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REVIEW PAPER

A Review on Si-Based Ceramic Matrix Composites and their Infiltration Based Techniques

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Abstract

This review paper aims to look at silicon-based ceramic matrix composites and infiltration-based approaches for them. There are many different types of infiltration-based manufacturing processes, each with its own set of features. The best technique is chosen depending on the needs and desired attributes. With these considerations in mind, any type of infiltration might be selected to meet the requirements. Silicon-based ceramics has been highly used in the fields of aerospace, medical, automobile, electronics, and other various industries so it is important to study about their applications as well. This review outlines the evolution of composites from early 7000 BCE to composites today and discussed about various infiltration techniques for manufacturing silicon based ceramic matrix composites. This article also gives the comprehensive review of general characteristics and mechanical properties of silicon-based composites used in a variety of engineering sectors. The application section entails the wide range of engineering fields with consideration of infiltration techniques, which would be helpful for researchers to study and correlate the different infiltration techniques for end applications.

Keywords Ceramic composites · Silicon carbide · Silicon nitride · Silicon dioxide · Infiltration techniques · Engineering applications

1 Introduction

Silicon-based ceramics are specifically attractive components due to their diverse optic and electro-optic, magnetic, thermal, mechanical, and electrical properties. The most commonly preferred Si-based ceramics such as silicon carbide (SiC), silicon nitride (Si_3N_4), and silicon dioxide (SiO_2), have a broad range of applications in various fields like chemical industries, aluminium processing, fossil fuel extraction, and manufacturing of solar panel, due to its combined special properties and applications. This Silicon-based ceramics and composites are excellent candidates for structural components in heat engines and heat exchangers. Possibilities of common applications from a wide variety of industries are considered for each material type, while the property characteristic is taken into consideration [1, 2]. The SiC fiber-reinforced SiC matrix (SiC_f/SiC) composite has been widely employed in high-velocity and high-temperature applications such as nozzles, rocket engines, aerospace applications, braking discs, nuclear reactors, and the semiconductor industry. Thermodynamic stability, creep resistance, low density, notable wear resistance, oxidation, corrosion resistance and exceptional damage tolerance under difficult conditions are all advantages of SiC_f/SiC composites over typical metallic alloys and monolithic ceramics [3, 4]. A multitude of processes is utilized to make SiC ceramics, depending on the production cost, size, and shape. Hot pressing, Chemical Vapor Infiltration (CVI), Chemical Liquid–Vapor Deposition (CLVD), Liquid Silicon Infiltration (LSI), and Polymer Infiltration and Pyrolysis (PIP) are examples of these techniques [5–7].

Ceramic Matrix Composites (CMCs) have become a more essential and cost-effective material in recent years. The name "ceramics" refers to a diverse group of materials, each with its own set of characteristics. Clay ware, pottery, and refractories are examples of traditional ceramics. Most materials based on Magnesia (MgO), Alumina (Al_2O_3) and SiO_2 belong to the oxide group of ceramics [8]. Low electrical conductivity, low thermal conductivity, and chemical inertness are only a few of the benefits of

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ceramics. Ceramic's mechanical qualities are determined by their macroscopic and atomic physical structures. Ceramics have a wide range of qualities, ranging from isotropic and dense glasses to bricks with a mixture of crystalline glassy phases, pores, and fissures [9]. CMCs find their application in important industries such as aerospace, energy, and automobiles. CMCs are a promising future solution in industrial sectors; for example, in the aerospace sector, they have been used as a substitute for nickel alloys due to their superior heat resistance and reduced weight. Electric vehicles have grown in popularity as part of sustainable development, so in order to make electric vehicles more successful, researchers and scientists say that reducing weight can increase run time, for which CMCs are an excellent substitute. CMCs made of Al_2O_3 and zirconia is used in biomedical applications such as orthopaedic device ball heads, finger joints, hip prostheses, and dental restorative materials. They also have a lot of potential in the medical field. CMCs can be used to make printed circuit boards in the electronics sector that require high heat resistance. CMCs for power turbines are used in industrial applications to assist reduce pollution and electricity consumption. Figure 1 outlines the evolution of composites from early 7000 BCE to the present-day composites have become inevitable in our day-to-day life.

Non-oxide ceramics including SiC and oxide ceramics including SiO_2 and Al_2O_3 are preferably used [10–12]. Due to their mechanical endurance at severe temperatures, non-oxide ceramic composites, particularly SiC-based CMCs like Carbon reinforced SiC (C/SiC) is very popular [13]. Several researchers have used Raman Spectroscopy or micro-hardness tests to investigate thermal expansion and processing temperature differences [14–17]. In ceramic structures, there are substantial levels of tensile or compressive residual stresses in a wide range of ceramic composites. Furthermore, due to features such as hardness, brittleness, orthotropy, mechanical and thermal behaviour, and the heterogeneous nature of CMCs, the machinability of ceramic composites is difficult. They are known for their high-temperature applications and excellent hardness. Hardness refers to a material's mechanical qualities. High mechanical and thermal cutting loads are produced by hard materials. Harder materials like SiC are frequently employed as a matrix and reinforcement in CMCs. Thus, CMCs tend to have high hardness with lower values of fracture toughness, which indicates the brittle nature of CMCs. However, the hardness and fracture toughness should be utilized simultaneously to compare the importance of these parameters in different materials. Figure 2 entails the conceptual representation of CMCs and its properties.

A most important property of ceramics is brittleness, this hampers the application of ceramics under conditions of shock or load [18]. The nature of bonding of the continuous fibers along with the matrix determines the brittleness in ceramics leading to its failure [19]. Creep generation is too high in unexpected loading in oxide ceramics. In glass ceramics, the orientation of the fibers dictates the fracture and the rate of crack growth within the composite. Defect of the composite easily occurs at the interphase of the material. When the stress is applied in the direction of the fiber, these micro-cracks spread in the direction perpendicular to the fiber, introducing brittleness to the fibers and rendering the CMCs prone to failure [20]. Each phase of the composite has its failure properties influencing the failure of the material [21]. The structure of the review paper is organized as follows:

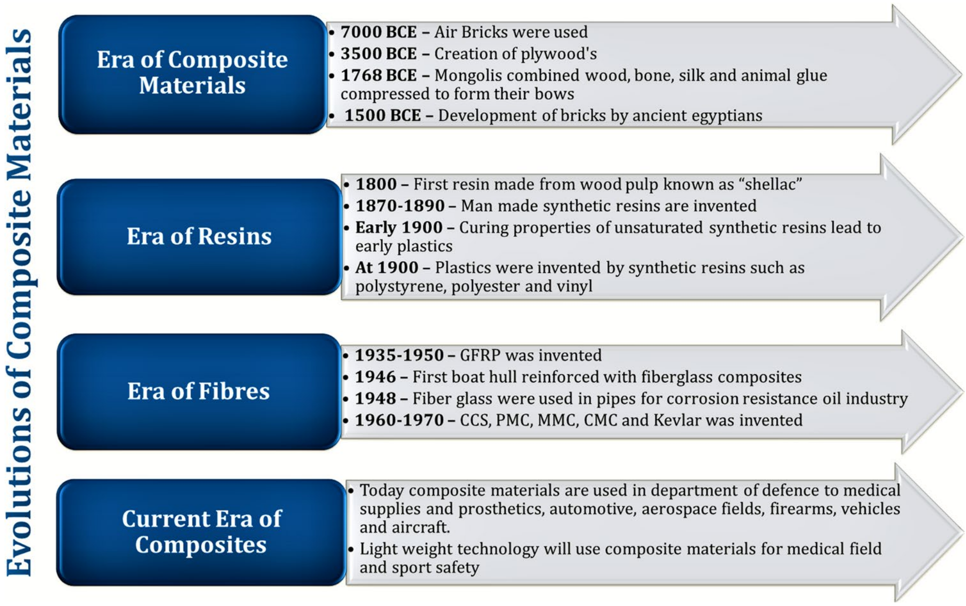


Fig. 1 Graphical representation of evolution of composite materials

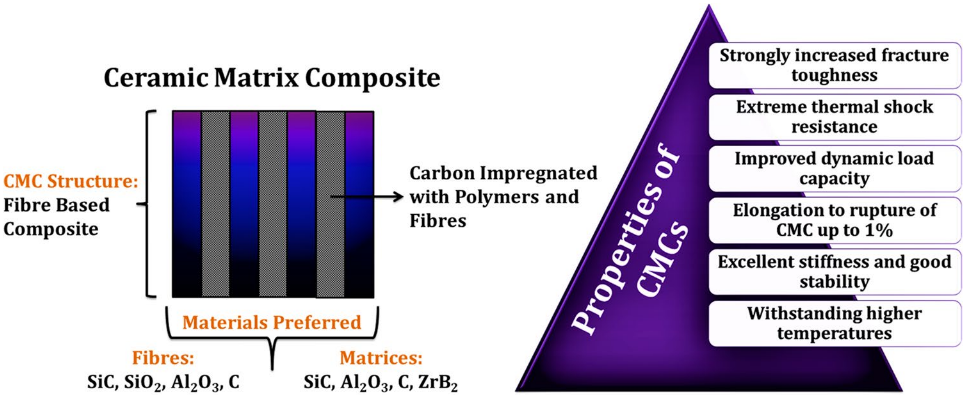


Fig. 2 Conceptual representation of CMCs and its properties

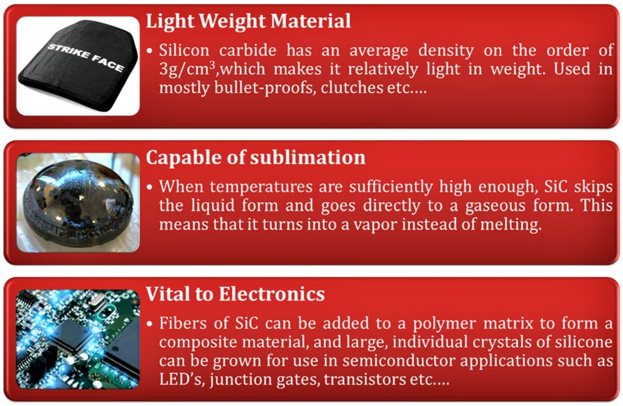
- The silicon-based ceramic composites are described in the first part. The behaviour of silicon-based composites such as SiC, Si_3N_4 and SiO_2 is reviewed, as well as the mechanical properties and their numerous domains of applications are also explored.
- The next section discusses the different infiltration techniques that are used to fabricate Silicon-based CMCs. This section briefly discusses the general aims, schematic illustrations, and scopes of this infiltration method for researchers. The significant effect of PIP process and the role of fillers in pyrolysis, as well as the CVI process, which is derived directly from the Chemical Vapor Deposition (CVD) process and the importance of CVI in manufacturing high purity composites, Reactive Melt Infiltration (RMI) used to manufacture gas turbine parts, Sol–gel infiltration, and Slurry Infiltration (SI) are briefly discussed. The overview of several infiltration techniques is discussed, including the specific purpose, preferable ceramics, preferable reinforcements and matrices, benefits and drawbacks with its inferences.
- The possibilities of Silicon-based composites in automobiles, aircraft, medical, industrial, military, and electronics are briefly reviewed in the next part, which includes schematic illustrations coupled with several sectors of applications for infiltration and combined infiltration processes.
- Furthermore, the future need for SiC-based composites in many industries is examined, as well as their use in the biomedical field, where they are employed in the development of biomedical devices that may be implanted into any part of the body. CMCs revenue share % and future research potentials are also mentioned.

2 Silicon-Based Ceramic Composites

Silicon-based materials are known for their high-temperature applications usually noticed in aerospace and automotive applications [5]. SiC, SiO_2 and Si_3N_4 form the most popular matrix choice for silicon-based ceramic composites because of their high strength and high-temperature properties often used in the form of the preform, although these materials are used as matrices and they are also used as reinforcements in the form of whiskers, long fibers, particles, etc., some of these materials are further reviewed below [22].

2.1 Silicon Carbide

This popular non-oxide ceramic has long been acting as both matrix and reinforcement, usually finding its applications in silicon-based CMCs such as turbine disks, turbopump rotors, nozzle exit ramps for rockets engines, pistons, bearings, etc., [23, 24]. The behavior of SiC as a reinforcement in the form of fiber is observed when bonded with Lithium Alumino-silicate (LAS). The LAS-SiC ceramic composite demonstrated properties of high strength and excellent toughness at 1000℃ with good elevated creep resistance but the properties of reinforcement highly depend upon the ply orientation of the SiC fiber in correspondence to the matrix [25]. The development of CMCs automotive power-train components was attained with superior mechanical properties including good thermal shock resistance and particle impact resistance. Different testing methods are performed to know about the characteristic evolution of the CMCs. For the ceramic gas turbine engine components, the backplate made of Carbon fiber-reinforced SiC (C_f/SiC) and Sialon (SiAlON), the orifice liner and inner scroll support are manufactured using C_f/SiC and SiC reinforced with SiN-C composites which withstood high-temperature tests capable of withstanding above 1200 °C [26]. Figure 3 shows the various fields of applications for SiC ceramic composites. SiC ceramics materials are hard to machine, the machinability properties of SiC can be improved when reinforced with C_f, the properties were analyzed by comparing both SiC and C_f/SiC when subjected to grinding forces hence demonstrating that C_f/SiC required much lesser forces than SiC. The C_f reinforcements when combined with SiC have also improved

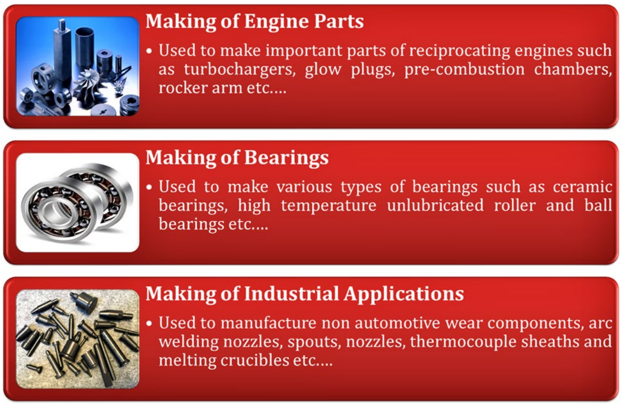


Light Weight Material
- Silicon carbide has an average density on the order of 3g/cm^3,which makes it relatively light in weight. Used in mostly bullet-proofs, clutches etc....

Capable of sublimation
- When temperatures are sufficiently high enough, SiC skips the liquid form and goes directly to a gaseous form. This means that it turns into a vapor instead of melting.

Vital to Electronics
- Fibers of SiC can be added to a polymer matrix to form a composite material, and large, individual crystals of silicone can be grown for use in semiconductor applications such as LED's, junction gates, transistors etc....

Fig. 3 Fields of applications of SiC-based ceramic composites



Making of Engine Parts
- Used to make important parts of reciprocating engines such as turbochargers, glow plugs, pre-combustion chambers, rocker arm etc....

Making of Bearings
- Used to make various types of bearings such as ceramic bearings, high temperature unlubricated roller and ball bearings etc....

Making of Industrial Applications
- Used to manufacture non automotive wear components, arc welding nozzles, spouts, nozzles, thermocouple sheaths and melting crucibles etc....

Fig. 4 Fields of applications of Si_3N_4 based ceramic composites

& enhanced the surface finish, resistance to brittleness and have made SiC easier to machine [24, 27–29].

2.2 Silicon Nitride

This Si_3N_4 is intriguing CMCs with a small market. Component costs and process unpredictability are the main roadblocks to commercialization [30]. To assist densify Si_3N_4 ceramics and enhance phase change, gas pressure sintering or hot pressing is necessary [31]. While manufactured by pressure less sintering, ceramics like Si_3N_4-Barium Alumino-silicate (Si_3N_4-BAS) display good mechanical characteristics. During cooling, the BAS matrix within crystallizes into a hexagonal phase, which offers excellent high-temperature characteristics. However, to reach practical application, more toughness development is required [32, 33]. Several attempts have been undertaken in recent decades to improve the microstructure of Si_3N_4 to increase its toughness. Si_3N_4 ceramics are composed of elongated β- Si_3N_4 grains in a fine-grained matrix with amorphous or partially crystalline grain boundary phases. The elongated grains, like whiskers, work to strengthen the matrix and increase the ceramic's fracture resistance by activating crack wake toughening mechanisms. The fracture toughness of Si_3N_4 grains at room temperature is determined by their size and shape, as long as an intergranular fracture mode is provided by a weak interface between Si_3N_4 and the grain boundary phase. Fracture resistance increases with crack extension in coarse-grained microstructures. Along with sintering processes, additional common toughening mechanisms were fracture bridging, crack deflection, and pull-out. Varied sintering techniques were utilized with different sintering profiles, resulting in different mechanical characteristics of Si_3N_4 [34–44]. Figure 4 shows the fields of applications for Si_3N_4 ceramic composites. As Si_3N_4 lacks toughness, many efforts have been made to improve it like self-reinforcement and incorporation of particles and whiskers [45–47]. SiC whiskers were added to Si_3N_4 matrix layers to strengthen them, and Si_3N_4 was inserted into the hexagonal Boron Nitride (BN) layers to change the bonding strength of the bonding layers to improve laminated Si_3N_4/BN [48].

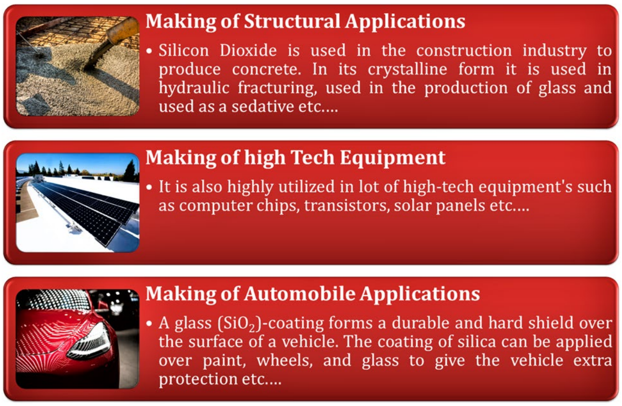
SiO_2 fiber-reinforced Si_3N_4 composite, which forms the part of the Continuous Fiber CMCs (CFCMCs) are made from a three-dimensional angle-interlocked fabric woven preform (SiO_2 fiber) which is further vacuum infiltrated with ammonia at 800 °C. The crystallization behavior of this composite conveys that Si_3N_4-based composites become weak due to the stretching of bonds which in turn weakens the bond when subjected to an elevated temperature above 1600 °C [49, 50]. SiC and Si_3N_4 are used for high-temperature purposes due to their excellent mechanical properties [51] The mechanical properties of Si_3N_4 and SiC brittleness of the ceramic components limit their application; they can be fabricated through CVI and hot isostatic pressing under higher temperature and pressure conditions. The flexural strength, fracture toughness, and restrained strength ratios differ along with the change in the temperature. The presence of high-strength filaments in the matrix without adhesion was demonstrated in SiC matrix composites reinforced with unidirectional SiC monofilaments, which improved the fracture toughness of the composite. Monofilaments with carbon-rich surface layers effectively prevented filament adhesion in SiC reinforced Si_3N_4 matrix composites, increasing the fracture toughness of the composites [52]

2.3 Silicon dioxide

The silicon oxides are represented in the molecular composition SiO_2 that is most often found naturally as quartz and in a variety of living species. Silica is a key component of sand in many locations throughout and one of the most complicated and plentiful material families, occurring as both a mineral constituent and a manufactured product. Fused quartz, fumed silica, silica gel, and aerogels are all good examples of this compound. It's utilised as construction materials, semiconductors, and foods and pharmaceuticals as an ingredient. This nano SiO_2 is used as filler material in natural fibres and reinforcing with other reinforcing substances to improve dynamic characteristics respectively. Because of its minimal price, low density, easy accessibility, and exceptional qualities, nano SiO_2 has been chosen as a filler substance [53].

Advanced materials based on CMCs, such as SiO_2, $Al_2O_{3,}$ SiC have been highlighted as a crucial material system for enhancing the thrust-to-weight ratios of higher performance aviation engines. The current research reviews related existing publications and our expertise in this sector to discuss the possible use of CMC to aviation structures. It includes material needs for aviation as well as developments in aero-engine materials efficiency connected to ceramic composites. [54]. Also, the research was conducted with the influence of nano-silica on the mechanical characteristics of micro-steel fibres reinforced with fly ash ceramic composites. The micro-steel fibres are remained constant while the fly ash and nano-silica concentrations are varied. The inclusion of nano-silica greatly improved the mechanical characteristics and morphology of micro-steel fibre reinforced composites by forming a stronger matrix and improving the intermediate regions, according to the results of testing. The optimum quantity of nano-silica to use in composite is 2%, according to the study findings [55]. Figure 5 shows the fields of applications of SiO_2 based ceramic composites.

Because of its strong strength, flexibility, outstanding hardness, lower density, exceptional wear rate, and reduced thermal expansion coefficient, continuous carbon—fibre—reinforcement $Li_2O–Al_2O_3–SiO_2$ (C_f/LAS composites) offer extreme temperature properties. C_f/LAS composite has attractive properties in increased temperature applications due to their superior thermo—mechanical qualities, such as thermal exchangers, elevated temperature windows, and laser devices. [56]. In another study, the CVI was used to create Hi-Nicalon/SiC mini-composite samples with three oxide interphase layers (amorphous SiO_2, monoclinic ZrO_2, and amorphous SiO_2). In the perspective of building ecologically resisting surfaces for ceramic composites, the possible benefits and risks connected with this multi-layer oxides interfacial method were examined. [57]. Relatively, the study conducted on plasma sprayed SiO_2 coating was found to result in a substantial rise in maximal pull-out effort, revealing improved bonding strength and improving interconnections between upgraded carbon fibre yarns and the concrete matrices. Also, research conducted on the combination of SiO_2-TiO_2/carbon fibre with TiO_2/C composite coating layer exhibit improved electrochemical behaviour and greater charging capacities [58]. In another investigation, by combining the two ceramic oxide materials like ZnO/ SiO_2 composite coatings has enhanced wear resisting property, improved hydrophobic durability, adhesion bonding and lower porosity is achieved in the paper mulch film respectively [59]. Table 1 shows the general and mechanical properties of silicon based ceramics with its applications.



Making of Structural Applications

- Silicon Dioxide is used in the construction industry to produce concrete. In its crystalline form it is used in hydraulic fracturing, used in the production of glass and used as a sedative etc....

Making of high Tech Equipment

- It is also highly utilized in lot of high-tech equipment's such as computer chips, transistors, solar panels etc....

Making of Automobile Applications

- A glass (SiO_2)-coating forms a durable and hard shield over the surface of a vehicle. The coating of silica can be applied over paint, wheels, and glass to give the vehicle extra protection etc....

Fig. 5 Fields of applications of SiO_2 based ceramic composites

3 Infiltration Methods of Ceramic Matrix Composites

Infiltration is a liquefied type manufacturing process in which a preform reinforcing materials such as ceramic powders, fibres, weaves, and other porous materials are impregnated eventually and fills the gaps in the molten metal matrices. One of the most important processes in the manufacturing of composites by infiltration techniques is the creation of a pore preforms with appropriate mechanical performance, consistent pores dispersion, pores dimension, and porous concentration. These infiltration procedures are often used to make CMCs reinforced with long fibers. The ceramic matrix is created by infiltrating a fluid (gaseous or liquid) into the fiber structure in this category of manufacturing processes (either woven or non-woven). The surfaces of the reinforcing fibers are coated with debonding interphase, which bonds weakly at the interface between matrix materials and the fibre before infiltration with a ceramic derived fluid. Weak bonding permits fibers to slide about in the matrix thus avoiding brittle fractures. Figure 6 illustrates the classification of infiltration methods of CMCs fabrication.

3.1 Polymer Infiltration and Pyrolysis

PIP is a technique of fabricating ceramic matrix that involves infiltrating a low viscous polymer into the reinforcement of ceramic structure such as fabrics, and then pyrolysis, which involves heating the polymer precursor in the lack of oxygen until it breaks down and changes into a ceramic component. This is an infiltrating process of a ceramic precursor

Table 1 General and mechanical properties of silicon based ceramics with its applications

Silicon based ceramics	General Properties	Ceramic Composites	Hardness (GPa)	Flexural strength (MPa)	Density (g/cm^3)	Fracture toughness (MPa.m$^{1/2}$)	Preferred Applications	Ref
Silicon Carbide (SiC)	Carborundum is a compound of silicon and carbon that is also known as silicon carbide. It is a semiconductor material that is becoming more popular for microelectronics technologies. It was also crucial to the industrialization, and it is still frequently used as a steel additives, abrasives, and structural ceramics. Its crystals become green or blue when impurities like nitrogen or aluminium are introduced	SiC/SiC	26–30	865	2.98—3.10	2.29—3.37	Gas turbines, Propulsion Systems, Aviation engines,	[64–66]
	Physical ● High hardness and mechanical stability at high temperatures ● Excellent thermal conductivity and low coefficient of thermal expansion ● High resistance to wear and corrosion properties	C/SiC	27.68–37.56	500–700	2.1	20.3	Heat shields, Space vehicles, Brake disc pads, Heat exchanger tubes	[67–69]
	Chemical ● It is stable, chemically inert and having interesting electrical properties ● Resistant to many organic and inorganic acids, salts, and alkalis ● It will start an oxidation reaction in the air when the temperature is at approximately 850 °C to form SiO_2	C/C SiC	-	160–300	1.9–2.0	-	Rocket nozzles and Brake discs	[67]

Table 1 (continued)

Silicon based ceramics	General Properties	Ceramic Composites	Hardness (GPa)	Flexural strength (MPa)	Density (g/cm^3)	Fracture toughness (MPa.m$^{1/2}$)	Preferred Applications	Ref
Silicon Nitride **(Si_3N_4)**	Silicon nitride is a non-oxide structural ceramic material with a smooth, highly reflecting surface texture. Its chemical compound of the elements are silicon and nitrogen and most thermodynamically stable	Si_3N_4-CNT	8 – 19	800–900	2.65—3.19	5.3 to 8.5	Cutting tools, Bearings, Sealing's, Parts of gas turbines, engines	[60] [61]
	Physical • High temperature strength and superior thermal shock resistance • Excellent wear resistance and good fracture toughness • Mechanically fatigue and creep, and good oxidation resistance	Si_3N_4-SiC	16.99	450	relative 97.85%	7.09—8.30	Turbine and Automobile engine components, Ball bearings, Turbochargers	[62]
	Chemical • It is chemically inert and attacked by dilute HF and hot sulphuric acid • Due to its greater stability of molecular and atomic interactions, it renders very resistance to corrosion	Si_3N_4-Fe_3Si	-	354	≥ 3.2	8.4	Metallurgical industries	[63]

Table 1 (continued)

Silicon based ceramics	General Properties	Ceramic Composites	Hardness (GPa)	Flexural strength (MPa)	Density (g/cm^3)	Fracture toughness (MPa.m$^{1/2}$)	Preferred Applications	Ref
Silicon dioxide **(SiO$_2$)**	Silicon dioxide (or silica) is a naturally occurring oxygen-silicon combination seen primarily in sand. Quartz, tridymite, and cristobalite are the three major crystalline forms of silica. It can create silicates when mixed with oxides and other metallic elements	Nano-SiO$_2$/ C/ Epoxy	18.75%	410–475	2.65	-	Structural, Tribological, Automotive, Aerospace	[54]
	Physical • Transparent to grey, crystalline, odourless, or in amorphous solid with melting—1713º C and boiling—2950º C • Silica is utilised as a dehumidifier because of its propensity to absorb moisture • Insoluble in both acid and water and soluble in hydrofluoric acid	Nano-SiO$_2$/ Steel fibres/ Fly ash	> 80 HRH	3.19–6.12	< 0.05	-	Construction Industry	[55]
	Chemical • Forms two double bonds with the oxygen and is very stable molecule • Has high dielectric strength • It is not a very reactive compound because the polarity of the molecule is zero	SiO$_2$/ Glass fiber/ Si oil	-	31.77–34.63	-	-	Aerospace, Shipping, Textile industries	[56]

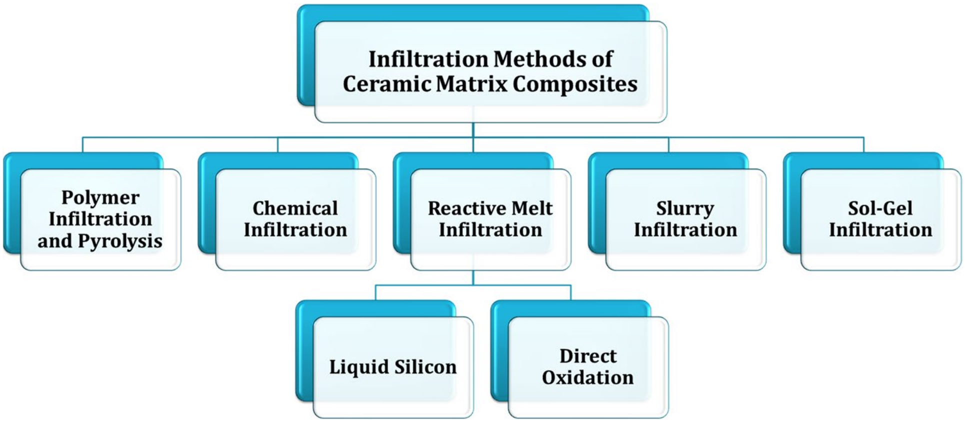


Fig. 6 Classifications of infiltration methods for fabricating CMC

into porous fiber preform followed by decomposition to form CMCs. It is repeated cycling of infiltration followed by pyrolysis. PIP is used for fabricating composites with SiC or other silicon-based matrices (Silicon Carbon Nitride (SiCN), Silicoboron Carbonitride (SiBCN) and Si_3N_4) [70]. SiC and carbon fibers have been used most frequently in the manufacturing processes of fiber-reinforced CMCs [71]. The pyrolysis process consumes a greater amount of time to produce a proper component with suitable mechanical properties. PIP processing takes less time and costs less than CVI processing for densification. For the desired ceramic, with exact stoichiometric quantities of elements, a polymeric resin can be produced which are suitable choices for a ceramic precursor.

Pyrolysis can result in significant gas evolution. As a result, the gases in the matrix must be allowed to progressively diffuse out. The temperature of the pyrolysis cycle can exceed 1,400 °C. Pyrolysis must take place at a temperature lower than the crystallization temperature of the matrix and the degradation temperature of the reinforcing fiber. Although argon and nitrogen are the most commonly used pyrolysis environment gases, ammonia produces a pure amorphous Si_3N_4 with very little free carbon [72]. Polymer-derived CMCs, like C/C composites, usually have a broken matrix as well as many tiny pores due to processing. The precursor shrinks around the fibers during pyrolysis, causing cracks. As the ceramic yield rises, fewer gases escape during the pyrolysis process, resulting in fewer pores. Certain modifications are made to the precursors such as Polycarbosilane (PCS)—Allyl-substituted to form AHPCS with 72% yield, polysiloxane—starfire systems resin with 78% yield, boron modified AHPCS with 75% yield, polymer-thysilane added before curing at 320 °C with 91% yield [73–75].

The PIP has been used to prepare a multi-walled carbon nanotube which is a reinforced C_f/SiC. The antimony substituted polymer-thysilane was used as a precursor. The ceramic yield of the component was increased with curing after each infiltration procedure [76]. Components produced with the help of this process can be widely used for high-temperature structural materials such as SiC_f/SiC composites. They are widely used in gas turbines, aerospace propulsion systems. As the pyrolysis temperature rises, so do the mechanical properties of the composites [77]. Moreover, by pyrolyzing and processing at lower temperatures, fiber degradation and the production of undesirable reaction products at the fiber/matrix contact can be avoided. The tensile strength of amorphous SiC fibers derived from precursors was reduced by crystallization. The ablation property of components is also important and if the composite's mass loss and linear recession rates were less, the ablation resistance was found to be superior [78]. Figure 7 shows the schematic representation of working process of polymer infiltration and pyrolysis method for CMCs.

The use of particle fillers in the matrix, when mixed with a polymer, reduces shrinkage and hardens the matrix material in the composite, which can control a significant amount of shrinkage. The filler must be μm-sized and have the same coefficient of thermal expansion as the polymeric matrix to permeate the bundle. The filler should not be used in excessive quantities, and the slurry should not be injected into the reinforcing fiber. Fiber architecture may have an impact on PIP. The wetting of the fiber bundles is one of the most important aspects. As the precursor contracts around the fiber during pyrolysis, cracks appear [79]. By imposing PIP fabrication procedures in the industrial sectors, may solve many present problems; it provides a method for fabricating CMCs at low temperatures without degrading the fibre while maintaining tight control over the microstructure and composition. Fabrication of desired shapes is possible, allowing CMCs to be utilised more often in the industrial sector. Here in PIP, the different types of reinforcing phases like particulate, fibrous may be used and even net shaped parts can be fabricated. Since there is no free silicon in PIP, therefore no brittle structures can be formed, and a variety of matrices may be constructed using alternative sources of reinforcement other than silicon.

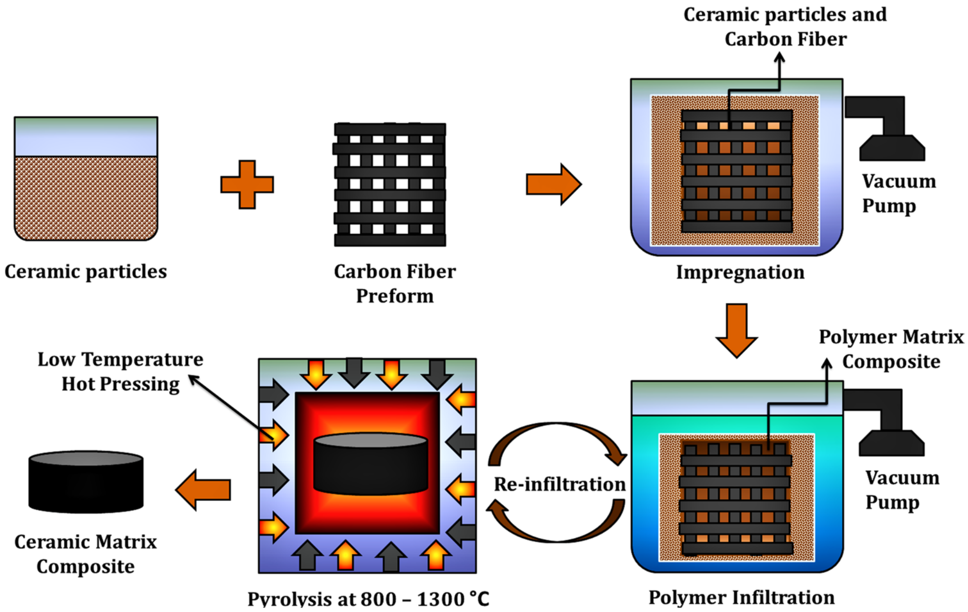


Fig. 7 Schematic of polymer infiltration and pyrolysis process

3.2 Chemical Vapor Infiltration

CVI is a technique of fabricating ceramic matrix in which reactive gases permeate into an isothermal porous preform comprised of long continual fibres and deposited. The deposited substance is the consequence of a chemical reaction on the outer surface of the fibres. It is similar to CVD, in which deposition forms when the reactive gases react on the outer substrate surface. It is widely used for fabrication of SiC matrix composites reinforced by SiC long continuous fibers. The commonly preferred vapor reagents supplied to the preform in a stream of a carrier gases are hydrogen, argon, helium etc. A method directly derived from CVD in which chemicals directly deposit on the surface of the substrate. The CVI process is a specific kind of CVD process [80]. Until now SiC ceramics were manufactured by processes such as castings, rolling where these processes have resulted in shrinkage and serious whisker damages hence calling the need for the CVI process [81–83]. Manufacturing silicon carbide whiskers reinforced Silicon Carbide matrix (SiC_w /SiC) ceramics by CVI has been investigated by researchers particularly focusing on the advantages of the process, SiC_w is ball milled into slurry using Polyvinyl Butyral (PVB) as the binder followed by casting the slurry into the mold and subjecting the specimen to isobaric/isothermal (I-CVI) process. Figure 8 illustrates the flow process of CVI steps used in manufacturing of SiC_w /SiC, the results of the process show increased volume fraction of SiC_w and therefore inferring its ability in control of the volume fraction and the porosity of the ceramic, only being limited by the fluidity of the slurry [84].

The SiC/SiC used in high-temperature applications such as nuclear reactors require high purity, are typically manufactured by the Forced Chemical Vapor Infiltration process (FCVI). The feasibility of the process is studied by comparing the results obtained from conventional CVI to FCVI [85]. The results obtained display that FCVI is a much faster process in terms of process time, higher deposition rates, lower porosity, and higher uniform densification [86]. Hence larger application of FCVI can provide a path for its application in nuclear reactors. This C/SiC has become promising material of choice possessing excellent thermal, mechanical, and ablative properties [87–90]. The deposition channels/pores in C/SiC get easily blocked during the infiltration process further giving rise to bottleneck effects and limited densification [91, 92]. Figure 9 depicts the schematic view of working process of CVI method for CMCs.

These issues were tackled using Laser Assisted Chemical Vapor Infiltration (LA-CVI). LA-CVI technique fabricated C/SiC by processing the infiltration of the preform by SiC at 1800 °C for 2 h in a vacuum. To generate mass transfer channels, a sapphire laser system was employed to cut holes with a diameter of 0.5 mm. The results showed that C/SiC produced by LA-CVI displays properties such as lower porosity, flexural strength, and enhanced density when compared to the conventional CVI process [93]. Gaseous precursors can be manufactured by the pulsed Pressure Chemical Vapor Infiltration (PCVI) process. C/SiC manufactured by PCVI under the range of 2–5 kPa displays the ability of the process to manufacture multi-layered interphases with the highest pore filling ability, making it a promising method to manufacture highly tailored ceramics [94]. Because of the low infiltration temperatures, this sort of vapor-based chemical infiltration approach may be utilised to create matrices with excellent purity and little fibre damage. The CVI can provide minimal residual mechanical stresses due

Fig. 8 Fabrication flow process for SiC$_w$ /SiC ceramic composites

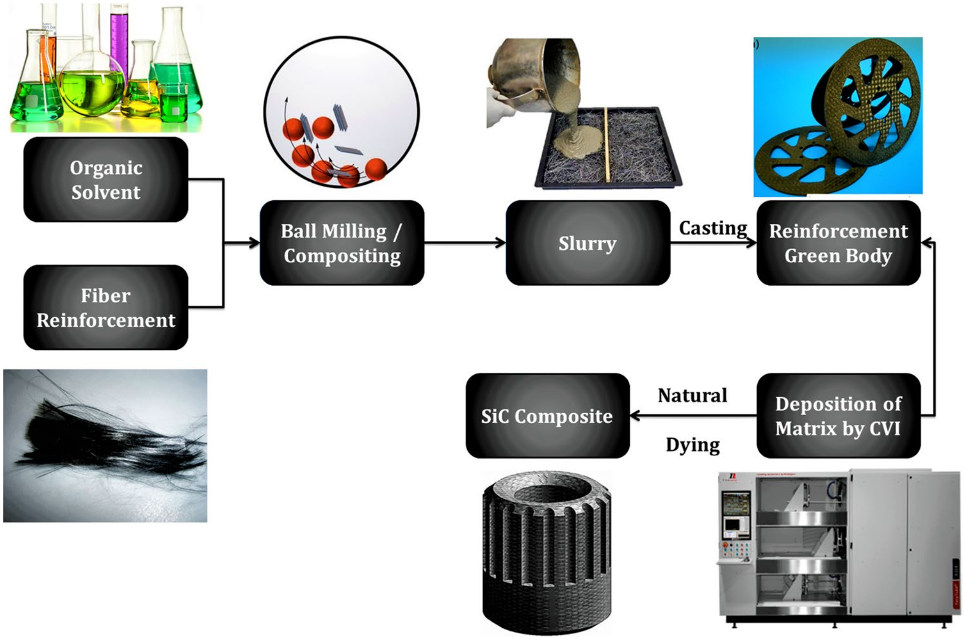
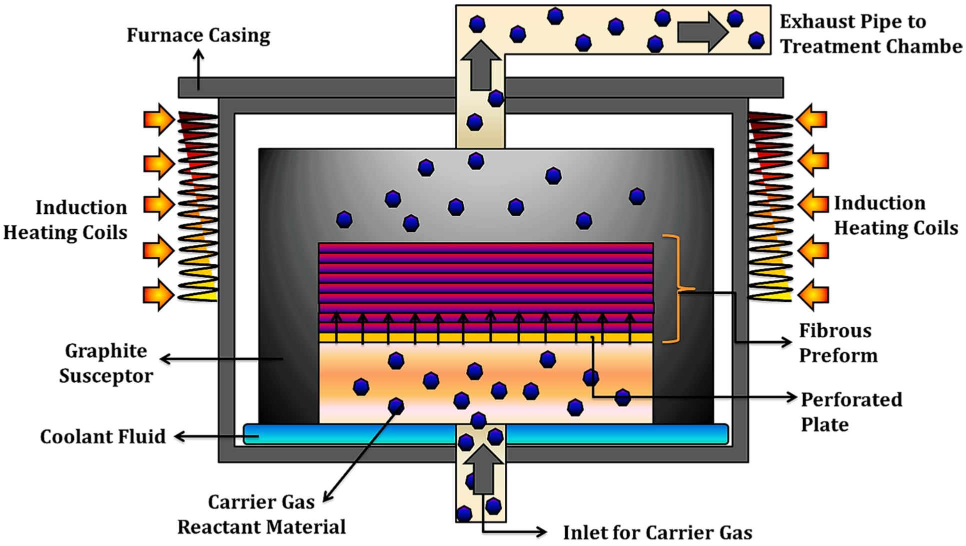


Fig. 9 Schematic view of chemical vapor infiltration process



of the low infiltration temperature. This infiltration process has improved mechanical qualities including strength, elongation, toughness, and resisting capacity in thermal shock, creep, and oxidation properties. The CVI has the capacity to construct a variety of ceramic compositions, including SiC, C, Si_3N_4, BN, B_4C, ZrC, and others, and can give more innovation in manufacturing a variety of high-quality materials.

3.3 Reactive Melt Infiltration

Melt infiltration allows for the creation of microstructures that would otherwise be impossible to accomplish by sintering. Before melt penetration, reactive components, for example, can be injected into porous bodies and new phases are produced during infiltration as a result of interactions with the melt. This can be used to manufacture a dense component from a porous moulding body as a replacement to sintering process. The substrate material must have a porosity body with a greater melting point than the invading substance as a requirement. In addition, the melt needs to moisten the substrate material. The porosity body and infiltration substance can then be reheated until the infiltrating material's melting point is reached. Capillary forces pull the melt through the body's pores, entirely filling the pore volume and get a thick component once it cools down.

3.3.1 Liquid Silicon Infiltration

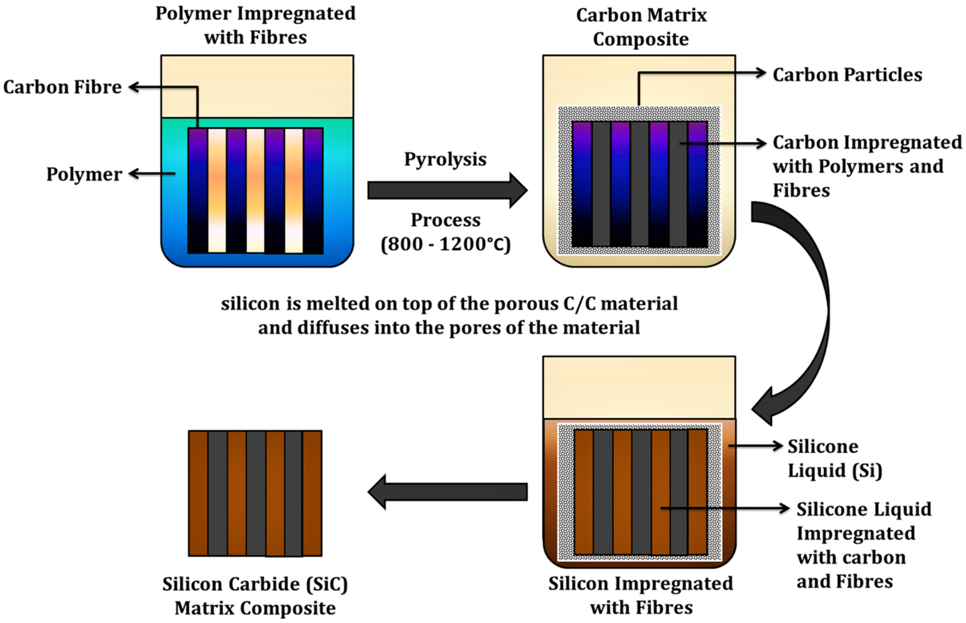
This Liquid Silicon Infiltration (LSI) technique is a type of RMI technique in which the ceramic matrix develops as a result of chemical relationship between the molten material infiltrated into a porous reinforcement phase preform and the substance surrounding the melt, which can be solid or gaseous. Generally SiC matrix composites are made with this method. The procedure includes infiltrating molten silicon into a carbon microporous preform at a temperature higher than its melting point. The molten silicon wets the carbon preforms surface and the capillary pressure help the melt seep into the porous material. Figure 10 shows the schematic of working process for liquid silicon infiltration process for ceramic composites.

The MI process also known as LSI is an alternative route, where the CMCs are fully densified [95]. This process is widely used to make composite material from the ceramic preform with porosities. The wetting conditions between the solid ceramic and liquid metals are important for performing the MI process. During the phase of infiltration, the weight of the final composite can be monitored. It can be measured before consolidation as well as through the process of this infiltration [96]. For the fabrication of the melt infiltrated CMCs, there developed a variety of processing schemes. Where the one process is the prepreg process and the other one is known as the slurry cast process. The gas turbine engine components are made up of SiC/SiC CMCs that is manufactured through the slurry cast MI process as they have high thermal conductivity, also with higher thermal shock, creep, and oxidation resistance [96]. The melt is inert to the fiber preform in a nonreactive process, so it is not distorted during the infiltration where the furnace uses Radio Frequency (RF) coils to melt the infiltrant and its melt drains upon the preform to make it a dense composite [97].

Along with the addition of BN interphase to SiC composite (SiC/BN/SiC), the applications can be enhanced and used in higher temperatures [98]. But it is hard to prevent BN interphase and SiC fiber from getting oxidized at intermediate temperatures [99]. The laminated Silicon Carbide reinforced Titanium Silicon Carbide (SiC/Ti_3SiC_2) can be fabricated by LSI [100]. For Ti_3SiC_2 the energy absorbing mechanism which includes delamination, crack deflection, and grain pull-out has also been explored [101, 102]. The laminated ceramics has considerable properties and enhances the impact and damage resistance on the material as they contain multi-scale hierarchical structures [103, 104].

The Carbon reinforced Carbon-Silicon Carbide C/C-SiC is a novel class of high-performance ceramic material with a multiphase matrix composition and internal SiC layers, which gives it several advantages in the various applications where it can be employed. The LSI technique is used to fabricate this lightweight, thin-walled C/C-SiC. Because of their excellent thermal conductivity and less coefficient of thermal expansion, C/C-SiC possess excellent thermal shock stability and some abrasion resistance [105–107]. The parameters of the carbon preform play a big role in the success of an LSI of SiC creation. To reduce the amount of residual carbon and silicon phases in the LSI reaction result, carbon performs are developed and microstructures are better tailored. MI enables the development of surface morphologies that would be impossible to achieve with sintering alone. As a result of interactions with the melt, new phases

Fig. 10 Schematic view of liquid silicon infiltration process



are formed during infiltration. This LSI technique has the capacity to fabricate complex and near net-shape components. During this process, more carbon can be added to porous material and this carbon interacts with the silicon melt, forming additional SiC and significantly enhancing the hardness and stiffness of the Si/SiC material. Stresses can be decreased by adjusting the thermal expansion coefficients of the involved phases to one another. This method may be used to make even material composition and quality gradients and has the potential to satisfy a specific need for the manufacturing of certain ceramics.

3.3.2 Direct Melt Oxidation

The interaction of a molten metal with an oxidising gas is the basis of the directed metal oxidation process (e.g. aluminium alloy reacts with air to form Al_2O_3. This process is also known as the interaction of metals with dry gases that results in the development of oxides or any other substances on the surfaces; and it is only noticeable at high temperatures. This interaction result extends outwardly from the initial metal pool surface either into available space or into filler at a particular critical temperature range over the metal's melting point. The growth continues until the metal supply is depleted or the reaction front comes into contact with a barrier substance that prevents any further reactions. Figure 11 illustrates the schematic view of direct melt oxidation working process for CMC.

A study performed on ZrC–W composites was made by reacting Zr_2Cu into a Tungsten Carbide (WC) preform at 1200 °C respectively. The WC substance in the alloy totally interacted with the Zr, and the inclusion of tungsten increased the flexural and fracture toughness properties of the ZrC–W composites [108]. Tin oxide (SnO_2), as a viable contender, has considerable promise for lithium and sodium batteries due to its comparatively large capacities and outstanding stability. A study was conducted on the incorporation of tin oxide nano-particle into CNTs through a melt infiltrating procedure for improving the performance of lithium and sodium ion storing devices. The finding indicates that this composite is capable of producing reversible discharging in these batteries [109]. Similarly, in another study, thick alumina-$TiAl_3$ composites drew a lot of interest due to their superior fracture tolerances and for wear resisting properties [110].

3.4 Sol – Gel Infiltration

This Sol–Gel infiltration technique is preferred for making ceramic matrix comprises the matrix from a liquid colloidal suspension of small ceramic particles (sol), which soaks a preform and then solidifies (gel) in formations. When very nanoparticles with radii up to 100 nm get precipitated in a water or organic solvent, then a colloidal suspension is generated as a result of a chemical process. Because the liquid sols have a low viscosity, they may easily penetrate the preform. Here sols containing organometallic compounds such as metal alkoxide precursor undergo cross-linking process like polymerization at increased temperatures by either the poly-condensation or hydrolysis mechanisms. Then the polymerization turns a sol into a gel, which is a polymer structure that contains liquid and gels may be converted to ceramics at a low temperature, reducing the risk of reinforcing fibre breakage.

The sol–gel method is preferred for attaching Zirconium (Zr) to silica-covered Al_2O_3 particles and using phosphate-based monomer as an adhesion booster [111–113]. Wet-ground pre-sintered Zirconia (ZrO_2) blocks were sectioned into 0.5 mm thick discs after being wet-ground into 18 mm diameter cylinders. Before being immersed in SiO_2 solution for five days, the pre-sintered ZrO_2 discs are divided into groups. After the immersion period, the ZrO_2 discs which are pre-sintered are baked at 100 °C for a couple of days. The sintered specimens are examined using x-ray diffraction.

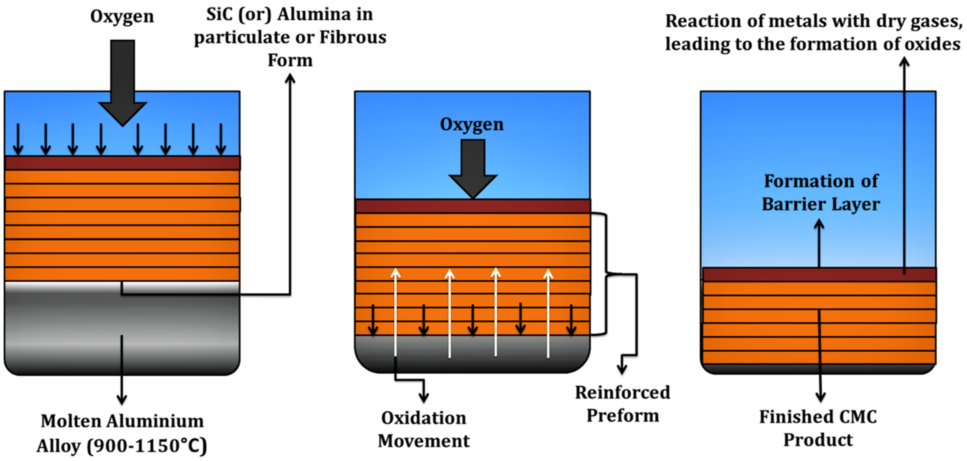


Fig. 11 Schematic of working procedure of direct melt oxidation process

The material's homogeneity was shown to be superior to that of other treatments when employing weibull analysis [114]. SiO_2 deposition results in glass/ ZrO_2/glass sandwich layers with graded ZrO_2 properties. Furthermore, unlike air abrasion, the sol–gel process does not affect ceramic surfaces [115–117]. Figure 12 shows the schematic view of working process of sol–gel infiltration process for CMC.

Composites of SiC in a pure SiO_2 gel matrix were prepared. Before gelation, SiC fibers or whiskers were mixed with a SiO_2 sol. Tetraethyl Orthosilicate (TEOS) was hydrolyzed with HCl in ethanol to produce a SiO_2 sol with a mole ratio of 1:4:0.5:0.0G of TE0S: water: alcohol: HCl. Sol–gel processing was used to create high purity ZrO_2 powder and thin-film applications such as porous membranes for gas filtration, thick-coated layers for corrosion protection. Additionally, the sol–gel technique can be used to create partially stabilized ZrO_2 fibers for making Zr matrix composites with increased mechanical properties [118–121]. A sol–gel technique with metal alkoxides was used to make monoclinic ZrO_2ceramics with a biomorphic structure from jelutong wood, as well as biomorphic Al_2O_3, TiO_2, and ZrO_2 ceramics from cellulose fiber preforms [122–124].

Fabrication of Si_3N_4-SiO_2 composites by sol–gel together with gel casting has been studied by researchers, the fabrication process includes gel casting of porous Si_3N_4 using acrylamide, followed by SiO_2 infiltration in a vacuum, the results from this research showed that with the addition of SiO_2, the porosity decreased significantly from 49.3% to 22%, with a recognizable increase in density from 1.62 g/cm3 to 2.18 g/cm3, with an increase in flexural strength and dielectric properties and better thermal shock resistance with a decrease in porosity [125, 126].

Using sol–gel processing, parts such as heat shields for space shuttles are made using a combination of glass fibers of Al_2O_3-B_2O_3-SiO_2 (Nextel 312 fibers) with high-purity SiO_2 fibers. Unlike the powder or slurry precursors, sol–gel has many advantages such as less fiber damage, good chemical composition flexibility, low densification at temperatures, and improvement in oxidation behavior of infiltrated components [121, 127]. The sol–gel method is simple, economical and efficient method to produce high quality coverage and has the capacity of sintering at low temperatures, between 200–600 °C. Sol–gel spin coating technique was used to create colloid-based highly reflective coatings on glass substrates, consisting of alternating layers of quarter wave thick high and low refractive index components. The bonding regions were enhanced with the increasing concentration of SiO_2, the sharp angles surrounding the pores were also softened, and some interconnected pores might be separated into distinct pores after the sol–gel infiltration and sintering process. This kind of microstructure made it difficult for the cracks to propagate, so the flexural strength and fracture toughness were distinctly improved.

3.5 Slurry Infiltration

In Slurry Infiltration (SI) process, the reinforcing fibres are allowed to flow through slurry that penetrates the pores structure of the reinforcing phase in the infiltration process. The capillary effect is the primary force behind infiltration, however vacuum or pressure can help speed up the process. These infiltrating fibres are coiled onto a mandrel during the lay-up process. After that, it's dried, sliced, and placed out and they are chopped and placed up on a tooling after drying (mold). Then, at a high temperature and increased pressure, hot pressing process (sintering, densification) is done, which improves the dispersion of the ceramic material between the particles absorbed into the fibres structure. The particles clump together, resulting in a dense composite with reduced porosity level. Figure 13 represents the schematic

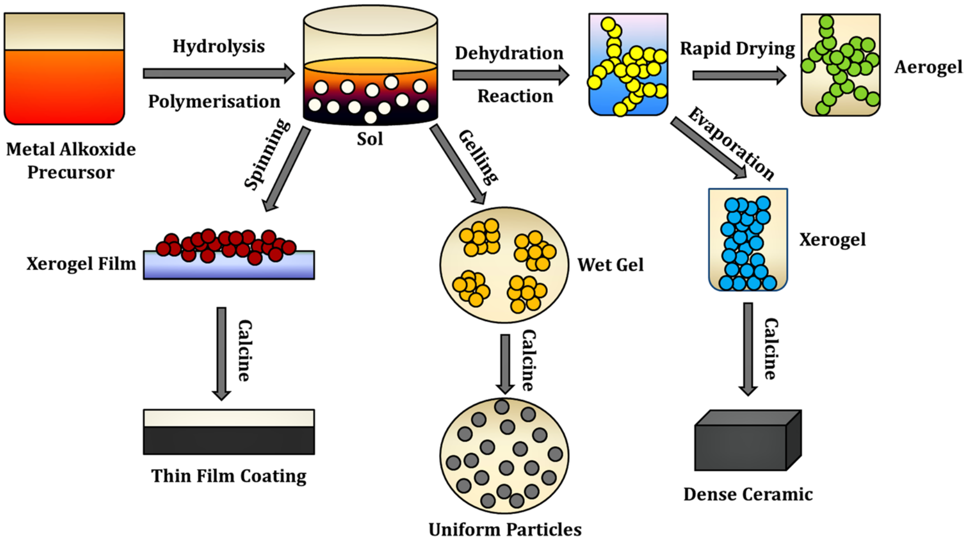


Fig. 12 Schematic of working process of sol–gel infiltration method

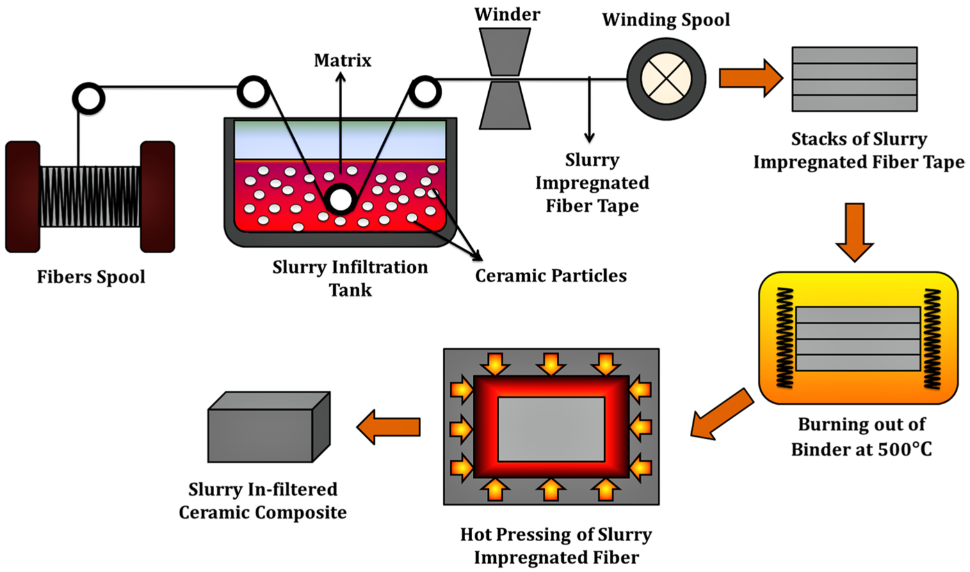


Fig. 13 Schematic of working process of slurry infiltration method

view of working process of slurry infiltration process of ceramic composites.

Continuous fiber-reinforced CMCs have long been recognized as promising materials usually finding their applications in brake disks, heat exchangers, aero-engines, and fusion reactors because of their high toughness, low density, thermal & chemical stability [128–131]. C_f/SiC has been the chosen composite because of its low cost and better thermal stability, usually being processed by complex processes such as liquid–vapor infiltration and hot pressing [132–135]. The effects of the addition of SiC particles to 2D-C_f/SiC as filler which is then fabricated by SI process have been studied [136]. The former composite was then manufactured by using 2D woven C fiber which was used to prepare fiber preform, followed by an infiltration of SiC filler, enhancement of infiltration efficiency was assured by using a vacuum pump. The properties of the composite obtained were compared and analysed for two different pyrolysis temperatures (800 & 1100 °C). The results showed that the amount of SiC had a significant effect on physical and mechanical properties of the composite, lower (800 °C) pyrolysis temperature exhibit lowest failure stress whereas, with an increase in the temperature (1100 °C), the composite exhibits failure stress two times higher with an increase in interfacial bonding [137].

Surface tension, viscosity, and volatility were considered as factors in the choice of solvent [139]. For a better dispersion of the slurry, the solvent must have low surface tension and low viscosity, as well as a higher viscosity to convey the slurry particles and a lower vapor pressure to avoid solvent vaporization. When the slurry no longer absorbs into the pores, the surplus slurry can be brushed off the material's surface. The microstructure and ablation behavior of Ti_3SiC_2 modified C/SiC composites manufactured using a combined SI and LSI process was investigated. The manufacturing process of C/SiC-TiC-C composites is performed by infiltrating porous C/SiC composites with TiC/C slurry and later using a vacuum freeze drier, they are dried [138]. Then the slurry is made using by dissolving TiC particles (1–2 m, 60 wt%) with graphite powders (5 m, 6 wt%) in deionized water and later ball milling it for 24 h. Then, the infiltration of molten silicon of C/SiC-TiC-C composites at a temperature of 15,000 ℃ for 30 min under vacuum was processed. The internal bundle pores of the C/SiC composite are filled with TiC-C particles after SI.

Various SI alterations result in various implications and changes in material properties for the processes such as precursor and pyrolysis for SiC_f/SiC composites. Corresponding to a relative density of 68%, the density of the SiC_f / SiC filler green body was 2.20 g/cm^3[140]. The infiltration of bulk graphite blocks is performed using the SI slurry process to make graphite composites such as SiC and Si_3N_4 reinforcements; it's effective by increasing the wear resistance by morphological changes by increasing porosity of bulk graphite. These characteristics are advantageous to parts such as piston rings, sealing rings, bearings, electrodes, crucibles, extrusion guides, and moulds [141]. The SI manufacturing method is comparable to the sol–gel infiltration process; however, because of the increased solid content, SI generates a denser structure with less shrinkage. This SI infiltration process is basically driven by the capillary forces. One of the main advantages of this SI infiltration technique is its low porosity rate and good mechanical properties. However, the high pressure applied to the reinforcing fibres may cause damage, and the hot pressing step necessitates highly expensive equipment; in addition, as compared to other infiltration techniques, simple and compact pieces are manufactured. Figure 14 depicts the various combined

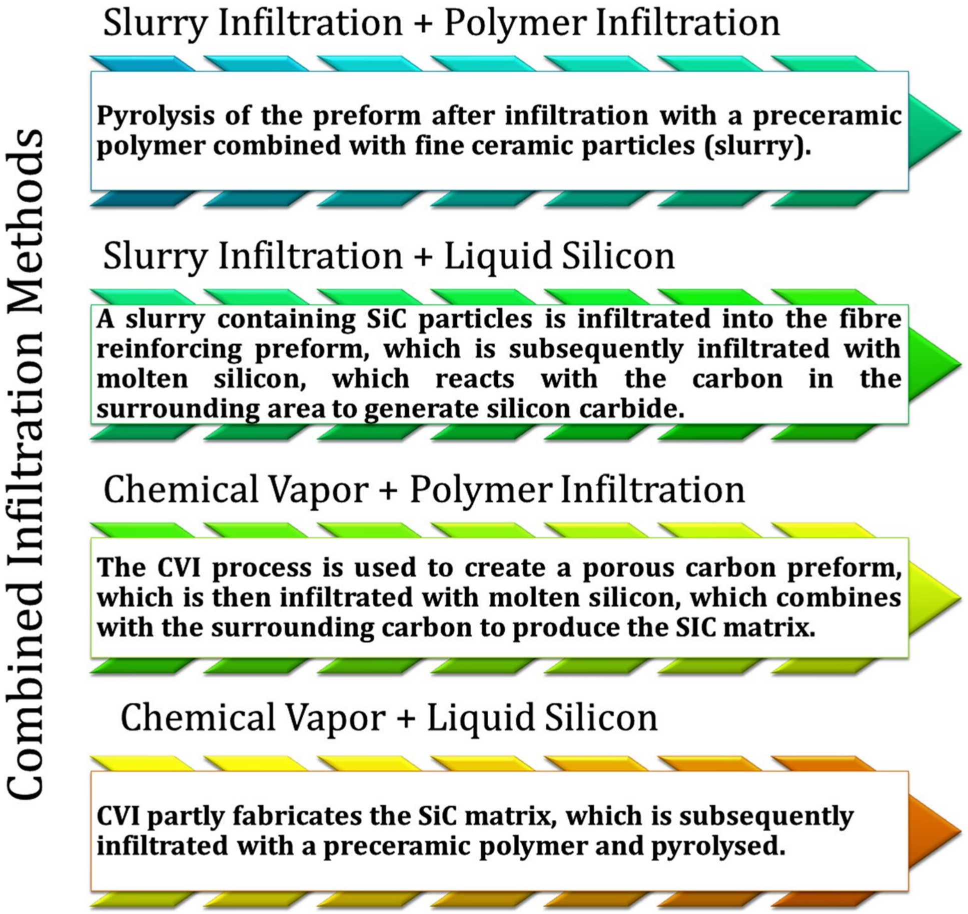


Fig. 14 Combined infiltration process of ceramic composites

infiltration process of CMCs. Table 2 shows the summary of various infiltration techniques of CMCs.

4 Applications of Si-Based Ceramic Composites

They can personalize and reduce their negative features while allowing beneficial properties to coexist in the same component. The following are the engineering applications of Si-based ceramics: Fig. 15 resembles the CMCs in various fields of applications.

4.1 Automotive

In sectors such as aircrafts, missiles, automotive and others, the demand for lower density and high-strength materials is growing in replacing conventional higher density metal alloys. Emerging materials such as C_f/SiC are replacing metal alloys due to their lower density, higher melting point, higher hardness, chemically inert,superior oxidative and erosive resistance [142, 143]. Both C/C–SiC and C_f/SiC composites have been identified as potential material for the utilisation of braking discs owing to its outstanding friction qualities, which include a higher frictional coefficient, strong abrasive resistance, and a slight reduction in friction coefficient during moist situations [144, 145]. The usage of carbon-fiber-reinforced with ceramic composites in common automobile parts such as brake discs, valves, spark plugs, etc. is increased in large numbers in recent years because of its higher load stability [146]. Moreover, Ceramic Matrix Nano Composites (CMNCs) are used to make materials stoves, nozzle assembly, energy conversion systems, thermal engines, and gas turbines [147, 148]. C/SiC composite brake discs are approved and commercially used in premium automobiles due to their enhanced properties compared to other similar materials. They are manufactured using the LSI technique [149].

4.2 Aerospace

The C/C-ZrB_2-SiC composite have prompted the concern for aeronautical engineers owing to its improved properties such as lower density, higher-temperature strength, lower coefficient of thermal expansions, good thermal conduction, and great thermal shock protection. However, the oxidizing and ablation resisting property of C/C composites can be enhanced, as carbon may be rapidly oxidised at temperature

Table 2 Summary of various infiltration methods of CMCs

Infiltration Techniques	General Purposes	Possibilities of Ceramics	Possibilities of Reinforcements & Matrices	Merits	Demerits	Inferences
Polymer Infiltration and Pyrolysis	A low viscosity preceramic organo-metallic polymer infiltrated into a preform as a result of pyrolysis forms the ceramic matrix	SiC Si_3N_4	Silicon carbonitride Silicoboron- carbonitride C_f/SiC SiC_f/SiC	• Fiber damage is prevented • Good control of matrix composition and micro-structure • No residual silicon is present in the matrix	• Fabrication time is relatively long • Residual porosity decreases the mechanical properties • High production cost	• PIP is used for fabricating composites with SiC or other silicon-based matrices [70] • Pyrolysis process consumes a greater amount of time to produce a proper component with suitable mechanical properties [71] • PIP takes less time and costs less than CVI processing for densification [71]
Chemical Vapor Infiltration	As a process of chemical breakdown, a preceramic gaseous precursor (vapour) infiltrates the fibre reinforcing preform and changes to ceramic	SiC Si_3N_4 BN B_4C ZrC	SiC_w /SiC SiC/SiC C/SiC	• Low fiber damage • Matrices of high purity • Increased Creep and oxidation resistance	• Slow process rate • High residual porosity • High capital and production costs	• Forced Chemical Vapor Infiltration process (FCVI) is a much faster process in terms of process time, higher deposition rates, lower porosity, and higher uniform densification [86] • C/SiC has become promising material of choice possessing excellent thermal, mechanical, and ablative properties [87]
Liquid Silicon Infiltration	During the reaction of molten silicon infiltrated into the preform with porous carbon, a silicon carbide matrix formed	SiC Ti_3SiC_2 BN	SiC/SiC SiC/Ti_3SiC_2 C/C-SiC	• Low cost and short production time • Very low residual porosity • High thermal and electrical conductivity	• Fiber damage may cause due to molten silicon • Residual silicon is present • Lower mechanical properties	• C/C-SiC possess excellent thermal shock stability and some abrasion resistance [105] • To reduce the amount of residual carbon and silicon phases in the LSI reaction result, carbon performs are developed and microstructures are better tailored [107]
Direct Oxidation	Ceramic matrix is made from molten metal such as usually aluminium that has been oxidised by the air	SiC Al_2O_3	ZrC–W SnO_2-CNTs Al_2O_3- $TiAl_3$	• Low shrinkage • Simple equipment and raw materials cost • Low residual porosity	• Low productivity • Fabrication time is too long (2-3 days) • Non-reacted aluminium may present in oxide matrix	• SnO_2-CNTs composite is capable of producing reversible discharging in these batteries [109] • Dense alumina-$TiAl_3$ composites drew a lot of interest due to their superior fracture tolerances and for wear resisting properties [110]

Table 2 (continued)

Infiltration Techniques	General Purposes	Possibilities of Ceramics	Possibilities of Reinforcements & Matrices	Merits	Demerits	Inferences
Sol–Gel Infiltration	A sol preceramic precursor infiltrates the preform, polymerizes (gels), and is subsequently transformed into a ceramic at a high temperature	Al_2O_3 Z_2O_3 SiO_2 Ti_3 Si_3N_4	Si_3N_4-SiO_2 Al_2O_3-B_2O_3-SiO_2 SiO_2 ZrO_2/glass	• Less reinforcing fiber damage • Low equipment and manufacturing cost • Fabricate large and complex parts	• Possible of matrix cracking • Low mechanical properties • High cost of sols	• Sol–gel processing was used to create high purity ZrO_2 powder and thin-film applications such as porous membranes for gas filtration, thick-coated layers for corrosion protection [118] • Sol–gel has many advantages such as less fiber damage, good chemical composition flexibility, low densification at temperatures, and improvement in oxidation behavior of infiltrated components [121–123]
Slurry Infiltration	Matrix is made from slurry containing small ceramic particles that infiltrates the preform and, after drying and heat pressing, transforms to ceramic	Al_2O_3 SiO_2 Mullite SiC Si_3N_4	C_f/SiC 2D-C_f/SiC C/SiC-TiC-C SiC_f/SiC TiC/C	• Low porosity • Good mechanical properties • Produces denser structure with smaller shrinkage	• Reinforcing fibers may be damaged • Requires hot pressing operation • Fabricate small and simple parts	• C_f/SiC has been the chosen composite because of its low cost and better thermal stability, usually being processed by complex processes such as liquid–vapor infiltration and hot pressing [132] • SI infiltration process is basically driven by the capillary forces and the main advantages of this SI infiltration technique is its low porosity rate and good mechanical properties [141]

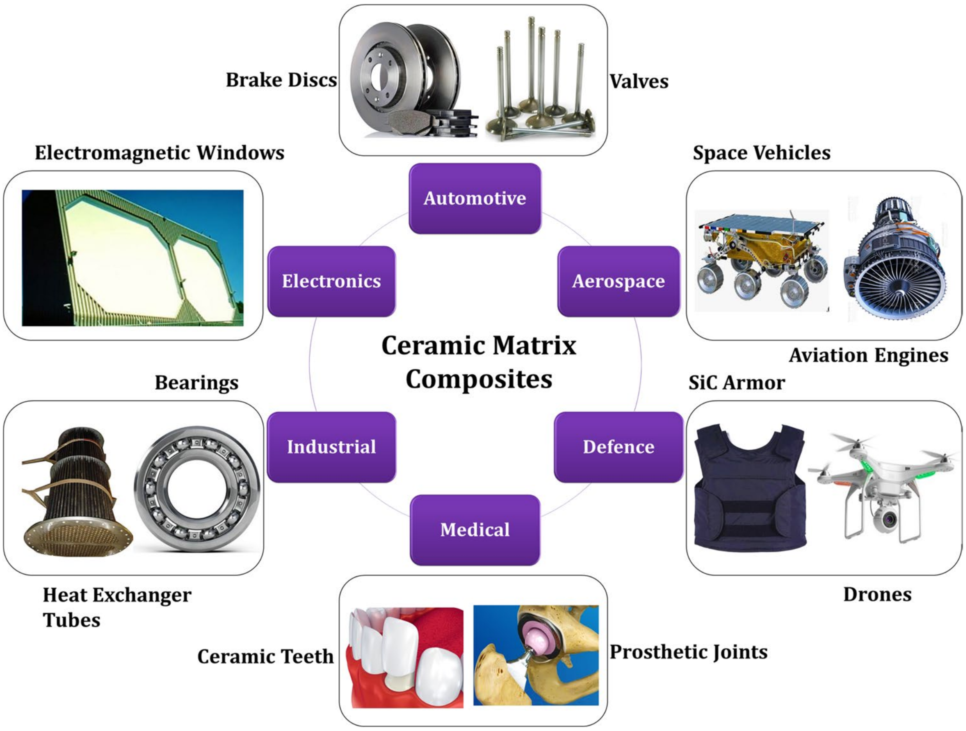


Fig. 15 Applications of CMC in various fields of applications

above 450 °C under oxygenated circumstances, limiting its employment in aeronautical industries [150]. A composite material made up of SiC reinforcing fibres and SiC matrices are termed as SiC_f/SiC. These fibres absorb fracturing energy, due to its higher fracture toughness than monolith ceramics. These composites are now being explored for structural purposes in the aircraft industry and aviation sectors [151–155]. This SiBCN ceramic offers greater thermostability, oxidative resistance, chemical resistant, and creeping resistance than other materials. As a result, it is projected to be exploited as a temperature resisting structural material in the aerospace sectors [156]. Due to low density and good wear corrosion, Silicon Carbide-Aluminium Metal Matrix Composites (Al-SiC MMC) is used to make a variety of aerospace industrial parts. Moreover, the fibers of these materials are used as reinforcing material to make fuselage skins which have properties such as ultimate tensile strength and high yield stress [157].

4.3 Medical

The laminated $SiC/TiSi_2$ and SiC/Ti_3SiC_2 ceramics are great instances of biologically produced substances and materials because they have the adaptability to give particular anisotropy qualities such as strength properties, durability, and stiffness, as well as impact and damaging resistance [158]. Owing to its optical characteristics, dental ceramics such as zirconia and silica resemble real teeth in appearances. Other properties of these ceramics, such as strength and chemical resistance, allowed these materials to be manufactured promptly for dental usage, in order to fulfil the growing need for aesthetics and longevity. A zirconia infiltrated with silica gel improves in two directions such as structural uniformity and resin cemented adhesion. This type of infiltration procedure is straightforward to carry out and control in a prosthetic laboratories [101, 159]. Siloxane is a silicon-based organic–inorganic layer is used in various medical applications. They have essential properties such as chemical stability and inertness, low toxicity, biocompatibility which are important to medicinal and its industrial applications [115].

4.4 Industrial

SiC with porous structure is a type of tailored ceramic substance that has attracted to a wide range of high-temperature engineering application fields. Due to its minimal density, strong heat resistivity, reduced thermal conductivity, and excellent mechanical qualities at extreme temperatures this porous ceramic also preferred in metallurgical field and chemical industries [160–164]. Due to its considerable importance in high temperature applications, this silicon-based ceramics such as SiC and Si_3N_4 are being explored significantly. Among the non-oxide ceramics, these SiC and Si_3N_4 ceramics have the best oxidation resistance properties [165]. Si-SiC composites are chosen for ceramic brake pads and furnace components due to their excellent thermo-mechanical characteristics. Among these composites, ZrB_2 has received a lot of attention due to its higher melting ranges, toughness, thermal and chemical stability [166]. Carbon linked carbon—fiber composites are a type of C/C composites with a minimal density and higher porosity structure. They were used as thermal protection in vacuuming and inert-gas furnaces which can withstand temperature up to 2800 °C [167]. Industrial applications include the chemical sector, aluminum manufacture, oil and gas production, and solar cell manufacturing. The SiC-based flow reactors and heat exchangers, industrial pump seals and bearings [168].

4.5 Military

Carbon fibre coupled with ZrC-SiC composites is recommended for high temperature applications including supersonic vehicles and sharper surfaces in aircrafts. These composites have outstanding features such as fracture toughness, thermal shock absorption, and possess good mechanical characteristics under higher temperatures [169, 170]. These C/C-SiC and SiC/SiC composites are extensively used as functional materials in the aeronautical and aviation industrial sectors due to their higher thermal prevention, enhanced propulsive systems, and other properties such as higher fracture toughness, strength at higher temperatures, reduced density, superior thermal conduction, and oxidative resistance [171, 172].Various ceramics are used to fabricate or manufacture different parts especially ceramics such as Si_3N_4, Al_2O_3, and SiC parts such as ballistic-resistant exterior tiling for planes, helicopters, and drones, supplanted metal-based armor plates for body armor are fabricated. Among the ceramics mentioned Al_2O_3 is used in most parts because of its hardness, modulus of elasticity, refractoriness, and low cost [173].

4.6 Electronics

Electronic ceramics account for a significant portion of the advanced ceramics market. For the creation of electrical and electronic circuits, multilayer ceramics such as multi-layered capacitors, multi-layered packages and substrates, and other ceramic electrical components such as PTC resistors, IBL capacitors, PZT ceramics, and dielectric resonators are employed [174]. Due to its outstanding mechanical qualities, strong thermal shock protection, and erosive resistance, Si_3N_4 ceramic is a prospective for tail rotors and photovoltaic systems. These ceramics are also potential material for electromagnetic windows which are nearly transparent to electromagnetic radiation in the frequency ranges and employed in modern systems [175, 176]. Likewise, the composite boron nitride combines with SiC/SiC-Si are a suitable substance for both electronics field and photonic products, along with higher temperature activities [177]. SiCN has significant concern due to its ability to combine the characteristics of both SiC and Si_3N_4 substances. This SiCN is a higher temperature resisting material that may be used for a variety of purposes, including Radio Frequency Identification (RFID) shielding which act as a conducting barrier that entirely encloses the device to prevent from environmental disturbances [178–180]. Table 3 resembles the summary of fields of applications of different infiltration process with its flexural strength of ceramic composites. Table 4 resembles the summary of fields of applications of combined infiltration techniques with its flexural strength of ceramic composites.

5 Future Scope of Si-based Ceramics

Ceramic matrix composites are likely to see increased demand from the aerospace, defense, automotive, energy, and power end-use industries, as well as their ability to withstand high temperatures and have remarkable mechanical qualities. Product type, end-user industry, and geography are the various segments observed in CMC's market, and its by-product type market is segmented by C/SiC CMCs, C/C CMCs, Oxide/Oxide CMCs, SiC/SiC ceramic matrix. Automotive, aerospace, defence, energy and power, electrical and electronics and other user industries are segmented by industry. SiC is well known for its numerous benefits in a variety of sectors, including the biological field. The full potential of this material has yet to be realized, owing to the presence of a high degree of flaws. Despite its wide bandgap, high thermal conductivity, and strong breakdown electric field, when employed in traditional power devices, its performance fails to meet the acceptable limitations at high temperatures due to flaws.

As a result, understanding these faults is critical for furthering their application in the biomedical industry, as they are employed in the development of biomedical devices that go into every region of the body, such as membranes, bio micro electro mechanical systems, stents, drug delivery, biosensors, and so on. The best alternatives for metallic alloys are SiC/SiC CMCs, which are typically employed in gas turbines. The revenue shares of silicon-based ceramic composites in the year 2020 is shown in Fig. 16 because of its remarkable oxidation and radiation resistance qualities, SiC/SiC CMCs have seen increased use in the energy and power industries in recent years. For high-temperature structural applications, Cf/SiC is considered the most promising material. Large-scale Cf/SiC composite components with complicated geometries are often difficult to manufacture, necessitating the use of appropriate joining procedures to link them to themselves or other materials. Despite the transitory impact of COVID-19, the demand for SiC/SiC matrix composites is expected to dominate the CMCs market throughout the forecast period due to rising investments in the energy and power sector.

Table 3 Summary of fields of applications of infiltration process with its flexural strength of ceramic composites

Ceramic Material	Ceramic Matrix Composites	Infiltration Techniques	Flexural Strength (MPa)	Applications	Inferences
SiC	C_f/SiC	Polymer and Pyrolysis	67—138	Aerospace, Missiles, Automobile industries	C_f/SiC composites replaces currently existing metals alloys due to its higher density in various industries like aerospace, missile, automobiles [142]
SiC	CNT- C_f/SiC	Polymer and Pyrolysis	423	Automotive, Aerospace, Aviation industries	Owing to its superior mechanical and electrical characteristics, CNTs have received a lot of interest, and reinforcing with C_f/SiC composites is regarded as a viable potential material for high temperature applications [143]
SiC	C/SiC	Sol–gel	-	Heat shields, Space vehicles, Brake disc, Heat exchanger tubes	C/SiC composites have outstanding thermo-mechanical capabilities at extreme temps, making them viable options for highly-demanding applications for heat shielding, launch vehicles, and braking discs [145]
$ZrB_2 - SiC$	$C/C - ZrB_2 - SiC$	Polymer and Pyrolysis	309.30	Aerospace sectors	Molten SiO_2 combined with ZrO_2 aids in the sealing of flaws such as fractures, and holes, following oxidizing in an extreme temperature of aerobic atmosphere, during ablation process [150]
SiC	SiC_f/SiC	Polymer and Pyrolysis	-	Propulsion Systems, Aviation engines, Projectiles	SiC reinforced fibers are tendency to absorb fracturing energies and reinforcing with SiC for aerospace applications [151]
SiBCN	SiBCN aerogel/graphene	Sol–gel	-	Aerospace sectors	SiBCN ceramic offers greater thermostability, oxidative resistance, chemical resistant, and creeping resistance than other materials [156]
SiO_2, SiC	SiC_f/SiC	Slurry	-	Propulsion components, Jet engines	These fibres absorb fracturing energy, due to its higher fracture toughness than monolith ceramics and being explored for structural purposes in the aircraft industry and aviation sectors [154]
zirconia and silica	Y-TZP/Silica	Sol–gel	859.7—1104.4	Dental fields	Zirconia infiltrated with silica gel improves in two directions such as structural uniformity and resin cemented adhesion and this infiltration process carried in prosthetic laboratories [101]
SiC, $TiSi_2$	SiC/$TiSi_2$	Liquid Silicon	225	Biomimetic materials	Laminated composites having great instances of biologically produced substances and materials because they have the adaptability to give particular anisotropy qualities such as strength properties, durability, and stiffness, as well as impact and damaging resistance [158]
SiC, Ti_3SiC_2	SiC/Ti_3SiC_2	Liquid Silicon	165	Biomimetic materials	

Table 3 (continued)

Ceramic Material	Ceramic Matrix Composites	Infiltration Techniques	Flexural Strength (MPa)	Applications	Inferences
Porous SiC	SiC_{nw}/SiC	Chemical Vapor	122—270	Catalyst supports, Filters, Combustion burners	Due to its minimal density, strong heat resistivity, reduced thermal conductivity, and excellent mechanical qualities at extreme temperatures this porous ceramic also preferred in metallurgical field and chemical industries [161]
Porous SiC	SiC/SiC	Reactive Melt	77	Catalytic support, Mechanical seals, Gas turbines, Heat exchanger tubes	Porous silicon carbide is a type of tailored ceramic substance that has attracted to a wide range of high-temperature engineering application fields [163]
ZrC, SiC	C/ZrC–SiC	Polymer and Pyrolysis	142	Hypersonic vehicles, Sharp aero-surfaces	ZrC-SiC composites is recommended for high temperature applications including supersonic vehicles and sharper surfaces in aircrafts [169]
SiC	C/C-SiC	Liquid Silicon	134—174	Aeronautics and Space industries	C/C-SiC composites are extensively used as functional materials in the aeronautical and aviation industrial sectors due to their higher thermal prevention [171]
SiC	Si/SiC	Liquid Silicon	300	Machinery manufacturing, Aerospace, Chemical equipment, Electronic devices	Si/SiC composites are widely employed in the production of machinery, aircraft, chemical appliances, and electronic gadgets [180]
Si_3N_4, SiO_2	Porous Si_3N_4–SiO_2	Sol–gel	92.6 – 148	Electromagnetic windows and Tail rotors	Porous Si_3N_4 ceramics are also potential material for electromagnetic windows which are nearly transparent to electromagnetic radiation in the frequencies ranges [175]

Table 4 Summary of fields of applications of combined infiltration process with its flexural strength of ceramic composites

Combined Infiltration Methods	Ceramic Matrix Composites	Flexural Strength (MPa)	Applications	Inferences
Slurry + Polymer & Pyrolysis	C_f-ZrB_2-SiC	190–500	Hypersonic aerospace vehicles, Atmospheric re-entry vehicles and Energy fields	Due to their increased strength to weight ratio, superior toughness, and thermal shock tolerance at higher temperatures, C_f-reinforced ceramic composites are interesting options for equipment's in automotive, military, atomic, and aerospace areas such as braking devices, gas turbines, facing materials, engine components, launchers, and rockets propellers [181]
	$C/C-ZrB_2-SiC$	309.30	Aerospace fields	ZrB_2 ceramics have received a lot of interest due to its higher melting range, hardness, thermal shocks and abrasion resistance, and oxidation effects The inclusion of SiC enhances the mechanical qualities as well as the oxidative protection [182]
Slurry + Chemical Vapor	C/C-ZrC and C/SiC-ZrC	-	Hypersonic flight and High-speed propulsion vehicles	Borides, carbides, and nitrides are higher temperature withstanding ceramics with highest melting ranges, greater atmospheric resilience, and effective strength maintenance at extreme temperatures [151]
	C/SiC–ZrB_2–TaC	255	Aircraft—engines, nose caps, leading edges, nozzles, space vehicles	The inclusion of TaC in the C/SiC–ZrB_2 composite enhances the ablation resisting property for aircraft and aerospace components under extreme temperatures [183]
Chemical Vapor + Polymer & Pyrolysis	SiC—CH_3SiCl_3/H_2	-	Energy production and Alternative energy sources	The most frequent types of volumetric receivers used in solar energy generation are made of cellular ceramic with porous structure having good energy transmission capabilities [184]
	SiC_f/SiC	-	Gas turbines and Aviation fields	Because of their outstanding oxidative resistance, superior temperatures in creep and mechanical performance, lower density, higher specific strength and flexibility, SiC_f/SiC composites are the most attractive choice for gas turbine implementations [185]
Chemical Vapor + Reactive Melt	C/C–ZrC	239.5	Hypersonic vehicles and Rocket propulsion	During the process the formation of ZrO_2 barrier film was produced on the surfaces, and the composite demonstrated outstanding ablation resistance for aerospace applications [186]
Slurry + Liquid Silicon	C/SiC–Ti_3SiC_2	-	Aerospace and Aircraft sectors	C/SiC composites cannot withstand ablation at higher temperatures, so by inclusions zirconia, titania, and tantalum substances improves the ablation property which is applicable for aircraft and aerospace applications [187]

Table 4 (continued)

Combined Infiltration Methods	Ceramic Matrix Composites	Flexural Strength (MPa)	Applications	Inferences
Slurry + Vapor Silicon	$MoSi_2$-SiC-Si	-	Aeronautic and Aerospace fields	$MoSi_2$ is a potential material with a higher melting range, minimal density, and strong oxidative protection in air at extreme temperatures, even in harsh conditions [188]
Sol–gel + Reactive Melt	C_f/SiC-ZrC-ZrB_2	-	Space vehicles and Hypersonic flight	Due to their impressive superior temperature qualities, such as minimal thermal expansion, strong mechanical stability, and great oxidizing protection, Cf/SiC composites are considered as functional materials for employed in thermal protective technologies [189]

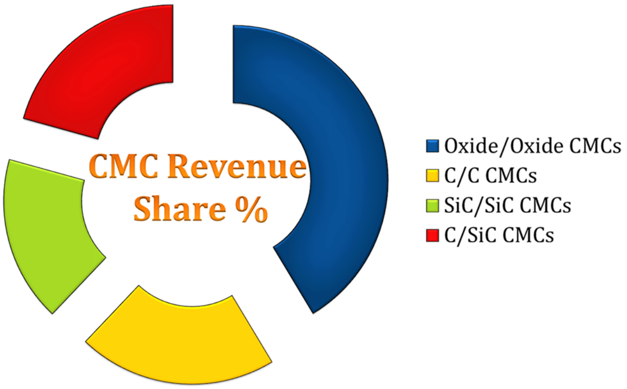


Fig. 16 CMCs market, revenue share (%) by product type, global, 2020

6 Conclusion

Even though ceramic composites are known for their hard machinability properties, the demand for these composites has reached an ever-increasing high; the recent growth of demand for CMCs in the aerospace and automotive industries has become a key factor in enhancing the understanding of its manufacturing process. In some ways, the demands paved the door for the use of new industrial processes. There are many different types of infiltration-based manufacturing processes, each with its own set of features. The best technique for the job is chosen based on the demand, the application's surroundings and conditions, the surface polish, and the material's cost charges. With these considerations in mind, any type of infiltration might be selected to meet the requirements. Ceramics must be manufactured at low temperatures to avoid fiber breakage, which can be accomplished using PIP. The microstructure and content are well controlled in PIP. Many different methods of reinforcement can be used, allowing a vast range of matrices to be created. Unlike MI, silicon matrices generated using PIP do not contain any free silicon [79]. Because there are more pyrolysis cycles required, the fabrication time is longer. CVI is versatile enough to produce any shape nevertheless; the process is constrained by its complexity, associated costs, equipment requirements, and careful management of the specimen before the process [80]. In comparison to ceramic materials acquired through CVI and LPI, CMCs materials such as C/C-SiC, SiC/SiC, and C/SiC ceramics produced through the MI process have much lower open porosities, giving them stronger shear strength and better thermal conductivity. C/C-SiC and C/SiC, on the other hand, confront few obstacles due to their low tensile strength and the short lifetime of SiC/SiC ceramics. In the MI process, there are chances of occurrence of matrix cracking which happens because of the change in volume during solidification. While performing SI, the composite will have uniform fiber/matrix microstructures along with good mechanical properties like high strength and toughness are achieved. As a result of this technique, low porosity of the ceramic material is achieved [190]. The sol–gel process is a remarkable process for manufacturing CMCs at low temperatures that reduces fiber damage, but it lacks certain characteristics such as manufacturing composites with large shrinkages, which causes matrix cracking, and the composites manufactured by this process have lower mechanical properties than their counterparts [191, 192]. Silicon-based CMC's has applications in fields such as automobile, aerospace, aeronautical, marine, and many other industries, It produces promising results in their respective fields. Silicon-based CMC's has a high temperature, resistance to corrosion, strength retention, stress rupture, and high corrosion resistance. Ceramic components display high brittleness with high hardness values. Such a critical component must be fabricated using proper methods such as infiltration techniques. Much research has been conducted using these techniques to study ceramic components. Popular and efficient infiltration techniques like SI, sol–gel and MI were discussed and their various features were outlined, thus providing insights in understanding the established work. Compared to powder or slurry precursor's sol–gel route is advantageous due to lower densification temperatures. Despite all these fabrication processes, the selection and application of the manufacturing process ultimately depend on the process application and the constraints in the working environment. In sectors such as aircrafts, missiles, automotive, and others, the demand for lower density and high-strength materials is growing to replacing conventional higher density metal alloys. Emerging materials such as C_f/SiC are replacing metal alloys due to their lower density, higher melting point, and higher hardness, chemically inert, superior oxidative and erosive resistance.

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Declarations

Ethics approval This is a review based on peer-reviewed data published on reputed journals, which requires no ethical approval.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Hereby declare our consent for the publication of identifiable details, which can include photograph(s) and/or details within the text ("Manuscript") to be published in the above Journal and Article. I confirm that I have seen and been given the opportunity to read both the Material and the Article (as attached) to be published by Springer.

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