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Addressing Processing Limitations in SiC-Based Ceramic Composites: A Review of Hybrid Approaches and Perspectives

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Abstract

This review presents an up-to-date overview of hybrid processing techniques for silicon carbide (SiC) matrix composites. These materials are widely used in systems where high temperatures, mechanical stress, and oxidation are serious concerns, such as in aerospace and energy applications. Although there are well-established fabrication methods for SiC composites, such as chemical vapor infiltration (CVI), polymer infiltration and pyrolysis (PIP), and reactive melt infiltration (RMI), each has its limitations. For example, while PIP is relatively simple, it often results in residual porosity. Additionally, CVI can yield high-quality microstructures, but it is a slow process and may still leave behind microporosity. Furthermore, RMI can deliver high densities, but may also cause fiber damage or leave behind residual silicon. Given the individual limitations of CVI, PIP, and RMI, hybrid approaches may be deployed to gain the benefits of multiple techniques. Most commonly, CVI and PIP are combined for hybrid processing, but other combinations of CVI, PIP, and RMI are possible. This review discusses how these combined processes are applied to various SiC-matrix composites, including carbon fibers in SiC matrix (C_f/SiC), carbon fibers in a matrix of C and SiC (C_f/C–SiC), and SiC fibers in SiC matrix (SiC_f/SiC). The main contribution of this review is summarizing how hybrid techniques influence porosity, microstructure, fiber-matrix bonding, and the overall thermal-mechanical properties. Many recent studies are also included in the topics of improved fiber architectures, polymer chemistries, and infiltration steps. While hybrid methods often lead to improved properties, there are still open questions, especially regarding internal oxygen from PIP, long processing times for CVI, and phase stability after many cycles at high temperatures. This review concludes with potential future directions for research efforts to make hybrid SiC-matrix processes more effective, scalable, and reliable.

Keywords: ceramic-matrix composites, CMCs, SiC-matrix composites, CVI, PIP, RMI, hybrid processing, CVI-PIP

1. Introduction

1.1 Ceramic matrix composites

Ceramic matrix composites (CMCs) have become increasingly important because they offer an uncommon combination of high stiffness, high strength, high toughness, and high stability in high temperature envrionments. Compared to unreinforced or monolithic ceramics, CMCs possess extrinsic toughening mechanisms via reinforcing fibers to overcome the brittleness of ceramics[1,2]. By adding reinforcing fibers and/or particles, the material gains better resistance to cracking under thermal and mechanical stresses[3]. Because of these properties, CMCs are often used in aerospace, defense, and energy applications where components must perform reliably under high temperatures and in chemically aggressive environments[4,5]. As illustrated in **Fig. 1**, these materials are particularly suitable for environments where conventional materials often fail.

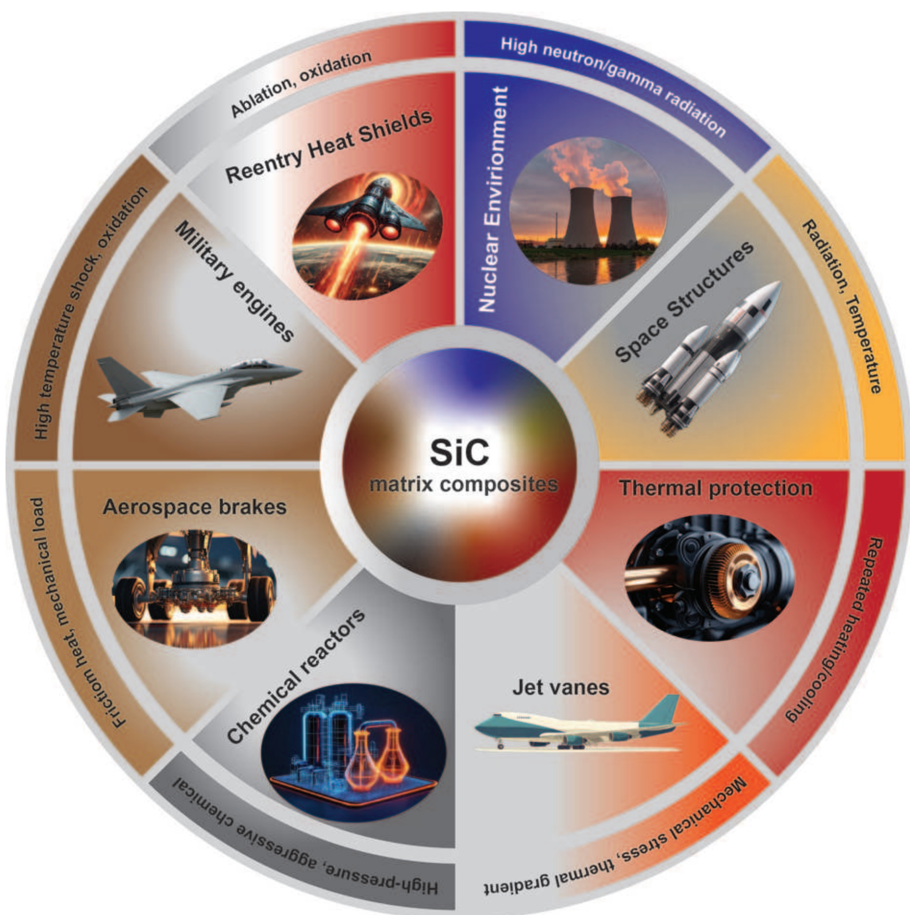


Fig. 1: *Extreme environments and representative application fields of SiC-matrix composites. Image source: Adobe Stock.*

1.2 Review Focus: SiC-Matrix CMCs

This review focuses on a critical assessment of the current state of the art in hybrid processing of SiC-matrix CMCs. Hybrid procesing is defined as the use of more than one matrix formation approach such as chemical vapor infiltration (CVI), polymer infiltration pyrolysis (PIP), reactive melt infiltration (RMI), and related methods to address fabrication challenges, enhance matrix uniformity, and improve fiber–matrix bonding. Special attention is given to C_f/SiC, SiC_f/SiC, and C_f/C–SiC systems, with discussion of recent progress in mechanical strength, thermal stability, and oxidation resistance. Although previous reviews have covered hybrid processing for ceramic matrix composites[6–8], this work highlights newer developments and explores how specific combinations of CVI, PIP, RMI, and other techniques influence microstructure and high-temperature performance. By comparing recent findings with established knowledge, this review identifies both prior achievements and areas requiring further research. Specifically, this paper makes the following contributions:

- Explains why CVI, PIP, and similar techniques are often combined for processing SiC-matrix composites;
- Describes how hybrid processing affects densification, porosity, and microstructural development;
- Summarizes key improvements in properties such as tensile strength, fatigue resistance, thermal stability, and oxidation behavior; and
- Presents recent experimental findings and discuss ongoing challenges and potential directions for future research.

1.3 Types of SiC-Matrix CMCs

Carbon and SiC fibers are the two most important reinforcing fibers for SiC-matrix CMCs. Carbon fibers have high stiffness, high thermal conductivity (particularly for pitch-based carbon fibers), and low density. Therefore, carbon fiber-reinforced CMCs may possess low density, high stiffness, and good resistance to thermal shock. SiC fibers have high stiffness and high resistance to oxidation, often leading to composites that can endure harsh temperatures and oxidative environments. In aerospace, where key priorities may include reducing weight and increasing speed/efficiency by enduring higher temperatures and harsher environments, carbon fiber– and SiC-fiber reinforced ceramics have helped address the limitations of metals and monolithic ceramics, particularly in sustaining high temperatures without significant loss of strength and stiffness[9–11].

Carbon fiber/Carbon (C_f/C) Composites

Much of the groundwork for SiC-matrix CMCs was established during the development of C-matrix CMCs. Among the earliest developments in CMCs, C_f/C composites stood out for their excellent thermal conductivity, high specific stiffness, and minimal thermal expansion. Composed of carbon fibers embedded within a carbon matrix, these composites have been successfully used in aerospace components such as nose cones, leading edges, rocket nozzles, and famously the tiles for the NASA Space Shuttles[12,13]. Despite the advantages of C_f/C, the carbon matrix oxidizes above about 400 °C, leading to structural degradation via the formation of CO and CO_2. Protective coatings, such as SiO_2, SiC, ZrO_2, and Al_2O_3, have been applied to address this problem. SiC coatings in particular offer oxidation resistance up to 1800 °C by forming a passive silica layer[14]. However, issues like delamination of the coating have limited the long-term performance of C_f/C in oxidizing environments[15]. Development of environmental barrier coatings remains an area of active research for C_f/C composites[16,17].

Carbon fiber/Silicon Carbide (C_f/SiC) Composites

To overcome the oxidation limitations of C_f/C systems, researchers began replacing the carbon matrix with silicon carbide (SiC), a ceramic known for its hardness, chemical stability and resistance to oxidation. This led to carbon fiber–reinforced silicon carbide (C_f/SiC) composites[18]. Carbon fibers reinforcement, either continuous or short fibers, are desirable for their high specific stiffness, while the SiC matrix enhances high-temperature and oxidation performance. As described later, the carbon fibers are typically derived from either polyacrylonitrile (PAN) or pitch precursors. While PAN-based fibers have higher strength, pitch-based fibers have much higher thermal conductivity and higher stiffness. Therefore, C_f/SiC composites made with pitch-based C_f also benefit from high thermal conductivity and low coefficient of thermal expansion, making them suitable for advanced aerospace and nuclear applications[19]. However, the thermal expansion mismatch between carbon fibers and the SiC matrix can induce tensile residual stresses, posing issues that may cause matrix cracking during cooldown, reducing the mechanical strength and durability of the composite.

Carbon fiber/Carbon–Silicon Carbide (C_f/C–SiC) Hybrids

C_f/C–SiC composites integrate a carbon fiber/carbon (C_f/C) core with a silicon carbide (SiC) phase, either as a coating or a secondary matrix phase. In a two-phase architecture, the carbon matrix contributes toughness and thermal conductivity, while the SiC matrix improves environmental durability. This structure blends the excellent mechanical strength, low density, and thermal shock resistance of C_f/C with the oxidation and ablation resistance of SiC, potentially addressing the shortcomings of pure C_f/C above 400 °C. These materials are particularly effective in aerospace thermal protection systems (TPS), including nose cones, leading edges, reentry heat shields, and high-performance braking systems[20,21]. The hybrid structure allows these components to withstand temperatures exceeding 2000 K, intense heat flow, and mechanical vibrations. Still, challenges remain regarding complex processing, potential interfacial stresses due to coefficients of thermal expansion (CTE) mismatch, and residual porosity affecting overall performance.

Silicon Carbide/Silicon Carbide (SiC_f/SiC) Composites

To achieve even greater oxidation resistance and thermal stability, systems have been developed by using SiC fibers in combination with a SiC matrix. SiC_f/SiC composites mitigate oxidation issues from carbon, providing excellent stability above 1400 °C. These composites exhibit good load-bearing capacity, outstanding oxidation resistance, and excellent creep resistance, making them widely used in turbine engine hot sections, hypersonic vehicle components, and structural parts in nuclear reactors[22]. Because of the closely matched coefficients of thermal expansion between fibers and matrix, these composites offer improved resistance to internal thermal stress buildup, enhancing durability during extreme temperature excursions[23–25].

1.4 Comparative Overview of SiC-Matrix CMCs

To provide a comparative understanding of the major fiber-reinforced CMCs, **Fig. 2** presents a series of Ashby plots that illustrate key performance metrics, such as flexural strength, modulus, and thermal conductivity, versus density. These plots highlight how common types of SiC-matrix CMCs differ in terms of mechanical and thermal properties. SiC_f/SiC composites consistently exhibit the highest flexural modulus and strength, reflecting their superior stiffness and load-carrying capacity, which result from the inherent stiffness of both the fibers and the matrix. On the other hand, C_f/C composites clearly lead in thermal conductivity due to the graphitic nature of carbon, making them attractive for thermal management applications. However, this thermal advantage is offset by their poor oxidation resistance, which limits their use at elevated temperatures unless protective coatings or other barriers are applied. Hybrid systems such as C_f/C–SiC occupy a middle ground, combining the conductivity and toughness of carbon with the environmental durability of SiC.

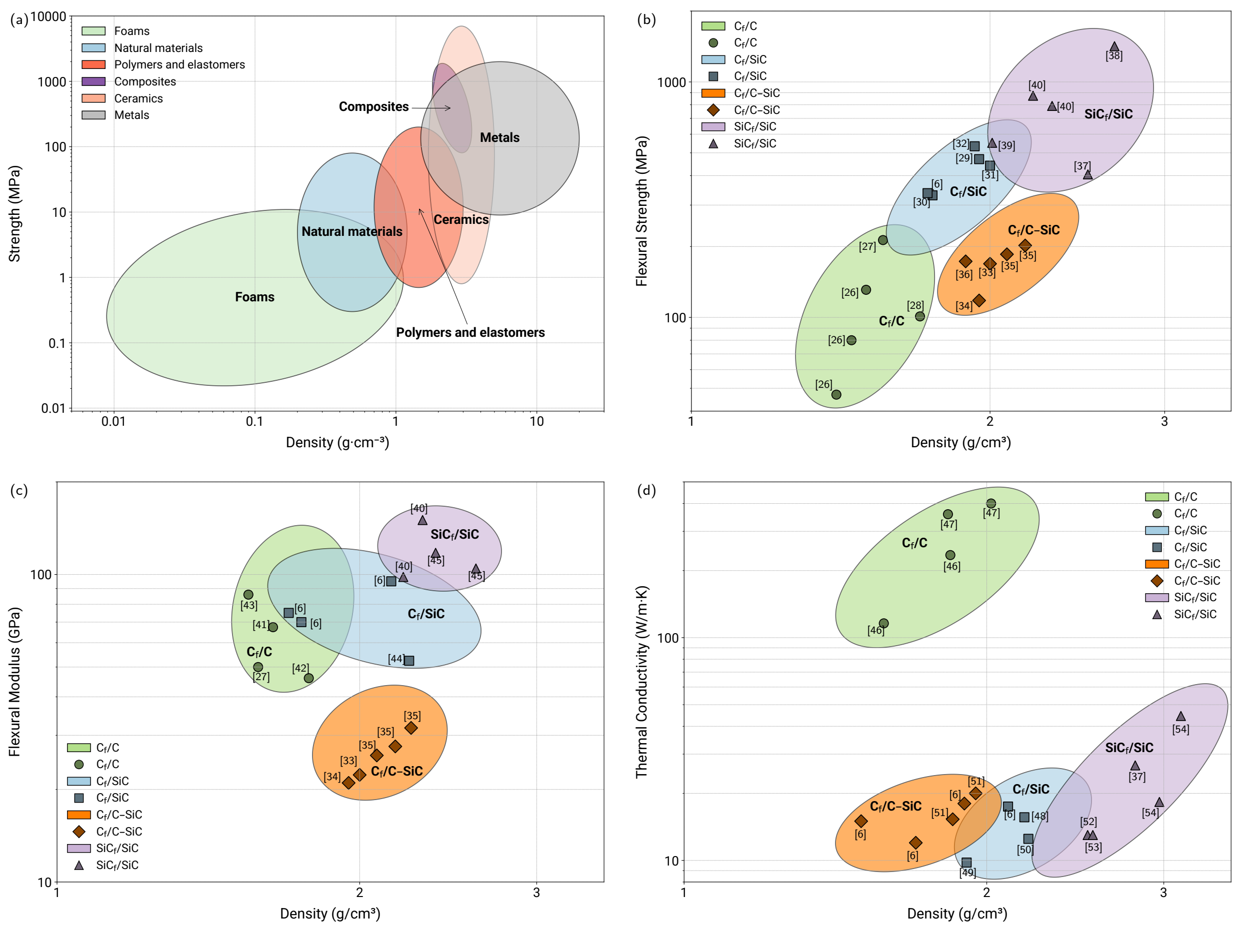


Fig. 2: *Ashby Plots of: (a) Strength versus density for different materials*[55]; *(b) Flexural strength versus density of SiC-matrix composites; (c) Flexural Modulus versus density; (d) Thermal Conductivity versus density.*

These trends highlight the need to balance stiffness, thermal performance, and oxidative stability when selecting a composite system, depending on the specific application. A more detailed side-by-side comparison of compositions, advantages, limitations, and typical applications is presented in **Table 1**.

Table 1: *Comparative overview of fiber-reinforced ceramic matrix composites*

Composite	**Fiber / Matrix**	**Advantages**	**Limitations**	**Applications**
C_f/C	Carbon/Carbon	Excellent mechanical strength and thermal conductivity; low density	Poor oxidation resistance limits use in oxidative environments	Rocket nozzles, brake discs, leading edges
C_f/SiC	Carbon/Silicon Carbide	Enhanced oxidation resistance; good thermal shock resistance; lightweight	CTE mismatch induces tensile residual stresses at the fiber/matrix interface, possibly causing matrix cracking during cooldown	Nozzles, wing panels, thermal protection systems (TPS)
C_f/C–SiC	Carbon/Carbon + Silicon Carbide	Combines thermal conductivity and toughness of carbon with oxidation resistance of SiC; hybrid matrix improves performance	Complex and costly processing; CTE mismatch may induce interfacial stresses; residual porosity affects strength and oxidation resistance	TPS, reentry vehicle structures, aerospace braking systems
SiC_f/SiC	Silicon Carbide / Silicon Carbide	High-temperature strength; excellent oxidation and creep resistance; low thermal expansion	Expensive processing; residual Si reduces creep resistance and may react with fiber or interphase; limited SiC fiber availability	Turbine blades, hypersonic vehicles, nuclear fuel cladding

After a comparative evaluation of SiC-matrix composites and their properties, the discussion now turns to the processing techniques, which in turn determine the microstructure, mechanical behavior, and overall performance.

1.5 Processing Techniques for SiC-matrix composites

The processing techniques play a crucial role in determining the final properties of CMCs[8]. Several fabrication techniques have been developed over time, such as chemical vapor infiltration (CVI), reactive melt infiltration (RMI), and polymer infiltration and pyrolysis (PIP). Broadly, these techniques can be grouped into gas-phase, liquid-phase, and solid-assisted processes, each with specific benefits and drawbacks. CVI provides excellent control over matrix development and typically yields composites with low porosity and uniform microstructures[56]. As a gas-phase method, CVI allows gradual and uniform matrix formation, but it is limited by very long processing times and high cost. RMI densifies composites rapidly by infiltrating molten silicon, but can result in residual/unreacted silicon and microcracks[57]. As a solid–liquid assisted route, RMI offers fast densification but often introduces chemical heterogeneity. PIP, known for its adaptability to complex shapes, involves infiltrating preforms with a polymer precursor like polycarbosilane (PCS), followed by curing and pyrolysis to convert the precursor into ceramic[58–60]. However, PIP is challenged by shrinkage and gas evolution during pyrolysis, requiring multiple cycles for adequate densification. As a liquid-phase process, PIP is versatile and scalable, though repeated infiltration–pyrolysis cycles are usually necessary to reduce residual porosity.

1.6 Hybrid Processing Approaches and Research Scope

To address the limitations of individual fabrication methods, such as the long processing times of CVI and the residual porosity of PIP, researchers have developed hybrid approaches that combine multiple techniques. For instance, CVI can establish an initial dense matrix, which is further densified through PIP, resulting in improved mechanical properties and reduced porosity[61–63].[1] These hybrid strategies are especially valuable for aerospace components exposed to mechanical loads, vibrations, and extreme thermal cycling[64]. Recent advances in polymer precursor chemistry and infiltration protocols have also contributed to better densification and microstructural uniformity[65].

2. Processing Strategies for SiC-matrix composites

The performance of SiC-matrix composites is determined by the process and resulting microstructure. Key decisions include fiber selection, fiber/matrix interphase design, and matrix deposition/formation method. Together, these elements control the resulting strength, damage tolerance, oxidation behavior, and thermal conductivity. For high-performance applications in aerospace, energy, and defense, the synergy between these performance criteria must be precisely engineered.

2.1 Fiber Selection

Since the processing route strongly interacts with the reinforcement, it is first necessary to consider the selection of fibers. The type of fiber dictates the chemical and thermal stability of the

[1] It is worth noting that some legacy works performed CVI before PIP, while most present-day works perform PIP before CVI.

composite, and influences the effectiveness of different matrix deposition methods. The choice of reinforcing fiber has a profound influence on the chemical, mechanical, and thermal behavior of the final composite. In carbon fiber-reinforced SiC systems (C_f/SiC and C_f/C–SiC), two dominant types of fibers are used: polyacrylonitrile (PAN)-based and pitch-based carbon fibers.

PAN-based carbon fibers are known for their high tensile strength, structural stability at elevated temperatures, and relatively reactive surfaces. These characteristics make them suitable for structural applications that demand good toughness and strength, and most polymer-matrix composites are fabricated with PAN-based fibers.

Pitch-based carbon fibers, by contrast, provide higher thermal conductivity and have a smoother surface, which allows for more uniform matrix infiltration. These fibers are often used in thermal protection systems and insulation components. Despite their thermal advantages, their lower tensile strength and higher brittleness limit their use in load-bearing roles.

In hybrid C_f/C–SiC composites, which combine a carbon matrix with an SiC phase, the selection of fiber also determines the interaction during the sequential infiltration steps. PAN-based fibers contribute to mechanical toughness and delamination resistance, while pitch-based fibers help improve heat dissipation.

In fully ceramic SiC_f/SiC composites, continuous SiC fibers such as Hi-Nicalon™, Tyranno™, and Sylramic™ are used. These fibers are derived from melt-spun polycarbosilane or polysilazane precursors and subsequently pyrolyzed. They offer excellent creep resistance, thermal stability above 1400 °C, and superior oxidation behavior. Boron- and nitrogen-doped variants have further extended their performance in extreme environments[23,66]. **Fig. 3** highlights the performance differences between fiber types. PAN-based fibers offer higher tensile strength, pitch-based fibers excel in thermal conductivity, and SiC fibers provide a balance with superior high-temperature resilience.

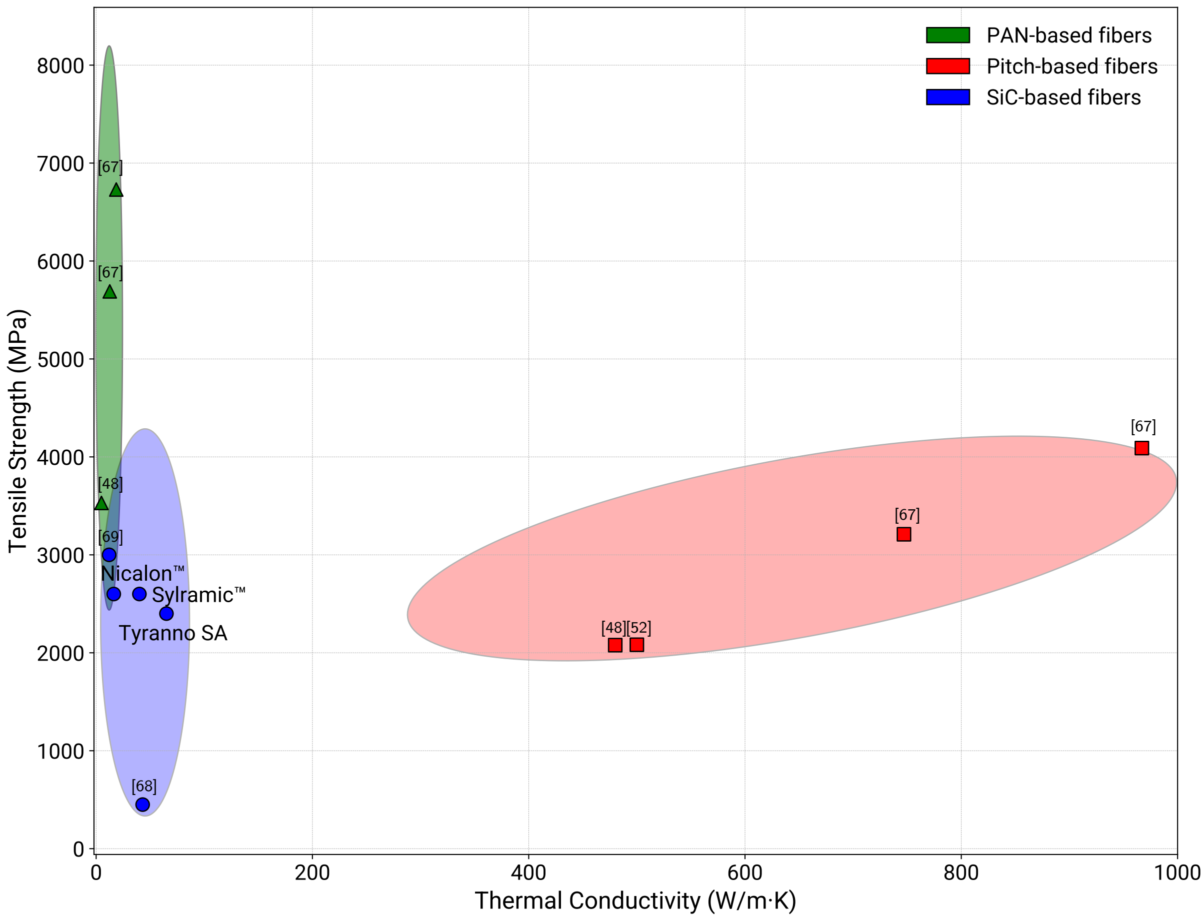


Fig. 3: *Ashby Plots of Tensile Strength versus thermal Conductivity for different fibers.*

2.2 Fiber/Matrix Interphase

Once the fiber type is established, attention shifts to the interphase, which is a mediator between fiber and matrix. The design of this interphase determines load transfer, damage tolerance and oxidation resistance. The fiber-matrix interface is a key component in SiC-matrix composites, as it controls how cracks propagate and how the material dissipates energy during failure. In contrast to a sharp interface, the fiber/matrix interphase is deliberately designed, typically as a few hundred nanometers to a few micrometers thick, to acts as a chemical and mechanical buffer between the solid ceramic matrix and the reinforcing fibers. Mechanically, the interphase forms a weak layer between the fiber and matrix, thereby enabling progressive damage formation, such as crack deflection, fiber debonding, and fiber pull-out. These damage-tolerance mechanisms delay fracture propagation and enhance toughness[2]. This contrasts with polymer-matrix composites — in the case of CMCs, weak bonding between the fiber and matrix is desired because it preserves damage tolerance. Chemically, the interphase inhibits reactions between the fibers and matrix at high temperatures (both during fabrication and in service) that would otherwise lead to undesirable fiber–matrix bonding[70–73]. Overall, the interphase is more than a passive boundary, it is an active design feature that must be carefully tailored to match the fibers, matrix, and processing method. Its role becomes even more critical in harsh environments, where thermal cycling and oxidative stress can rapidly degrade composites without a properly designed fiber-matrix interface.

The most commonly used interphase materials in SiC-matrix CMCs are pyrolytic carbon (PyC), boron nitride (BN), and multilayer systems like (PyC/SiC)*n* or (BN/SiC)*n*. These coatings are generally applied by CVI prior to matrix densification[74–76]. To ensure uniform interphase deposition, fibers must first be desized to remove residual surface treatments. This step can be performed thermally by heating the fibers in an inert atmosphere at approximately 300 °C[77], or chemically using solvents like acetone[78]. PyC is widely used in Cf/SiC and Cf/C–SiC composites because of its chemical compatibility with carbon fibers and its favorable mechanical behavior under thermal stress[79]. After desizing, PyC is often deposited via CVI using carbon-rich gases such as methane, toluene, or butane at temperatures around 850 °C[74–76]. BN is more common in SiC_f/SiC composites due to its excellent oxidation resistance. BN is often deposited via CVI using boron trichloride (BCl_3) and ammonia (NH_3). In the case of both PyC and BN, the desired phases include those that form 2D/sheet-like layers, e.g. with sp2 bonding, such that the atomic layers of PyC and BN slide easily between the fiber and matrix, yielding the desired low interfacial shear stress. However, the optimal interphases are often combinations of phases, as described below.

A key factor influencing the effectiveness of PyC interphases is their texture, which reflects the degree of graphitic ordering. This texture depends on CVI parameters such as temperature, pressure, gas flow rate, and precursor chemistry. Studies have shown that medium-textured PyC provides the best balance between strength and damage tolerance: it allows for stable crack deflection and long fiber pull-out lengths, which improve fracture toughness[75,76]. In contrast, high-texture PyC can lead to excessive bonding and brittle fracture, while low-texture PyC may result in early fiber–matrix separation and insufficient stress transfer[79].

Multilayer interphases, alternating layers of soft (PyC or BN) and hard (SiC) materials, are often used to combine mechanical and environmental functionality. The soft layers repel cracks and impart damage tolerance, while the hard layers increase oxidation resistance and maintain structural integrity at high temperatures. However, such designs require precise thickness control and uniformity, as poorly deposited interphases can hinder matrix infiltration, introduce porosity, or create localized stress concentrations that compromise performance.

The selection of the SiC-matrix processing method cannot be isolated from fiber type and interphase design. While the matrix provides thermal and oxidative stability, its interaction with the interphase and fibers must be carefully controlled. Residual porosity, mismatched coefficients of thermal expansion (CTE), and shrinkage stresses can all degrade performance if not properly managed during processing. PAN-based fibers are typically paired with PyC interphases and processed via CVI or PIP, while pitch-based fibers, due to their infiltration-favorable surfaces, may benefit from hybrid strategies with reduced interphase thickness.= In SiC fiber systems, the close chemical match with the matrix simplifies some interfacial challenges, but the use of BN or multilayer interphases remains essential for controlling damage and crack propagation, especially under cyclic thermal or mechanical loads.

The next section discusses the main fabrication processes for SiC-matrix composites, focusing on how they interact with fiber and interphase design to produce dense, defect-tolerant structures tailored for high-performance applications.

2.3 SiC-Matrix Processing Methods

SiC-matrix processing methods include CVI, PIP, RMI, and “hybrid” processing, or combinations of two or more of these methods. Each of these processing methods is discussed in the following sections.

Chemical Vapor Infiltration (CVI)

Among the various techniques for producing CMCs, CVI has emerged as one of the most effective methods. CVI belongs to a broader class of techniques known as chemical vapor deposition (CVD), which involves the decomposition or reaction of gaseous precursors to form solid materials on a substrate[80]. CVD deposits material onto surfaces using gaseous reactants and is widely used to form thin films of metals, non-metals, or alloys. In contrast, CVI allows gases to penetrate porous structures, forming material within the bulk rather than just on the surface. Both methods support near-net-shaping and precise thickness control through repeated cycles. However, they typically require high temperatures, often above the degradation point of organic substrates. CVD achieves deposition rates of several hundred nanometers per minute, while CVI is significantly slower due to the need for deep infiltration. Unlike CVD, CVI uses lower pressures (10–100 Torr) and slower gas flow rates to ensure uniform diffusion through the porous preform without clogging the surface[80,81]. Overall, the CVI approach can result in composites with excellent uniformity, structural integrity, and minimal damage to the fibers, even at high temperatures.

CVI is carried out at moderate temperatures (typically 900 to 1200 °C) and low pressures. It involves the decomposition of gaseous precursors that diffuse into the porous network of the fiber preform. For the fabrication of C_f/SiC composites, methyltrichlorosilane (MTS, CH_3SiCl_3) is the most commonly used precursor. When introduced with hydrogen as a carrier gas, MTS decomposes at elevated temperatures to deposit solid SiC and release gaseous byproducts, as seen in **Equation** (1), with

$$CH_3SiCl_3(g) + H_2(g) \rightarrow SiC(s) + 3HCl(g) + H_2(g). \tag{1}$$

This reaction produces near-stoichiometric β-SiC with high purity. Hydrogen serves not only as a carrier but also maintains a reducing atmosphere, which suppresses unwanted side reactions and helps preserve fiber integrity[82,83].

Typical CVI conditions for SiC include a precursor to hydrogen molar ratio of 1:10, temperature around 1100 °C, pressure near 100 kPa, and a flow rate of 250 mL/min[84]. Luo et al.[71] demonstrated successful densification of 3D T-300 carbon fiber preforms using MTS and a 100 nm PyC interphase. The porosity was reduced from 25 % to 9 %, and the density increased to approximately 2.2 g/cm^3.

A major drawback of conventional isothermal CVI is its inherently slow infiltration rate. Due to diffusion-limited gas transport, precursors tend to react and deposit near the preform surface, leading to premature pore closure and hindering matrix growth in the interior regions. As a result, full densification of complex or thick-section components can require several hundred hours. Additionally, the commonly used precursors for SiC deposition, such as MTS, generate hydrogen chloride (HCl) as a byproduct. The accumulation of HCl within the infiltration chamber not only poses corrosion concerns for equipment but can also shift equilibrium reactions, potentially reducing deposition efficiency and further exacerbating densification challenges[9,85].

Despite these limitations, **isothermal CVI (I-CVI)** remains widely used due to its simplicity, control over deposition chemistry, and compatibility with large and complex preforms[86]. Recent studies have focused on optimizing I-CVI through fiber architecture and interface design. For example, Krishna et al.[87] compared 2.5D and 3D C_f/SiC composites fabricated via I-CVI using a multilayered $(PyC/SiC)_4$ interphase. While the 2.5D composites showed higher flexural strength (335 MPa), the 3D structures provided better toughness (19 MPa$\cdot m^{1/2}$) due to improved crack deflection and stress redistribution across the thicker architecture.

Laser-assisted CVI (LA-CVI) refers to a process where conventional CVI is combined with localized structural modification to improve gas-phase infiltration. In the study by Wang et al.[29], C_f/SiC preforms were first partially densified using standard isothermal CVI. Once the preform reached an intermediate density of 1.5 g/cm^3, femtosecond laser micromachining was employed to create additional mass transfer channels. These channels facilitated better precursor access during the subsequent CVI stage, resulting in more uniform matrix deposition and reduced residual porosity. The optimized spacing of 3 mm between channels led to a flexural strength of 528 $\pm$ 12 MPa, marking a 12.2 % increase over reference samples. The improvement was attributed to denser SiC bands near the channels and enhanced crack deflection and fiber pull-out, as confirmed by Scanning Electron Microscopy (SEM) and X-ray computed micro-tomography (μCT) analysis. This approach demonstrates how controlled post-processing of partially densified preforms can be effectively used to improve the mechanical performance of C_f/SiC composites.

Microwave-assisted CVI (MW-CVI) is a modified infiltration technique that employs volumetric heating by microwave radiation to overcome the limitations of conventional isothermal CVI. Instead of heating the preform externally, MW-CVI deposits energy directly within the material via dielectric absorption, resulting in an inverted thermal gradient (hotter inside than at the surface). This facilitates inside-out densification, delays premature surface pore closure, and enhances precursor penetration into the core. D'Ambrosio et al.[88] applied MW-CVI to fabricate $SiC_f/(SiC/BN)_3/SiC$ composites reinforced with Hi-Nicalon™ Type S fibers. Using a custom pilot-scale reactor equipped with three solid-state microwave sources operating at independently tunable frequencies (2.4–2.5 GHz), they optimized field uniformity through multiphysics simulations. The MW-CVI process was performed at approximately 960 °C and 200 mbar for 10 hours. μCT and SEM-Energy-Dispersive X-ray Spectroscopy (EDS) analyses revealed that porosity in core regions decreased from 40 % to approximately 15 %. Although the chemical efficiency remained low (4.5%), the process achieved deeper infiltration and reduced processing time compared to traditional CVI, which typically requires several hundred hours. These results highlight the potential of MW-CVI as an effective and scalable route for densifying SiC-matrix composites, particularly when precise thermal and electromagnetic control is implemented.

Electromagnetic-Coupled CVI (E-CVI) accelerates precursor transport using internal Joule heating and electromagnetic fields. Hu et al.[21] fabricated a C_f/C–SiC sandwich structure in 20 hours, producing a composite with high ablation resistance (0.38 μm/s at 1700 °C) and flexural strength of 325 MPa.

Pulsed CVI (P-CVI) alternates precursor flow and evacuation to prevent early pore closure, though it requires careful control[89].

Other CVI process variants have been explored to overcome the diffusion limitations of conventional isothermal CVI. For instance, **Thermal Gradient CVI (TG-CVI)** introduces a controlled temperature difference across the preform, directing deposition preferentially from the colder regions inward. Similarly, **Forced Flow CVI (F-CVI)** enhances precursor transport by applying a gas pressure gradient, which increases infiltration efficiency. Although these methods are not as widely adopted as I-CVI or MW-CVI in the systems examined, they represent promising strategies to improve densification uniformity and reduce surface pore closure when carefully controlled[90].

Overall, CVI enables the production of complex-shaped, high-purity composites with well-tailored microstructures, especially when used in conjunction with engineered fiber architectures and interphase coatings.

In the next sections, we will talk about liquid-phase methods as well as how hybrid processing strategies address residual porosity and densification time by combining CVI with liquid-phase methods.

Polymer Infiltration and Pyrolysis (PIP)

PIP is a versatile and cost-effective method for fabricating SiC-matrix composites, particularly suitable for complex-shaped components. The process involves infiltrating a porous fiber preform with a liquid organosilicon polymer precursor, most commonly PCS, followed by curing (thermal crosslinking) and then pyrolysis in an inert atmosphere, typically between 1100 and 1600 °C. During pyrolysis, the polymer undergoes thermal decomposition and converts into a ceramic SiC matrix. However, this transformation is accompanied by significant volumetric shrinkage and gas evolution, resulting in residual porosity. Consequently, multiple PIP cycles are required (typically 5 to 12) to reach acceptable densification levels. The efficiency of this process depends on the viscosity, ceramic yield, and kinetics for infiltration, curing, and pyrolysis of the precursor.

Compared to CVI and RMI, PIP requires simpler equipment and allows better control over the precursor formulation, infiltration parameters, and heat treatment conditions. The primary limitation of PIP lies in the relatively low ceramic yield of standard precursors, which can limit the density and crystallinity of the final SiC matrix, especially at pyrolysis temperatures below 1400 °C[91].

To investigate the behavior of PIP composites under elevated temperatures, Wang et al.[92] examined the fracture mechanisms of C_f/SiC composites using both experimental methods and phase-field simulations. They observed a transition in fracture mode with temperature: from crack deflection at room temperature, to penetration, and finally to interfacial debonding at 1600 °C. This behavior underscores the need for temperature-adapted interphases and for testing at elevated temperatures. The composites used in the study were fabricated from T-300K carbon fibers coated with a pyrolytic carbon (PyC) interphase, then densified with a silicon carbide matrix through ten PIP cycles. The PyC interphase proved to be directly responsible for the material's changing behavior. At lower temperatures, it acted as a weak boundary that forced cracks to deflect, a key toughening mechanism. At 1600 °C, however, the intense heat caused the PyC interphase itself to graphitize, weakening the fiber-matrix bond even further.

Several fabrication strategies have been employed to improve the densification and mechanical properties of PIP-derived composites. For instance, Kumar et al.[65] used a 5:1 mass ratio of PCS to divinylbenzene (DVB), diluted in petroleum ether, to fabricate carbon fiber laminates composed of both unidirectional (UD) and bidirectional (BD, 0°/90°) fiber architectures. After 5 to 6 PIP cycles and pyrolysis between 1400 and 1600 °C, the composites reached flexural strengths of up to 720 MPa. In another study, Xiang et al.[32] synthesized PCS by thermally decomposing polydimethylsilane (PDMS) in xylene under nitrogen. This precursor was used to infiltrate 3D-braided T-300 carbon fiber preforms, followed by pyrolysis in argon at 1200 °C. A total of 9 to 12 cycles yielded well-densified (1.93 g/cm^3) matrices with uniform microstructure.

Zhang et al.[93] proposed a graded concentration approach (GC-PIP), gradually increasing the PCS concentration from 0.4 to 0.8 g/mL in each cycle. This approach enabled efficient pore filling, resulting in a relative density exceeding 94 % and formation of a nanocrystalline SiC matrix with good toughness due to fiber pull-out and crack deflection.

Some studies focused on infiltration control, such as Zhong et al.[94], who used vacuum infiltration with PyC-coated needle-punched preforms, or Park et al.[95], who introduced a nano-SiC suspension and applied spark plasma sintering (SPS) to accelerate densification, reaching over 500 MPa at 2000 °C.

For SiC fiber systems, Yin et al.[96] optimized the thermal profile and interphase properties to enhance integration with Tyranno SA fibers. Almeida et al.[97] assessed cyclic durability under tension–tension loading and found that PIP composites retained mechanical integrity up to 1 million cycles, with some even showing post-fatigue strength improvement.

To improve the homogeneity of ceramic particle distribution and minimize matrix cracking during pyrolysis, Zhang et al.[98] introduced a pressure-assisted gel impregnation technique prior to PIP. In their method, a SiC slurry was impregnated into 3D needle-punched carbon fiber preforms using pressures up to 8 MPa, followed by in-situ gelation and pyrolysis with liquid vinyl perhydrogen PCS (VHPCS). Higher pressures (especially 8 MPa) led to uniform SiC particle distribution even within fiber bundles, effectively reducing shrinkage-induced cracking and improving matrix continuity. Moreover, when combined with a PyC interphase, this strategy yielded a maximum flexural strength of 360.6 MPa and fracture toughness of 8.57 MPa·$m^{1/2}$. These results underscore the synergistic role of particle-filled matrix design and interfacial tailoring in enhancing the mechanical performance of the composites.

A novel modification of the PIP process was proposed by Akaoglu et al.[99], introducing a particle-enhanced PIP (PE-PIP) method to address the common issues of low matrix crystallinity and residual carbon. By incorporating a mixture of micro- and nano-sized SiC particles (SiCp) coated with amorphous SiO_2 into the PCS precursor, they enabled carbothermal reactions during post-pyrolysis heat treatment at 1400 °C. This approach led to improved crystallinity, higher true density of the polymer derived ceramic matrix, and significant reduction of free carbon content. Compared to conventional PIP, the PE-PIP route reduced the number of required cycles from nine to six while maintaining comparable or better densification and microstructural quality. The study highlights that optimal SiCp loading (20 wt%) yields the best balance between densification and crystallinity without introducing excess porosity. Although further sealing of residual porosity may be needed, this strategy demonstrates a promising route toward high-performance SiC_f/SiC composites using a modified low-temperature PIP approach.

As shown in **Fig. 4**, the porosity of C_f/SiC and SiC_f/SiC composites significantly decreases with an increasing number of PIP cycles, highlighting the importance of repeated infiltration–pyrolysis steps in achieving effective densification.

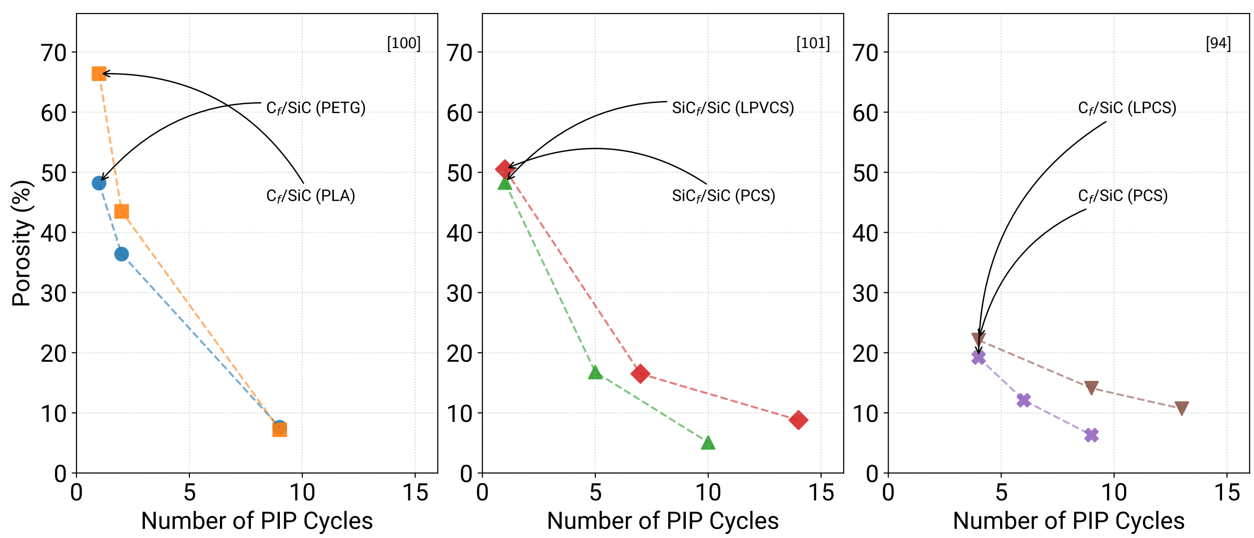


Fig. 4: *Effect of number of PIP cycles on the porosity of C_f/SiC and SiC_f/SiC composites. Bracketed numbers in the upper right hand corners of the plots indicate data source.*

Overall, PIP remains a promising and tunable route for SiC-matrix composite synthesis. Its ability to preserve fiber architecture and adapt to diverse preform geometries makes it attractive for both structural and thermal applications. However, improvements in precursor chemistry, infiltration control, and cycle efficiency remain key to optimizing performance and reducing production time.

Reactive Melt Infiltration (RMI)

RMI, also termed Liquid Silicon Infiltration (LSI) was developed in the 1970s as a method that combines principles from the PIP process and the reaction bonding of silicon-infiltrated silicon carbide materials[102]. The main goal is to create C/C preforms with pore structures that allow molten silicon to penetrate efficiently while preserving fiber integrity and enabling full densification. The in-situ formation of SiC during infiltration results in a well-bonded matrix distributed throughout the preform volume. One challenge with RMI is residual free silicon in the matrix, which can be minimized by techniques like adding B_4C to consume excess Si and form additional SiC and boron–silicon compounds such as SiB_6 or SiB_4[103]. Processing times are shorter than those required for PIP or CVI, which makes this technique attractive for scalable manufacturing[102].

Jiang et al.[104] demonstrated RMI using PAN-based T-300 carbon fibers. Fiber tows were impregnated with a solution containing formaldehyde–phenol resin and curing agents, chopped, hot-pressed, and pyrolyzed at 900 °C to form porous C/C preforms. These were subsequently graphitized at 2500°C and infiltrated with molten silicon at 1650 °C for two hours. The resulting C_f/SiC composites showed high densification with good interfacial bonding.

Further advancements were demonstrated by Cao, et al.[105], who applied a PyC interphase followed by a thick SiC barrier coating via CVD (160 hours) to protect the fiber structure during silicon infiltration. Additionally, the preforms were impregnated with B_4C slurry prior to infiltration. This not only improved wetting but also minimized free silicon in the matrix. The final composites, after silicon infiltration at 1600 °C and post-deposition SiC coating (80 hours), exhibited improved thermal stability and oxidation resistance.

A study by Zhang et al.[106] focused on SiC_f/SiC composites prepared by RMI. By adjusting the pore structure of SiC fiber preforms through different re-impregnation strategies, they found that homogeneous pore distributions significantly improved silicon infiltration and reduced residual porosity. The best performing sample, made using a polymer blend impregnation, achieved a flexural strength of 200.5 MPa, elastic modulus of 79.2 GPa, and a β-SiC/α-SiC ratio of 5.21. This confirmed that controlled pore architecture directly influences infiltration kinetics and mechanical performance.

Recent work by Shang et al.[107] provides further insights into RMI microstructure. TEM analysis of SiC matrices formed via RMI revealed significant grain refinement compared to CVI and PIP approaches. Although some amorphous SiC regions persisted near residual free silicon pockets, the reaction zone displayed tight fiber–matrix integration with minimal debonding. Raman spectroscopy confirmed the formation of well-crystallized β-SiC and reduced graphitic carbon content, suggesting that high infiltration temperatures contribute to favorable microstructural evolution.

In a comparative study, Guo et al.[108] evaluated 3D-braided SiC_f/SiC composites processed via RMI and CVI, both using Cansas 3303 SiC fibers and BN interphase. Although RMI composites had lower initial tensile strength (417.8 MPa vs. 566.6 MPa) and fiber modulus

(255 GPa vs. 328 GPa), they showed improved thermal stability under heat treatment up to 1400 °C. The residual strength after prolonged exposure remained higher for RMI, attributed to the higher initial densification and resistance to microstructural degradation.

It can be assumed that despite the advantages in densification and processing time, RMI requires careful interphase engineering due to the aggressive nature of molten silicon. Common interphases include PyC or BN layers, often in dual configurations (e.g., PyC–SiC or BN–SiC), which help preserve fiber integrity and promote toughening mechanisms such as crack deflection. However, the thermal mismatch between fibers, matrix, and residual free silicon may still lead to microcracking under thermal cycling[105,107].

Overall, RMI is a fast and scalable method for producing SiC-matrix composites that are close to their final shape, minimizing the need for additional processing. With proper control of fiber coatings, pore structure, and infiltration conditions, RMI enables the fabrication of dense C_f/SiC materials exhibiting high thermal conductivity, relatively low porosity (< 5 %), and robust interfacial bonding. These attributes make RMI suitable for components subjected to high thermal flux and mechanical stress, particularly where time and cost constraints limit the use of slower densification routes.

Hybrid approach: a strategic solution to tackle processing limitations

The traditional processing routes described above, though effective, have their limitations as they often fall short in achieving complete densification, ensuring interfacial compatibility or even controlling grain growth which can compromise the structural integrity and performance of the composites. The covalent nature of SiC bonding, together with its complex thermal behaviors of reinforcement phases and its low diffusion rate and ability to sinter, contributes to these limitations[109].

Hybrid processing approaches combining chemical, physical, and mechanical techniques have recently been emerging as a transformative solution by integrating complementary methods to allow precise control over microstructure, densification, kinetics, and property tailoring. The overarching goal is to enhance SiC-based composites' performance and open avenues for multifunctionality in the pursuit of next-generation ceramic composites. This work specifically examines how synergistic effects can be created by strategically combining multiple processing routes. The table below shows which different phases of SiC are used in which techniques.

In this context, it is useful to classify hybrid approaches according to the dominant transport phase that drives densification—gas, liquid, solid, or their combinations. Gas-phase routes (CVI-led) offer precise control of interfaces but require long processing times; liquid routes (PIP, RMI, LSI) enable faster infiltration and high densification; solid-assisted methods provide shrinkage control and improved homogeneity. When combined, these routes can complement one another, addressing individual shortcomings.

Table 2: *Example hybrid processing routes for SiC-matrix CMCs grouped by dominant phase. Representative processing times, best reported densities/porosities, and references are shown.*

Dominant phase	Hybrid route	Process time	Density/porosity	Refs.
Gas	CVI → PIP	100–300 h + 5–10 PIP cycles	2.2–2.7 g/cm^3; 10–20%	[110–114]
Gas + Liquid	CVI → RMI	Shortened CVI (tens of h) + 1–2 h infiltration	2.10 g/cm^3; <5%	[84]
Liquid	PIP → RMI	5–9 PIP cycles + 1–2 h infiltration	1.7 g/cm^3; <10% porosity	[115]
Liquid + Solid	PIP + SiC filler	6–9 cycles (PE-PIP ∼6)	>94% relative density; improved homogeneity	[98,99]
Gas + Liquid + Solid	CVI + PIP + RMI	Multi-step (week-scale)	Near-theoretical density; residual Si <2 vol.%	[116]
Liquid + Gas	PIP → Pulsed CVI (3D orthogonal-weave Cf/SiC)	Preform by PIP (PCS), then PCVI $SiCl_4$–CH_4-H_2 at 1373 K, 80 kPa; 60,000 pulses to saturation	Final porosity 6% (surface to 0.5 mm), ¡9% to 1.5 mm depth	[117]
Liquid + Gas	PIP → CVI	5-9 PIP cycles + additives, pyrolyzed at 1400 °C, then CVI with MTS	0.38 g/cm^3 Lightweight honeycomb (very porous by design); Flexural Strength: 3.8 MPa	[118]

By combining different routes, such as CVI + PIP, PIP + RMI, or CVI + RMI, researchers aim to synergistically balance microstructural quality, density, mechanical strength, and cost. For example, CVI followed by PIP infiltration reduces porosity and improves oxidation resistance while mitigating the long processing time of pure CVI. Similarly, PIP combined with RMI enhances densification and scalability. Despite these advantages, hybrid methods also face challenges, including stress accumulation at interfaces, porosity gradients, and difficulties in large-scale reproducibility.

Existing literature focuses heavily on hybrid fillers where a combination of reinforcement phases including ceramic-based (ZrB_2, HfC), carbon-based (CNTs, graphene, carbon fibers), MAX (Ti_3SiC_2) or others (Y_2O_3, $MoSi_2$) and metallic (Ti, Ni) are added to enhance the composites' properties. These studies are well represented and include both experimental and modeling approaches[24].

In contrast, there remains a comparative scarcity of published work on hybrid processing techniques which combine two or more distinct fabrication methods. Several studies, as discussed below, have demonstrated the potential of such dual-processing routes to resolve densification and matrix–reinforcement bonding challenges. There is thus a clear research gap and valuable opportunity for researchers to fully map the synergistic effects of process–process hybridization.

Combining CVI and PIP for Enhanced Performance

Hybrid processing methods, particularly the combination of CVI and PIP, are used to improve the densification and structure of SiC-matrix composites. While CVI yields high-purity crystalline SiC with control over fiber interfaces, it is inherently slow and often leaves residual porosity, especially between fiber bundles. PIP, on the other hand, is more effective in filling larger gaps between fiber bundles, but requires more cycles and can introduce oxygen or residual species such as carbon, affecting the final properties. The combination of CVI and PIP allows the advantages of both to be exploited. Typically, the process begins with CVI to deposit a uniform SiC matrix around the fibers, particularly within the fiber bundles. This is followed by PIP cycles, where a liquid pre-ceramic polymer such as PCS is infiltrated into the preform, cured and pyrolyzed to deposit additional ceramic material, effectively closing the pores between the bundles[8].

To better illustrate the sequential steps involved in hybrid CVI–PIP processing, **Fig. 5** outlines the schematic route used for fabricating SiC-matrix composites. The approach begins with CVI-based deposition of a crystalline matrix within the fiber bundles, followed by PIP cycles to fill larger interstitial voids, enabling optimized microstructural control. While most studies using CVI-PIP hybrid for SiC matrix start with CVI, there are some cases where PIP is performed first[112,119], particularly to reduce cost and pre-densify the preform. The sequencing depends on the targeted microstructure, processing limits and desired matrix distribution. When CVI is used first, it fills the internal porosity of the fiber preforms while leaving open channels for PIP. This results in better infiltration depth, high purity initial SiC layer and enhanced thermal stability. On the other hand, when PIP is used first followed by CVI, porosity is reduced due to pre-densification of the preform, reducing CVI time and thus cost of the process. This may however lead to slightly reduced infiltration depth.

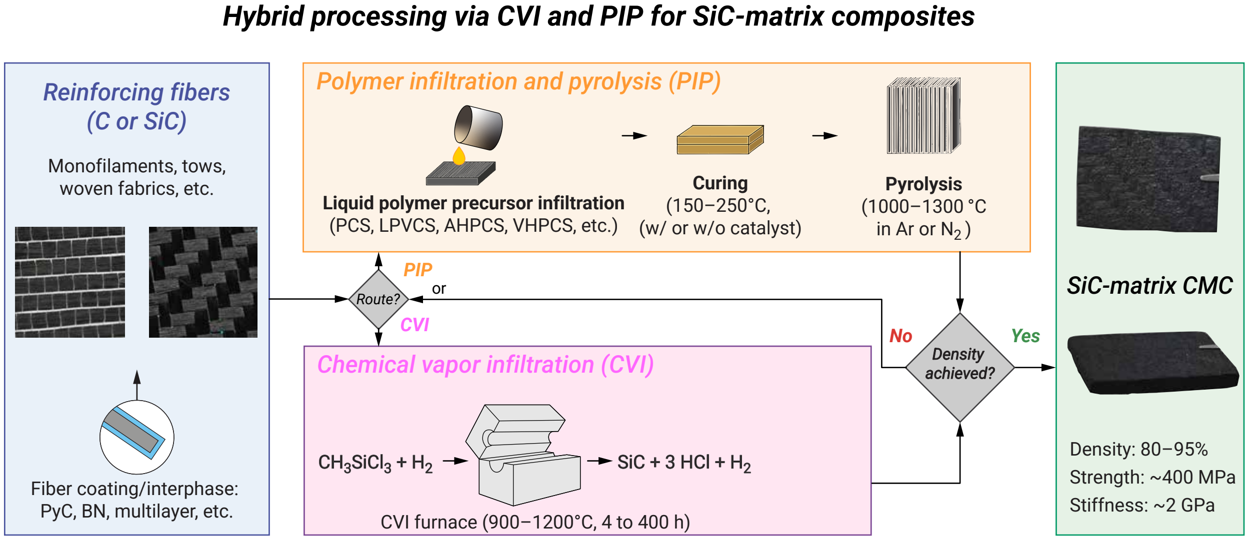


Fig. 5: *Schematic representation of the hybrid processing technique for the fabrication of SiC-matrix composites.*

Hybrid CVI–PIP processing has been investigated in many recent studies, mostly because it seems to improve both densification and mechanical performance. One example is the work by Im et al.[110] which demonstrated that combining CVI and PIP with high-pressure pyrolysis led to dense C_f/SiC composites of 2.15 g/cm^3 density. The pressure-assisted PIP enhanced fiber–matrix bonding and minimized microcracking. Similarly, Liang et al.[120] incorporated 3.2 vol % SiC nanowires into a CVI–PIP matrix, increasing the strength by bridging cracks and reducing matrix discontinuities. Xiao et al.[20] used a stitched 3D C_f/C–SiC architecture, filling intra-bundle pores via CVI and larger voids via PIP, achieving a porosity of $<$9 %.

Kim et al.[112] applied a hybrid method to 2.5D needle-punched preforms using CVI and multiple PIP cycles. The final porosity was around 20 % and the density 2.17 g/cm^3. This approach helped delay crack propagation and maintain microstructural integrity over thermal fatigue cycles.

Han et al.[121] explored how adjusting the CVI-to-PIP ratio influences porosity and matrix stresses in 2D SiC_f/SiC composites. A 3:1 CVI:PIP volume ratio yielded the best results, decreasing tensile residual stress and suppressing microcrack initiation. Liu et al.[111] noted that low CVI deposition rates allowed deeper infiltration, optimizing the distribution of crystalline SiC in the matrix. In their 2.5D SiC_f/SiC composites, the density reached 2.5 g/cm^3.

Yucong et al.[114] investigated the effect of pyrolysis temperature during the PIP step. At 1100 °C, the hybrid composites achieved optimal matrix crystallinity and pore closure without damaging BN interphases. Zhang et al.[113] found that after 200 h at 1200 °C in air, CVI–PIP fabricated SiC_f/SiC composites retained 76 % of their original strength, while PIP-only samples dropped to 31.8 % after just 100 h. The dense CVI-derived SiC layer acted as an oxygen barrier, reducing interfacial degradation and preventing strong bonding from silica formation.

Wei et al.[122] showed that manipulating internal stress in the CVI–PIP matrix could strengthen fiber bonding and improve shear strength in the SiC_f/SiC. This emphasizes how internal stresses, when balanced, can be used as a tool rather than a drawback.

To address some of the limitations of conventional hybrids, Yao et al.[123] proposed a more complex architecture C/(C–SiC)–CVI–(ZrC–SiC)–PIP composites to improve high-temperature behavior. The PIP stage used ZrC–SiC precursors, which filled residual pores and modified the interface. Composites with a C–SiC ratio of 0.91 showed flexural strength of 352.8 MPa and tensile strength of 181.7 MPa at room temperature, with strength increasing by about 17 % at 1700 °C due to thermal crack healing. In ablation tests at about 2100 °C, lower-carbon variants performed better, forming dense oxide scales.

Hybrid CVI-PIP processing has also been applied to 3D woven SiC_f/SiC composites, where fiber architecture plays an important role in mechanical and thermal behavior. Bhatt et al.[124] produced 3D woven SiC_f/SiC composites using Sylramic™-iBN fibers and hybrid CVI–PIP matrices, where CVI was used to deposit SiC within the fiber bundles, and subsequent PIP processing filled the remaining larger voids to improve the overall density. The composites showed high tensile strength and good creep performance (300 h at 138 MPa, 1482 °C). Improvements were also observed in transverse thermal conductivity and interlaminar tensile strength. The 3D architecture, with increased Z-fiber content, delayed matrix crack formation compared to 2D CVI-based systems.

Most composites fabricated using CVI-PIP processing exhibit porosity levels around 20 % and flexural strengths in the range of 200-500 MPa, while PIP-only composites often exhibit porosity greater than 30 % and lower strength unless a large number of infiltration-pyrolysis cycles are applied. Hybrid processing tends to reduce porosity and increase density in shorter CVI durations compared to CVI-only approaches (**Fig. 6**).

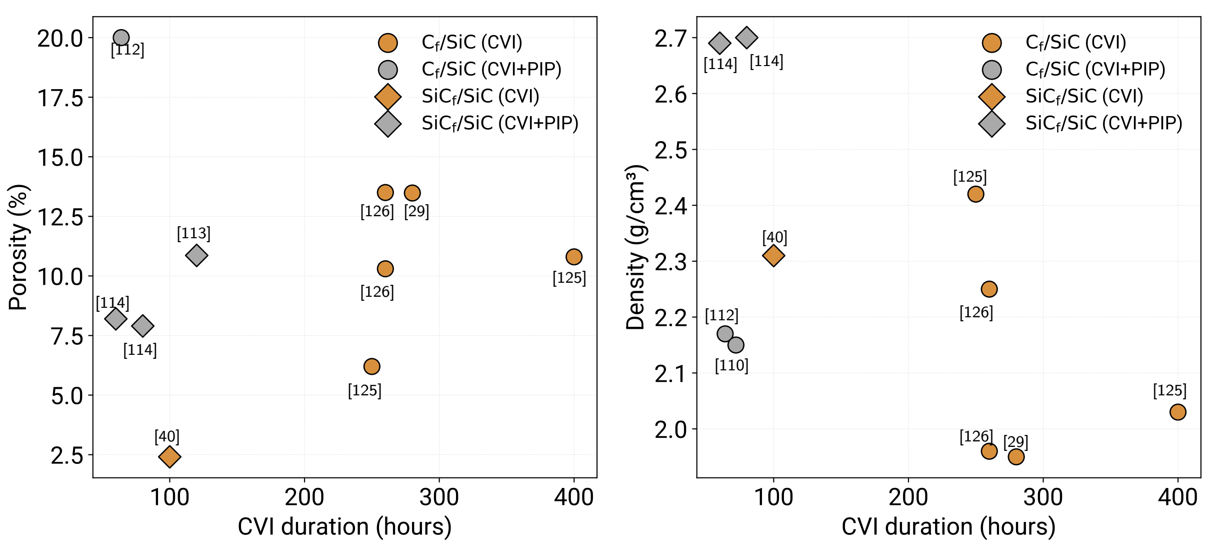


Fig. 6: *Effect of CVI duration on porosity and density of C_f/SiC and SiC_f/SiC composites fabricated by CVI and hybrid CVI-PIP methods.*

Other Hybrid Approaches

Beyond CVI–PIP, other processing combinations have been explored to optimize densification and structural performance. One common approach combines PIP with RMI. For instance, Zhang et al.[115] used vacuum bag forming and thermal pressing before PIP and RMI. SiC powders added during PIP helped control shrinkage, and the final matrix had improved continuity with reduced interfacial corrosion.

Xu et al.[84] integrated CVI with Silicon Melt Infiltration (SMI).[2] CVI deposited a PyC interphase and initial SiC layer, while SMI filled macro-voids between fiber bundles. The result was a dense composite with 2.10 g/cm^3 density and 484 MPa flexural strength. Annealing at 1550 °C preserved 87.2 % of its strength.

Yin et al.[127] applied Electrophoretic Deposition (EPD) followed by PIP to deposit nano-SiC into the preform prior to pyrolysis. EPD enables effective filling of large voids among the fiber tows before conducting the PIP process. This increased relative density from 84.7 % (PIP-only) to 91.9 % after seven PIP cycles.

An alternative route to densification without extensive PIP cycling was proposed by Süß et al.[61], who combined nitrogen-free PIP with LSI to improve matrix quality and shorten processing time. Processing was done in argon to avoid Si_3N_4 formation. This hybrid approach reduced residual carbon content by 70 % compared to LSI-only materials and shortened the processing time by 55 % compared to the standard PIP route. Despite these improvements, the final open porosity of the material was 11.4 % , and the authors noted that a completely dense matrix was not yet achieved.

Researchers have also looked into combining CVI, PIP, and liquid silicon infiltration (LSI), either in sequence or at the same time, to gain better control over how the matrix forms. Jeong et al.[116] combined CVI, LSI, and PIP to fabricate SiC_f/SiC composites with a fiber volume fraction of 30 vol %. Matrix uniformity was improved by adjusting the distribution of each phase. Final density reached 2.77 g/cm^3, with residual free silicon below 2 vol %. Transmission electron microscopy showed that the crystallinity of the PyC interphase had a clear effect on how cracks formed and spread, as well as how the fibers debonded from the matrix. This points to how important the interface structure is for maintaining strength at high temperatures.

A performance comparison of different fabrication methods is illustrated in **Fig. 7**. Each method, CVI, PIP, RMI, or hybrid methods, has different advantages and limitations in key processing and performance metrics. While RMI-based routes offer the fastest densification with good scalability, they often suffer from reduced oxidation resistance due to residual/unreacted silicon. On the other hand, CVI-based approaches provide excellent oxidation resistance, but require long processing times and offer limited scalability. Hybrid methods, especially CVI+PIP and CVI+PIP+RMI, strike a balance by improving strength and porosity without excessively increasing processing costs or compromising durability. This comparison highlights the importance of selecting or adapting hybrid techniques depending on the specific performance requirements and end-use application.

[2] It is noted that RMI, SMI, and LSI all refer to the same class of molten Si infiltration methods.

Performance Criteria

Metric	1 (Low)	3 (Medium)	5 (High)
Densification Time	>1 week	2-5 days	<12 hours
Porosity	>20%	10-20%	<5%
Strength/Toughness	<150 MPa	150-250 MPa	>300 MPa
Oxidation Resistance	Unstable >600°C	Stable to 900°C	Stable >1200°C
Processing Cost	Very High	Moderate	Low/simple
Scalability	Lab-scale only	Pilot/demo scale	Fully scalable

Fig. 7: *Comparative overview of different hybrid processing approaches*

These findings highlight the flexibility and efficiency of hybrid approaches in tailoring the densification path, improving pore elimination, and tuning the matrix architecture for better reliability in demanding applications.

We will now examine how these processing improvements translate into enhancements in mechanical and thermal properties.

3. Mechanical and Thermal Properties of Hybrid Processed SiC Composites

The mechanical and thermal behavior of fiber-reinforced SiC-matrix composites strongly depends on the microstructure, fiber orientation, and the method of matrix formation. Hybrid CVI–PIP processing allows for tailored densification, resulting in composites with improved mechanical properties compared to single-stage routes, including nearly twice the flexural strength[111]. Aside from densifying the matrix, hybrid processing also gives more control over the fiber–matrix interface. With interphases like PyC or BN, and by adjusting how they are applied, it is possible to influence how strongly the fibers bond to the matrix. This makes a difference in how the material handles stress, it can promote crack deflection and fiber pull-out, both of which help prevent sudden failure. These mechanisms are especially important in parts that deal with temperature swings or repeated loading, like thermal protection systems or braking components in aerospace.

Hybrid composites exhibit a dense and uniform SiC matrix formed by the combination of CVI-deposited crystalline SiC and PIP-infiltrated polymer-derived ceramics. This combination effectively reduces residual porosity and enhances mechanical strength. For example, Xiao et al.[20] showed that stitched 3D C_f/C–SiC composites produced using CVI, PIP, and a final CVD SiC coating achieved a tensile strength increase from 199.5 MPa at room temperature to 297.4 MPa at 1500 °C. The reduced porosity (below 9 %) and enhanced fiber alignment were key factors. Kim et al.[112] demonstrated that 2.5D C_f/SiC composites fabricated with hybrid CVI–PIP and multiple PCS-based cycles reached a flexural strength of 244 MPa at room temperature and 423 MPa at 1300 °C. Porosity was approximately 20 %, and the material showed fatigue stability over 1380 cycles at 1000 °C, indicating strong thermal fatigue resistance.

Liang et al.[120] incorporated 3.2 vol% SiC nanowires in CVI–PIP matrices and improved the flexural strength from 156 MPa (CVI-only) to 248 MPa. Similarly, Li et al.[128] reported an 86 % improvement in flexural strength (to 466.4 MPa) and a 30 % increase in elastic modulus by using optimized matrix design and interface engineering.

Han et al.[121] found that a 3:1 CVI:PIP ratio in SiC_f/SiC composites provided the best combination of strength and toughness. Flexural strength reached 720 MPa, tensile strength 427 MPa, and fracture toughness 34.2 MPa·$m^{1/2}$, with the internal stress shifting from tensile to compressive due to the increased CVI content.

As shown in **Fig. 8**, the fracture surface morphology varies significantly depending on the processing method and fiber architecture. In CVI–PIP processed C_f/SiC composites, Kim et al.[112] observed quasi-brittle fracture features with limited fiber pull-out, suggesting moderate interfacial bonding and some microstructural heterogeneity. In contrast, the SiC_f/SiC composites fabricated with optimized hybrid processing exhibited more uniform crack propagation with fiber bridging and reduced interfacial debonding[121]. Additionally, the stitched 3D C_f/C–SiC composites prepared by Xiao et al.[20] revealed extensive fiber pull-out and deflection, indicating enhanced damage tolerance due to toughened interfaces and multidirectional fiber alignment.

These observations underscore how processing routes and fiber configurations critically affect energy dissipation and overall mechanical behavior.

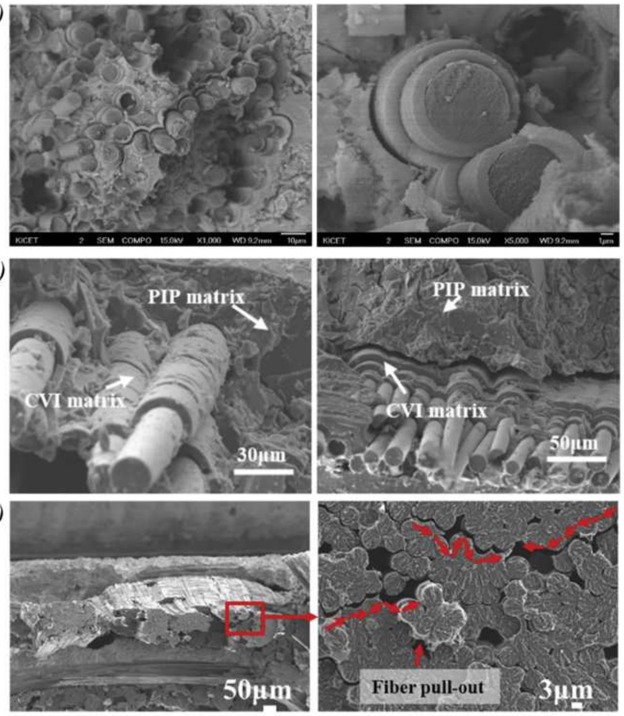
a)
b)
c)


Fig. 8: *SEM micrographs of fracture surface morphologies for C_f/SiC (a)[112] (Copyright© 2018 Korean Ceramic Society), SiC_f/SiC (b)[121] (Copyright© 2025 Elsevier) and C_f/C-SiC (c)[20] composites (Copyright© 2025 Elsevier)*

In thermal performance, Zhang et al.[113] showed that hybrid composites retained 76% of their flexural strength after 200 h at 1200 °C in static air, compared to 31.8% retention in PIP-only composites after just 100 h. The dense, crystalline SiC matrix formed during CVI acted as an effective oxygen barrier, while the PIP-filled regions provided additional densification.

Bhatt et al.[124] produced 3D woven SiC_f/SiC composites that demonstrated excellent long-term creep resistance. These composites withstood 300 h at 138 MPa and 1482 °C without structural degradation, attributed to improved interlaminar strength and matrix continuity from the hybrid approach. Jeong et al.[116] reported hybrid CVI–PIP–LSI composites with high thermal stability and minimal residual silicon ($<$ 2 vol%). Elastic modulus reached 152.3 GPa and ultimate tensile strength 144.1 MPa at 1400 °C, supported by a tailored PyC interphase and dense nanocrystalline matrix. Yao et al.[123] used ZrC-modified PIP to create high-temperature hybrid architectures. These composites exhibited strength gains at 1700 °C due to crack healing and a linear ablation rate of just 0.94 μm/s under 2100 °C ablation testing. Almeida et al.[97] observed fatigue retention of 90 % tensile strength after 10^6 cycles in PIP-processed C_f/SiC systems, illustrating energy-dissipating mechanisms such as fiber pull-out and interface debonding. Zhang et al.[93] applied a GC-PIP method to create nanocrystalline SiC matrices with over 94 % relative density and superior thermal shock resistance.

Together, these findings confirm that hybrid processing not only enables enhanced densification but also leads to improved damage tolerance, crack resistance, and oxidation durability across a wide range of service conditions. Proper control of matrix composition, interphase design, and thermal treatment is crucial for optimizing the mechanical and thermal performance of SiC-matrix composites.

Even though CVI–PIP processing has clear advantages, it also comes with some challenges. Oxygen introduced during the PIP step can cause oxidation-related degradation during use, and differences in shrinkage or densification rates between CVI and PIP can lead to internal stresses in the material. The final properties of the composite largely depend on how well key parameters are controlled, like the ratio between CVI and PIP in the matrix, the choice of interfacial material, and the amount of fiber in the structure.

The mechanical properties of hybrid-processed SiC composites depend on how the matrix is built up, what kind of fiber layout is used, how the interface behaves, and how the material is treated during processing. These methods give more room to adjust things, but they also come with more variables to control. If the steps are not balanced properly, defects can show up, or the material might not hold up over time. Even though better tensile strength, oxidation resistance, and fatigue performance have been reported, the key point is that the whole process needs to be carefully tuned to get consistent results, especially when the material is made for demanding use.

4. Applications of SiC-matrix composites in High-Performance Systems

SiC-matrix composites produced through hybrid processing, usually combining CVI and PIP, are used in applications where materials need to stay strong and stable at high temperatures. This process helps reduce porosity and improves the connection between the matrix and the fibers.

In aerospace, they are used in turbine engines, combustion liners, and thermal protection systems, where both low weight and heat resistance are important for overall performance. Hybrid processing enhances matrix densification and interlaminar bonding, improving resistance to creep and thermal shock during repeated high-temperature cycles[116,124,129].

Hybrid-fabricated composites can withstand extended exposure at elevated temperatures under load[124]. In the nuclear field, SiC composites are being considered for use in fuel cladding and structural parts of advanced reactor systems. Because they can handle radiation, do not absorb much neutrons, and stay stable at high temperatures, these composites could help make reactors safer and extend their service life. Hybrid-processed matrices exhibit improved oxidation resistance and interfacial stability, which are important in limiting irradiation-induced microcracking and embrittlement over time[113].

In the automotive sector, SiC composites are used in advanced braking systems. Their high thermal conductivity helps with heat dissipation during braking, and their resistance to wear allows the system to perform reliably through repeated use. The hybrid matrix structure contributes to crack tolerance and structural retention under thermal cycling, particularly when matrix continuity is supported by CVI and inter-bundle voids are effectively filled using PIP[112].

In defense, SiC composites are used in lightweight armor systems because of their high hardness and relatively low density. The hybrid matrix helps activate energy-absorbing mechanisms like fiber pull-out and crack deflection, which are key for stopping impacts and reducing damage during ballistic events. These features, combined with structural reliability, offer advantages over monolithic ceramics or purely polymer-based systems[9].

In the broader energy sector, SiC composites are applied in components of industrial gas turbines, heat exchangers, and burner nozzles. These systems often run at high temperatures and in oxidizing or corrosive environments, so the materials used need to hold their shape well and resist thermal shock. Hybrid processing helps with that by improving matrix crystallinity and keeping the structure more continuous, which lowers the risk of thermal fatigue or oxidation-related damage during long-term use[123,130].

Although not as common, SiC composites are also being explored for use in structural and biomedical applications. Their good wear resistance, chemical stability, and biocompatibility make them suitable for applications like orthopedic implants and dental tools, especially where both strength and corrosion resistance are needed. This use is mostly in the research phase for now[131].

Using hybrid processing makes it possible to adjust the matrix, the fiber–matrix interface, and the overall microstructure to meet the needs of specific applications. With better control over processing steps, these composites could see broader use in harsh environments.

For aerospace thermal protection systems, porosity has to be brought as close to zero as possible. In nuclear applications, oxidation resistance is the main concern. So far, results suggest that both goals can be reached by carefully managing how the hybrid process is applied.

5. Conclusion and Future Directions

Single route of SiC-matrix composites includes a trade-off between density, time, cost, and fiber integrity. Hybrid processing has helped improve matrix density, microstructure, and mechanical performance. Still, there are practical issues that limit broader use, including long processing times, high costs, stability at elevated temperatures, and consistency across batches.

One of the main technical problems is how to speed up the process without lowering the quality. CVI is slow, with long infiltration cycles that drive up both time and cost. PIP helps close pores and improve matrix continuity, but it does not fully compensate for the slow densification from CVI. Because of this, some recent work has focused on faster CVI approaches, like microwave or plasma-assisted infiltration, or improving preform architecture to make infiltration easier.

Another issue is oxidation over time. Oxygen introduced during the PIP step, coming from the polymer precursor, can remain trapped in the matrix. Upon exposure to high temperature, this internal oxygen contributes to fiber weakening and causes degradation of the composite microstructure[113]. One way to reduce this problem is by developing polymer precursors that have higher ceramic yield and release fewer volatile compounds during pyrolysis. Oxygen scavengers are also being studied as a way to slow down oxygen movement during both processing and service. Choosing better precursors will likely play an important role in improving long-term stability.

The fiber–matrix interface also deserves more attention. Most systems still rely on PyC or BN interphases because they support load transfer and help slow down crack growth, but they do not hold up well when exposed to high temperatures or oxidation for long periods. To improve durability, researchers are testing multi-layer interphases such as PyC/SiC or BN/SiC, which seem to offer better stability under harsh conditions.

There is also a need for research involving creep, fatigue, and thermal cycling at temperatures above 1300 °C, especially for composites designed for aerospace, nuclear, or energy conversion systems. Linking experimental results with modeling tools, like machine learning approaches that predict how processing affects properties (for example, how porosity changes with the number of cycles), can support more efficient process design and help tailor materials for specific applications.

So far, hybrid processing has shown good results, but there are still some open issues that need to be worked through before the method can be more widely applied. It is expected that hybridization will become the default by the end of this decade, with at least a two-step CVI-PIP or PIP-LSI.

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7. References

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