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Ceramic Matrix Composite Technologies for Space- & Hypersonic-Flight

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Abstract

Ceramic matrix composite (CMC) materials, made from ceramic or carbon fibers embedded in a ceramic matrix, are able to master the high temperature weakness of standard polymer based composites can be mastered. CMCs in lightweight design are representing promising material candidates that show high-grade resistance towards high temperature environment with comparatively high strength and against severe thermal shocks. In the rocket-engine realm (e.g. nozzles extensions) as well as during Earth's atmosphere vehicle ascent and re-entry specific components are confronted with harsh thermochemical and mechanical loading [1]. Temperatures hitting the vehicle-parts can rise well above 2000 °C, while corrosive gases and particles can strongly affect their surface. Thus, thermal protection systems such as CMC-modules must withstand extreme heat in combination with significant harsh conditions.

Typical Hypersonic systems refer to speeds of Mach 5 and beyond pose enormous challenges for material development, aerodynamics and thermal protection systems. The combination of composite materials and hypersonic applications is a promising field of research, as composites can better cope with the immense loads and extreme conditions in hypersonic-flight. Additionally in the field of Liquid Rocket Engines (LRE) suchlike materials are deeply considered [6].

The technical center for Ceramic Matrix Composites at ArianeGroup Germany (AGG) in Ottobrunn is covering the technologies of oxide and non-oxide ceramic composites as well as polymer composites. Its main activity is for "Customized CMC" development for both products and respective processes – meaning, the final application with the accompanying customer requirements is always in focus to provide end-to-end solutions from design to automated manufacturing including test and inspection. With the given technical installations and facilities the full ecosystem for CMC is available for development, prototyping up to small series production.

Keywords: *Ceramic Matrix Composites, Process Technology, Spaceflight, Hypersonic Flight*

Nomenclature

ArianeGroup Germany (AGG)

Ceramic Matrix Composites (CMC

Polymer Matrix Composites (PMC)

Chemical gas phase Infiltration (CVI)

Glass Fiber-Reinforced Plastic (GFRP)

Thermal Protection Systems (TPS)

Polymer Infiltration and Pyrolysis (PIP)

Carbon Fiber Siliconcarbide (C/SiC)

Liquid Silicone Infiltration (LSI)

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1. Introduction

The development of composite materials played a decisive role in advancing technology across various industries. Starting with the early innovations in Polymer Matrix Composites (PMCs), the field has evolved significantly, giving rise to more advanced materials such as Ceramic Matrix Composites (CMCs). These materials have been crucial in enabling the creation of high-performance components that withstand extreme conditions such as high temperatures, pressures, and corrosive environments.

The typical manufacturing process of Polymer Matrix Composites is based on the embedding of reinforcing fibers, such as glass, carbon, or aramid, into a polymer matrix. The polymers used can be thermosets or thermoplastics, whereby the matrix provides structural integrity and the fibers contribute to strength and stiffness. Glass fiber-reinforced plastic (GFRP) was one of the earliest forms of PMCs, and the introduction in industries like automotive and aerospace can be seen as a technological milestone. PMCs combine low density, corrosion resistance and potential ease of fabrication.
Typical applications of PMCs:

- Aerospace: Components like fuselages, wings, and radomes
- Automotive: Parts like body panels, bumpers, and interior components
- Sport Equipment: High-performance bicycles, tennis-rackets, and golf- as well as hockey-clubs
- Marine: Hulls, keels & decks of boats
- Etc.

While PMCs impacted significantly different industrial sectors, a need of composite-materials capable of withstanding higher temperatures and more extreme conditions was detected. This led to the evolution from PMC to of Ceramic Matrix Composites, which combine ceramic matrices (such as silicon carbide, alumina, or carbon) with reinforcing fiber-materials like carbon, oxide-fibers based on silica or alumina as well as silicon carbide.
Ceramics, with their inherent characteristics like high-temperature stability and wear resistance, offered a promising solution for being applicable under the harshest conditions, particularly in aerospace and energy generation applications. However, ceramics are typically brittle and so a reinforcement with fibers is mandatory to overcome this limitations to create a more damage-tolerant ceramic composite material.
Despite their impressive properties, CMCs are still relatively expensive and challenging to manufacture especially at large scales. Main issues related to fiber-matrix bonding as well as manufacturing processes itself and very special in an automated way have limited the general adoption of CMCs, particularly in industries like automotive… (see Fig. 1)

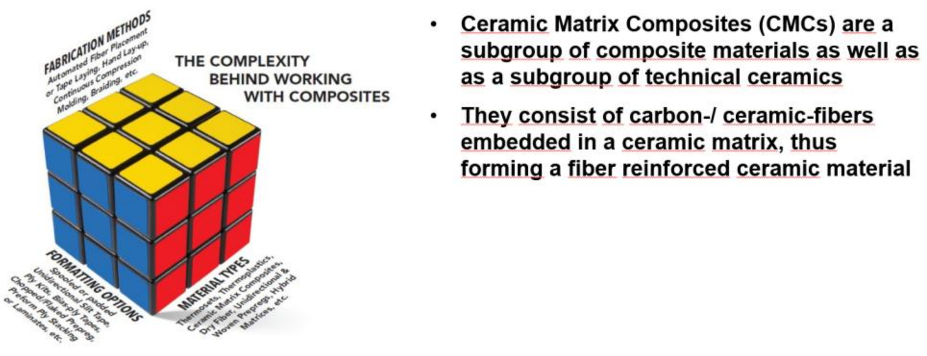

Fig 1. Complexity of CMC material [3]

2. Key Properties and main application fields of CMCs

2.1. CMC properties/ -characteristics

CMCs show exceptional properties, like:

- High-Temperature and Thermal Shock Resistance: CMCs can withstand temperatures far beyond the limits of traditional PMCs or metals in combination with significant damage tolerance linked to thermal shocking.
- Corrosion and Wear Resistance: Resistance to oxidation and degradation from harsh environments
- Low Density: CMCs can be manufactured in a typical lightweight design
- Improved Toughness: The fiber reinforcement enhances the fracture toughness compared to monolithic/ technical ceramics

Figure 2 shows those characteristics in an eye-catching way:

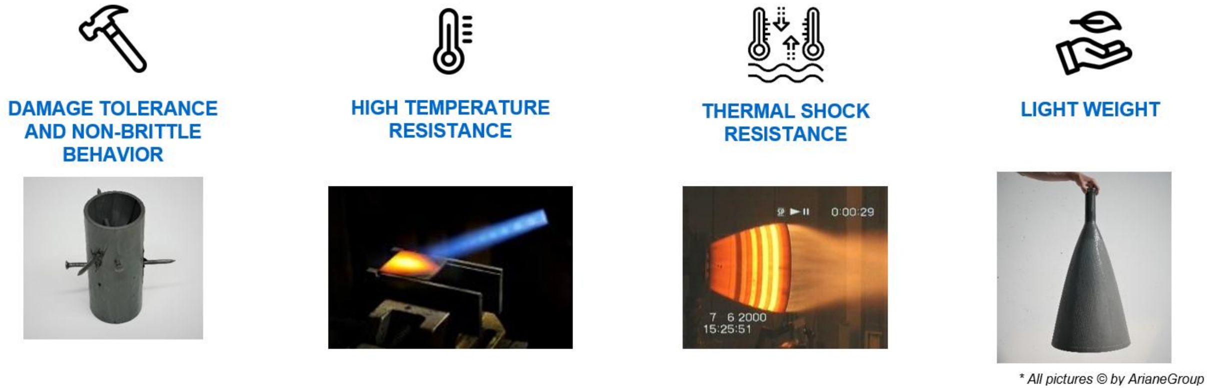

Fig 2. Key characteristics of CMCs

2.2. General Applications of CMCs

The ability of CMCs to be resistant against extreme environments led to their adoption in several high-performance applications like

1. Aerospace Industry

CMCs will be increasingly used in aircraft engines, as turbine blades, nozzles, and heat shields. These components must withstand temperatures > 2000°C far beyond the capabilities of metals or PMCs. By using CMCs the total weight of aircrafts can be reduced with increasing the efficiency.

2. Energy Generation

In the energy sector CMCs are used in stationary gas turbine engines, nuclear reactors and in particular in furnaces. CMCs help to improve the thermal efficiency and long term operation of power plants and gas turbines, which leads to energy savings with potentially reduced costs.

3. Defense applications

CMCs are employed in military applications like missile nose cones, armor-systems, exhaust nozzles for rocket engines and hypersonic propulsion components. Their high-temperature and impact resistance give them a clear benefit in comparison to traditional metals.

4. Automotive and Industrial Deployment

The automotive industry initiates the usage of CMCs in brake systems, clutch-, and engine-parts for high-performance cars. For the Formula 1 racing industry carbon-carbon-composite (CFC/ CMC) brake-discs that can handle extreme temperatures and provide excellent friction are currently standard. More and more industrial applications include CMC components in gas turbines, pumps and valves dealing with harsh media.

3. Application of CMCs in Space- and Hypersonic-Systems

In comparison to metals, which lose strength at high temperatures, CMCs retain their structural integrity (mechanical strength) at temperatures exceeding 1000°C or respectively 1300°C which is a typical range for the conditions experienced by space and hypersonic vehicles. This special high-temperature feature make CMCs particularly well-suited for the intense heat loading e.g. in (space-) propulsion systems or even aerodynamic heating during hypersonic flight. The following figure illustrates a rough overview of CMCs applied in the above mentioned sectors.

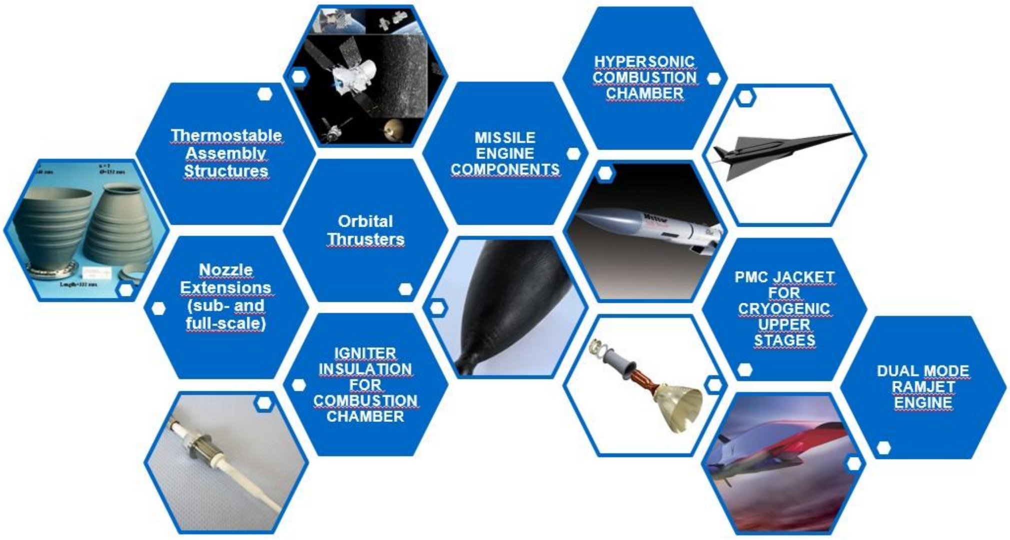

Fig 3. Space- & Hypersonic-applications of CMCs

3.1. Space Flight

Space exploration has always been at the cutting edge of technology, requiring materials that can withstand the extreme conditions of space (extreme temperatures, radiation and mechanical stresses). Spacecraft experience some of the most extreme conditions known to humanity. In space propulsion systems like solid or liquid propellant rocket engines, as well as from the high heat generated during re-entry into the Earth's atmosphere to the harsh environment of space, the materials used in spacecraft must be able to withstand a range of demanding scenarios. Here CMCs will offer a number of advantages and that’s the reason why those materials are already being integrated into various areas of space technology, particularly in heat shields, engine components, and advanced structures.

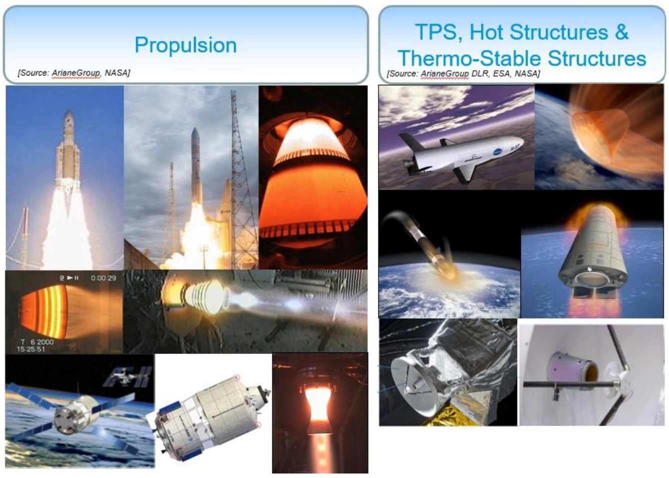

Fig 4. Space- & Hypersonic-applications of CMCs

With the illustrations in Fig. 4 the application of CMC in spacecraft can be seen in:

- Thermal Protection Systems (TPS)

A well-known application of CMCs in spaceflight is in thermal protection systems. Amongst others NASA as well as the space industry in Europe has been experimenting with SiC-based CMCs for use in heat shields for re-usable re-entry vehicles. These materials are capable of dissipating the extreme heat generated during re-entry, providing crucial protection for spacecraft. Besides that the application of ablative TPS is deeply investigated for re-entry purposes.

- Rocket Engines/ Orbital Thrusters

CMCs are also being used in rocket engine as well as orbital thruster components, such as combustion chambers and nozzles or a combination of both. The high-temperature and wear resistance as well as the thermal shock tolerance of CMCs make them an exceptional material choice for parts exposed to the intense heat and pressure during launch/ operation in liquid and solid propellant motors. They can increase the efficiency and service-life of rocket and satellite engines by withstanding the harsh conditions within the engine's combustion zone.

- Aerospace Structures

CMCs are being considered for structural components of spacecraft, such as vehicle frames, high loaded wing components, and other critical parts. The CMC materials will provide strength at significantly elevated temperatures as well as weight savings, helping spacecraft achieve higher efficiency, higher payload and with that potential lower launch/ operation costs. Additionally, the damage tolerance of such material class could gain more resilient space structures, capable of withstanding impacts or wear during particular mission-time.

- Satellite/ Space Probe Components

As satellites and space probes become more advanced and spend longer periods in space, the materials used in their design have to be able to master the environmental challenges. CMCs are ideal for components such as thermal radiators, antennas, thermos-stable-arrangement-structures and heat exchangers. Their potential to resist radiation damage and extreme temperatures makes them absolutely suitable for long-time use in orbit.

3.2. Hypersonic Flight

Hypersonic vehicles that travel at speeds greater than Mach 5, both, heat and aerodynamic forces are extreme. The Hypersonic approach combines different engineering challenges which demand advanced materials capable of mastering extreme conditions like intense heat, pressure, and mechanical stresses and additionally potential weight constraints.
The material class of ceramic matrix composites (CMCs) is one of the most promising material for enabling hypersonic flight vehicles performing effectively and safely in those specific harsh environments.

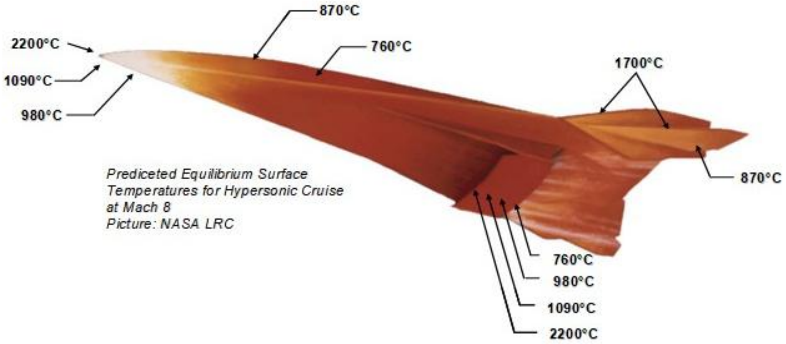

Fig 5. Hypersonic flight environment

Based on Fig. 4 the key applications of CMC materials in Hypersonic Flight Vehicles can be summarized like:

- Leading Edges and Nose Cones

Together with combustion chamber parts leading edges and nose cones of hypersonic flight vehicles experience the highest thermal and aerodynamic stresses. CMCs are well suited for such components due to their high thermal conductivity, high-temperature resistance, and ability to absorb mechanical stresses. Materials like C/SiC (carbon fiber-reinforced silicon carbide matrix) composites can be used to manufacture these critical components, offering resistance to erosion/ ablation as well as thermal damaging.

- Thermal Protection Systems (TPS)

Hypersonic vehicles require advanced thermal protection systems to shield sensitive components from severe heat. CMCs are ideal materials for TPS due to their ability to withstand the temperatures generated at hypersonic speeds. Materials like carbon-carbon (C/C) composites and SiC-based CMCs are used in tiles or ablative shields to protect the vehicle during re-entry or atmospheric flight. In less thermal stressed areas of the hypersonic vehicles even the usage of Oxide based CMC materials should be considered.

- Engine Components

Hypersonic engines, such as ScramJets (Dual Mode RamJets …), operate at extremely high temperatures due to the combustion of air and fuel at high Mach number. The engine's internal components, especially the combustion chamber and nozzle, are subject to severe thermal stresses. SiC based CMCs, potentially with an active cooling approach are ideal for these applications. Thea are able to withstand the high temperatures (especially with active cooling the thermal integrity could be well managed) and pressures within the hypersonic propulsion systems while maintaining structural integrity.

- Thermal Insulation for Avionics

Sensitive avionics systems onboard hypersonic flight vehicles need protection from the heat loads occurring during cruise at high velocity. CMCs can be used to create insulation layers that protect these electronic systems.

At ArianeGroup a high potential in applying CMCs in different hypersonic vehicle components is considered. Figure 6 depicts a schematic drawing of a particular designed small-scale demonstrator for easier and eye-catching explanation.

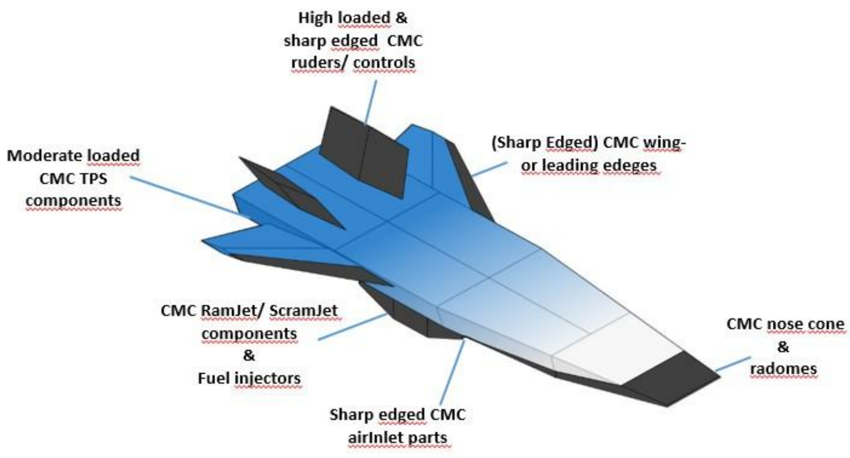

Fig 6. Generic Hypersonic flight Vehicle with potential application areas of CMCs

4. Manufacturing of CMCs at ArianeGroup *Germany (AGG)*

While CMCs show a promising applicability in the above mentioned technology fields, there are still l challenges to overcome before they can be widely considered in spaceflight and hypersonic applications. Manufacturing and cost are two of the main limiting factors. CMCs are complex to produce, and their production process requires specialized equipment and expertise. Additionally, their high cost relative to traditional materials has limited their use currently to high-budget technology areas. However, as technology advances and demand for more efficient and durable materials in hypersonic- and spaceflight increases, these challenges are and will be addressed. Progress in production techniques, such as automation and industrialization, may help to reduce costs and increase the scalability and reproducibility of CMCs.

With the combination of different automated and robot-assisted textile techniques like filament winding, braiding, weaving, stacking and sewing as well as appropriate cost-effective infiltration methods for producing different multidirectional (2D & 3D) ceramic composites time effective and therefore "low-cost" process techniques for the manufacturing of high-performance and high temperature composites in the form of uniformly densified near-net shaped structures are available at AGG.

4.1. Wet Filament Winding with Polymer Infiltration and Pyrolysis (PIP) of C/SiC

Within this process technology a carbon fiber siliconcarbide composite (C/SiC) in 2D fiber architecture is achieved via filament winding and/ or lamination technology combined with the polymer infiltration pyrolysis process (PIP). It offers the following benefits

- High flexibility in fiber lay-up (fiber orientation)
- High degree of automation and reproducibility (robot controlled)
- Complex geometries in near net shape design producible
- Composition of ceramic precursor AGG know-how

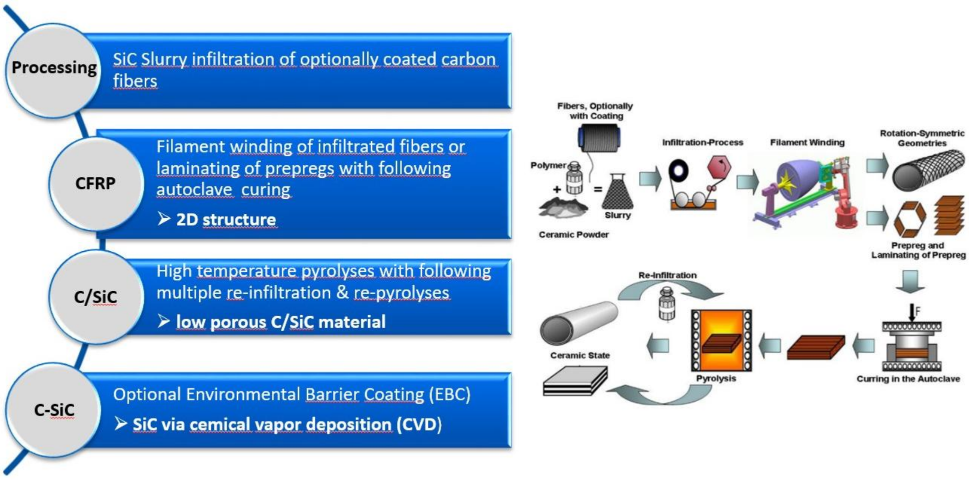

Fig 7. Manufacturing process for 2D C/SiC material at AGG

4.2. Textile Technologies with following special Gas-Phase-Infiltration, Slurry Impregnation & High Temperature Treatment (r-CVI +LSI)

Within this process 2D and 3D fiber architecture via robot assisted circular braiding combined with sewing techniques is feasible. The following densification/ infiltration to a carbon/carbon preform (C/C) is executed by the rapid chemical vapor infiltration (r-CVI) process which allows a significant reduction of infiltration time in comparison to standard CVI-methods and it gives the opportunity to tailor the carbon matrix during processing. In an optional step an environmental barrier surface infiltration can be applied by a reactive slurry to create SiC at the surface during a high temperature treatment –

similar to the typical liquid silicone infiltration process (LSI). As the process is fully automated it is a

- Cost-effective manufacturing technology with high automation degree and high monitoring potential (***INDUSTRY 4.0***)
- and offers comparable simple process management with comparable low processing times

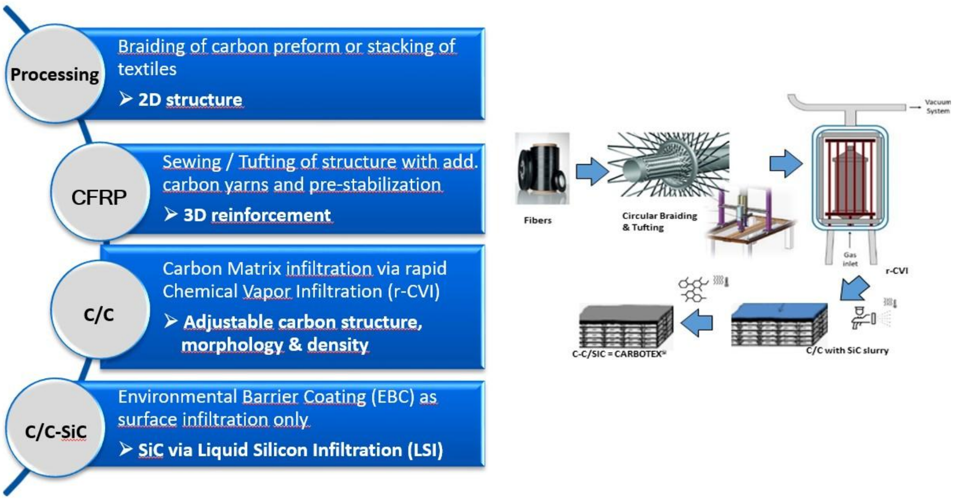

Fig 8. Manufacturing process for 2D &3 D C/C-SiC material at AGG

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Fig 9. Material- and Process Technologies for CMC Manufacturing at AGG

5. Conclusion

Ceramic matrix composites offer big potential for the next generation of space and hypersonic flight vehicles. With their exceptional high-temperature resistance, strength, and damage tolerance, CMCs provide solutions to the unique challenges of operating in harsh space environment at Mach 5 and beyond as well as in typical reentry scenarios. While technical and economic hurdles remain, the ongoing research and development in CMC process technologies including automation and industrialization are likely to pave the way for safer, faster, and more efficient space and hypersonic flight vehicles, revolutionizing both defense and civilian aerospace sectors in the coming years.

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