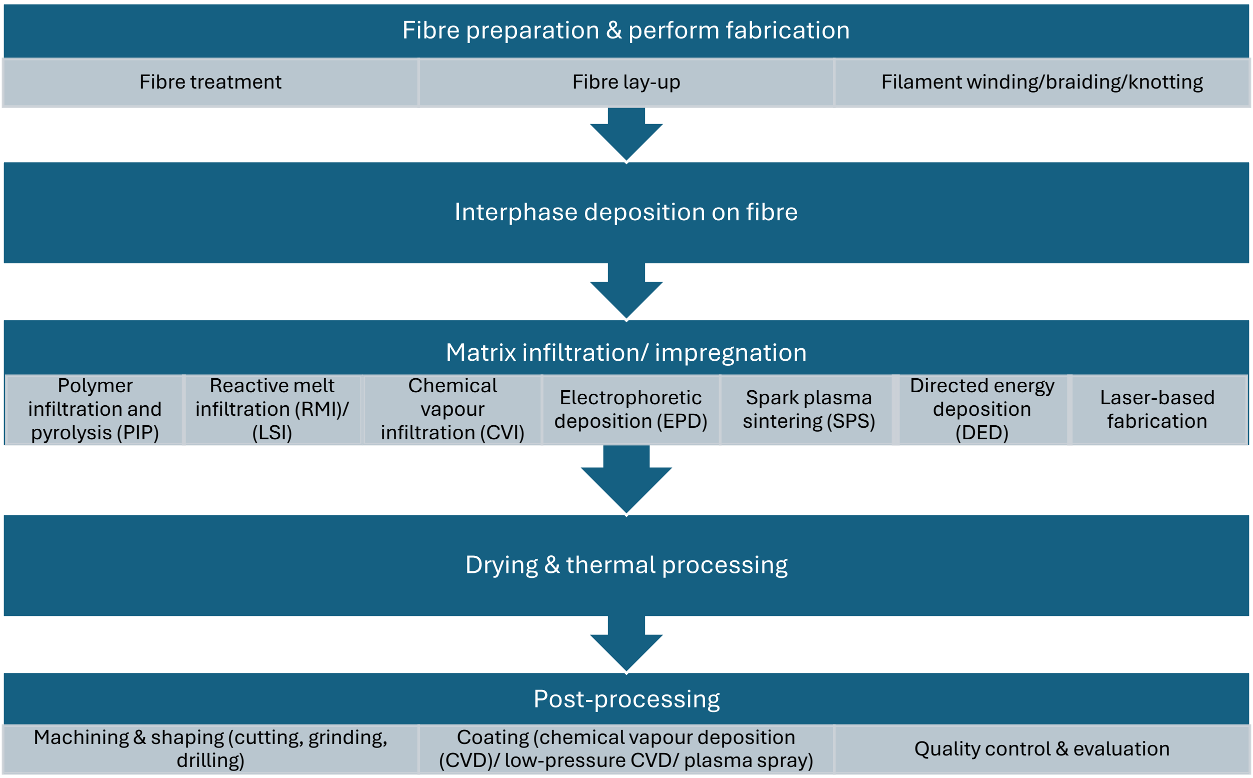
[24] Karadimas & Salonitis (2023). Ceramic Matrix Composites for Aero Engine Applications - A Review.

- Laser-based techniques offer shape freedom and potential additive capability, but strength levels and industrial maturity remain limited.

Overall, no single CMC process is universally optimal; instead, manufacturers select routes based on required mechanical and thermal performance, temperature capability, part size and complexity, and cost tolerance.

Figure 10 CMC manufacturing process steps. Source: Shrivastava et al. (2024); Karadimas & Salonitis (2023).



6.3.2 MMCs

The **MMC manufacturing process** can generally be divided into two overarching groups of techniques: liquid-state and solid-state processes, as presented in Figure 11.

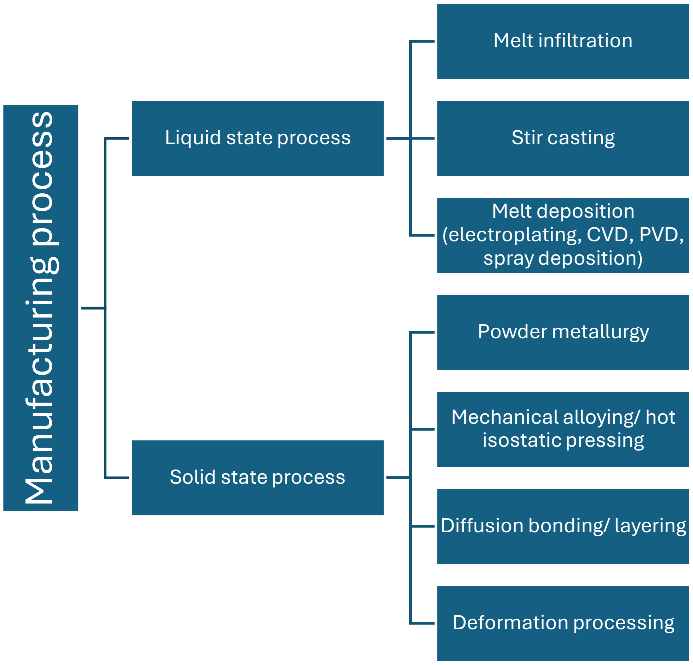
Liquid-state approaches – such as stir casting, melt infiltration, and various metal deposition techniques (CVD, PVD, electroplating, spray deposition) – focus on incorporating reinforcement into molten metal or depositing metal onto fibres/particles. These processes are typically better suited to high-volume or lower-cost production.

Solid-state processes – such as powder metallurgy, mechanical alloying, hot isostatic pressing, diffusion bonding, and deformation processing – create MMCs from powders or solid matter rather than from molten metal. These are generally chosen when higher levels of control over microstructure, reinforcement distribution, or final density are needed.

Similarly to CMCs, each method has its advantages and disadvantages. For example, stir casting is cost effective and suitable for mass production but it is not effective in uniformly distributing reinforcements within the matrix. Powder metallurgy ensures better final properties but is expensive.[25]

Figure 12 shows the share of MMC processes used over the 2005–2020 period. It shows that powder metallurgy, hot isostatic pressing and stir casting dominate, indicating that industry tends to favour well-established, scalable, and cost-efficient methods. More specialised routes such as PVD, electroplating, and squeeze casting appear much less commonly used.[26]

Figure 11 MMC manufacturing process routes. Source: Musatto et al. (2020); Pooja et al. (2025); Nagai (2023).



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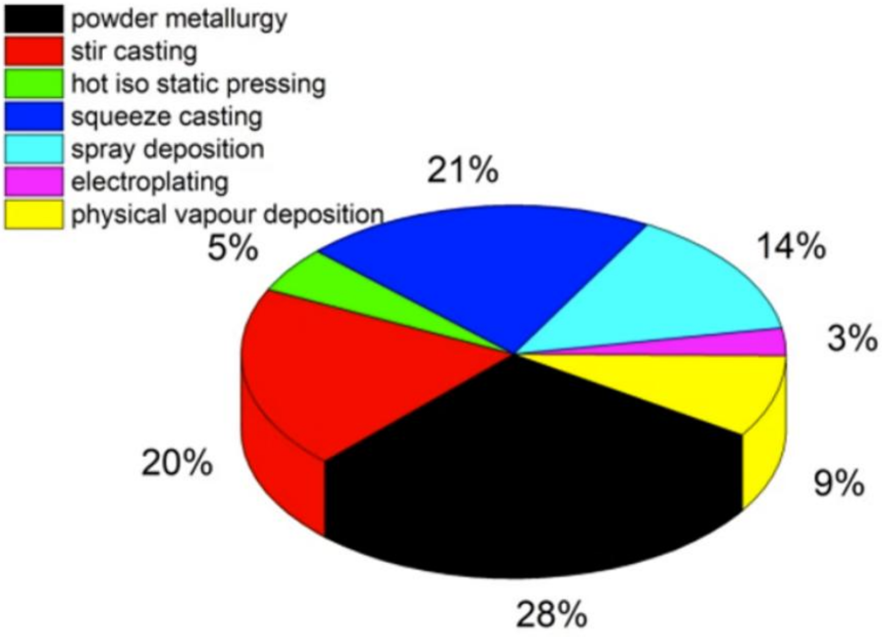
[25] Pooja et al. (2025). Metal Matrix Composites: Revolutionary Materials for Shaping the Future.
[26] Nagai (2023). Metal Matrix Composites: Classification, Manufacturing and Application.

Figure 12 Share of MMC manufacturing by route between 2005-2020. Source: Nagai (2023).



6.4 Review of key barriers identified in the literature

6.4.1 CMCs

As summarised in Figure 13, the literature consistently highlights that CMCs face manufacturing-related barriers, primarily the need for alternative or improved processing routes capable of achieving high quality, repeatability, and scale. Limited industrialisation, insufficient automation, and the high resource intensity of infiltration, machining, and furnace-based steps constrain throughput and raise costs.

Testing and evaluation also pose significant challenges. CMCs require specialised facilities, non-destructive inspection methods, and structural-health monitoring tools suited to complex, porous, or multilayer ceramic architectures. In parallel, progress is slowed by fragmented datasets, limited standards, and immature design codes, particularly for simulation, process modelling, and life prediction. Conventional structural design approaches cannot be readily applied to evaluate CMCs as their strength is governed by the influence of defects and this requires stochastic/probabilistic design methods rather than normally distributed material strength-based methods.

Material-specific challenges persist as well, including cracks at high stresses, heterogeneous behaviour, and the need for environmental barrier coatings (especially for

SiC-based CMCs, where oxidation and volatilisation can generate voids or degrade interfaces).

These issues are exacerbated by lack of successful business cases, high volume demand, supply chain constraints, including shortages of high-quality fibres, but also lack of skills, all contributing to high production costs and limiting wider uptake.

Figure 13 CMC barriers identified in existing literature. Source: Shrivastava et al. (2024); Karadimas & Salonitis (2023); NASA (2024); NCC (2025); HVMC (2025).

Manufacturing	Testing	Simulation, data and standards	Material properties/ science	Other	High costs
• Alternative or improved manuf. processes (in terms of price, time, net shape) • Need for research advancements in manufacturing processes • Sectors not sufficiently industrialised for high production rates or quality requirements (lack of automation, machining, furnaces, other processing equip.) • Need for manufacturing processes that do not produce extra silicon (that can volatilise and cause fissures) • Automation (AFP, ATP, factory automation, etc.) • Additive manufacturing • Reducing heat cycle • Need to optimise or remove process steps (joining, machining, etc.)	• Need for (manufacturing) facilities for simulation environments and testing for increased field and experimental testing • Need for more efficient repair methods; and related expertise, qualified and trained labour • Non-destructive evaluation techniques for in-line process control and post-process testing • Structural health monitoring	• Design for manufacturing • Finite Element (FE) simulations for technical specifications • Virtual testing • Factory, manufacturing, and process simulation • Limited datasets (due to expensive test coupons, unrefined test methods, proprietary datasets, inconsistent manuf. processes) • Need for material characterisation efforts improving design and life prediction tools to establish standards and databases • Lack of industry standards and design codes	• Performance improvements including increased functionality (electrical, thermal etc.) and improved properties (through thickness, temperature resistance, overall longevity) • Avoidance of cracks at high stress and strain environments • Need for developing environmental barrier coatings • Si-containing materials can volatilise at high temperatures leaving voids and cracks in the matrix • Need for iterations of composite material, manuf. process, testing, and post-test evaluation measures to better understand composite material interactions/ interphases/ chemistry	• Need for recyclability, closed loop recycling, bio-based materials • Unavailability of large quantities of continuous ceramic fibres, particularly SiC • Supply chain readiness is low • Lack of awareness, lack of acceptance • Skills needs (e.g., design and production) • Applications only in limited high-cost scenarios/ industries - need for business cases and demonstration of production of finished parts • Increased suppliers and end-users confidence in proceeding to final composite production	• Expensive raw materials, manufacturing processes, testing methods • Cost reductions could enable competitiveness with metals and monolithic ceramics • Environmental barrier coatings increase CMC prices • R&D investments • Access to capital

6.4.2 MMCs

The literature review suggests that certain MMCs face manufacturing complexity, especially in achieving reliable reinforcement distribution and minimising voids (e.g., liquid based processes). There is also the question of selecting process routes suited to specific matrix-reinforcement combinations. There are examples of MMCs where cost-effective and scalable joining, machining, and preform fabrication processes are underdeveloped, and infiltration or consolidation remains difficult. This is especially the case for composites were there is a lack of use cases, while aluminium and titanium are well understood.

Testing, simulation, and data availability impose further constraints: improved non-destructive inspection, design guidelines, process simulation tools, and standards for property prediction are needed to support robust product qualification.

Current applications in landing gear, engines and structural parts for aviation can be met with current MMC material systems. Fatigue life, creep resistance, strength and stiffness exceed current metals. Improved ductility and toughness will be required to expand the range of applications. Interface bonding needs work but again for future applications or optimisation. These do not prevent near-term industrialization and uptake.

Additional barriers include market demand signals, specifying component needs, recyclability and eco-friendly processing as metal can be recycled and reused through conventional metal recycling methods, energy intensity, limited cost–volume competitiveness until industrial scale manufacture is reached, and the persistent need for stronger industry–academia collaboration guided by industry pull. See MMC barriers summarised in Figure 14.

Figure 14 MMC barriers identified in existing literature. Source: Pooja et al. (2025); Mussatto et al. (2020); National Composites Network (2006).

Manufacturing

- Selecting appropriate manufacturing method for intended application
- Need to achieve uniform distribution of reinforcement within matrix
- Need to optimise manufacturing process to improve strength, durability, and wear resistance
- Minimising the formation of voids during manufacturing
- Need cost-effective processes with joining, assembly and machining
- Need better machinability
- Need cost effective fibre perform manufacture
- Low cost MMC production is challenging still
- Infiltration of performs under low/zero applied pressure
- Low-cost rapid solidification technology for particulate composites
- Challenges transitioning into high volume and high rate production

Testing, simulation, data and standards

- Need improved NDT in manufacture and service
- Reduce maintenance inspections
- Need cost effective fibre perform design
- Need for design data, design guidelines, capability directory
- Finite Element (FE) analysis/ modelling for better understanding of mechanical behaviour of MMC
- Process modelling
- Quantitative process simulation, process optimisation, and process control
- Fragmented materials data
- Prototyping is not available
- Lack of theoretically predicted properties
- Lack of standards in manufacturing technologies

Material properties/ science

- Need for new matrix materials for MMCs
- Need higher toughness materials and improved high temperature fatigue
- Struggle to achieve balance between properties (e.g., ductility, strength, toughness)
- Research into surface treatments and coating technologies could enhance interaction between matrix and reinforcement
- Improving (and better understanding the reaction process of) bonding between reinforcement and matrix
- Other areas for exploration: nano-MMCs, rapid solidification

Other

- Sustainability – eco-friendly production methods, recyclability of materials, life cycle assessment
- Cost to volume ratio is limiting growth – there is a chicken and egg situation
- Need breakthrough into high volume application
- Lack of critical mass
- Need for collaboration between industry, academia
- Need to develop materials for products (identify applications, driven by industry needs)