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Review Article

Breaking Boundaries with Ceramic Matrix Composites: A Comprehensive Overview of Materials, Manufacturing Techniques, Transformative Applications, Recent Advancements, and Future Prospects

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Ceramic matrix composites (CMCs) are a category of advanced materials which have gained significant interest recently due to their remarkable mechanical and thermal characteristics. These composites are composed of ceramic fibers, particles, or other types of ceramics incorporated in a ceramic matrix and have shown the capability to be implemented in several sectors, including aerospace, energy, and biomedical engineering. This review paper will provide a synopsis of the current scenario and recent progress in CMCs, including materials and processing techniques, characterization methods, and applications. The paper discusses the advantages and limitations of CMCs, recent advancements, and future trends in research. The microstructural and mechanical properties of CMCs are also reviewed, highlighting their potential for various applications. The paper's conclusion delivers a summary of the essential findings and a discussion of future directions for CMC research.

1. Introduction

Composites are typically categorized into Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs), and Polymer Matrix Composites (PMCs) based on the type of material forming the matrix. CMCs are recently developed and auspicious materials for advanced engineering uses that involve challenging and extreme conditions. It combines a ceramic matrix with a dispersed ceramic phase, such as carbides, oxides, or silicides. These composites possess extraordinary characteristics such as high-temperature strength, reduced thermal conductivity, good resistance to corrosion, enhanced resistance to wear, favourable frictional behavior, desirable fracture toughness, remarkable strength-to-weight ratio, and reduced density. Such properties contribute significantly to extended lifespan compared to conventionally used metallic or ceramic components [1]. The presence of ceramic material contributes to the outstanding performance of CMCs compared to other materials. CMCs are superior in comparison to other materials such as PMCs and MMCs due to their chemical stability and desirable damping characteristics. The main challenges associated with CMCs are their tendency to undergo thermal cracking and lack of ductility. By using a combination of manufacturing techniques and raw materials, the properties of CMCs can not only be improved but also tailored for specific applications.

The history of the composites that we use today starts from the 1930s. Since the 1960s, polymer reinforced composites have been used in various industrial as well as non-industrial sectors. During the 1970s, research was focused on making metal matrix composites in order to enhance the properties of aluminium alloys such as its high specific modulus and specific strength. The metal matrix composites back then were predominantly composed of aluminium alloys reinforced with SiC or whiskers. After the 20th century, low-cost reinforcement materials have gained a higher priority. Both MMCs and CMCs have been developed more recently compared to polymer matrix composites [2]. The usage of MMCs has significantly increased over the last decade [3]. They have been implemented in a wide variety of applications including aerospace, marine, automobile, railway, biomedical engineering, and electrical engineering [4]. The need for CMCs primarily arose to overcome the challenges associated with conventional ceramic materials, which tend to have low fracture resistance and crack easily under the influence of mechanical and thermomechanical loads. CMCs can be reinforced by fibers or particles. They are constantly evolving owing to research and modern technology today. Recently, a lot of attention has been focused on ultra-high temperature ceramics (UHTCs), which have the capability to withstand the harsh aero-thermo-mechanical environment in supersonic flight [5]. Adding a secondary reinforcement such as whiskers, nanoparticles, or nanofibers is also a widely sought method to enhance the properties of monolithic ceramics while also improving other properties such as hardness, thermal shock resistance, and thermal expansion coefficient [6]. Nonetheless, the manufacturing of CMCs is typically more expensive than that of MMCs and PMCs [7].

CMCs consist of ceramic fibers distributed within a ceramic matrix, resulting in a material reinforced by ceramic fibers. Despite the inherent brittleness of the constituent materials, CMCs exhibit toughness due to their well-designed fiber/matrix interface. This interface effectively halts and redirects cracks within the matrix, which hinders the fiber reinforcements from undergoing failure [8]. CMCs can be strengthened by adding fibers, either short (or discontinuous) or long (continuous). Long fibers generally exhibit higher strength in a certain direction. Incessant fiber-reinforced ceramic matrix composites (FRCMCs) are a type of robust ceramic material that derives its toughness from continuous fiber reinforcement and a well-optimized and weakened interphase between the Silicon Carbide (SiC) matrix and fibers.

The toughness of FRCMCs is achieved through mechanisms like crack deflection and crack bridging, resulting in both elevated strength and fracture toughness. These composites address the limitations of metal materials, such as low-temperature resistance and too much density, brittleness and poor reliability, and insufficient resistance to oxidation in the case of carbon materials. FRCMCs exhibit very good properties, including lightweight, resistance to high temperatures, corrosion resistance, wear resistance, oxidation resistance, and superior damage tolerance [9]. Some sintering additives such as Y_2O_3 and CeO_2 can improve mechanical properties of Si_3/SiC ceramic by reducing density of the composite. This decrease was caused by the resultant composites' increased porosity [10]. Short/discontinuous fiber composites are fabricated using traditional ceramic techniques, utilizing non-oxide (WC, SiC, ZrC, BN, etc.) or oxide (zirconia, alumina, silica, etc.) ceramic matrices. These can be further strengthened by SiC, AlN, and TiB_2 whiskers. Long/continuous fiber composites, on the other hand, are produced by incorporating long monofilament or multifilament fibers. The spreading phase in continuous fibers provides the most effective strengthening effect. CMCs are generally developed to address the toughness limitations associated with conventionally used ceramics [11].

Other common types of CMCs include oxide-oxide and aluminium oxide reinforced CMC [12], carbon/carbon CMCs [13], Carbon fiber-reinforced Silicon carbide (C/C-SiC) CMCs, [14] Silicon Carbide/Silicon Carbide CMCs [15], and zirconium oxide CMCs [16]. Yang et al. focused on studying thermal aged oxide/oxide CMCs subjected to cyclic thermal shocks [17]. Yang et al. researched the characterization of thermal ageing-induced damage for 2D woven oxide/oxide CMCs, studying both the micromechanisms and macroscopic mechanical behavior. Oxide/Oxide CMCs exhibit excellent oxidation confrontation, thermal stability, and thermal shock endurance. [18]. Zhu et al. developed Carbon fiber-reinforced SiC composites by implementing 3D-printing technology as well as liquid silicon infiltration to show the opportunity of making near-net shape composite parts possessing complex structures [19]. Recently, Titanium matrix composites (TMCs) have drawn immense interest owing to their desirable properties. Zhang et al. prepared TMCs reinforced with reticular quasi-continuous nano-TiB whiskers (nano-TiB_W), which were better than Ti64 alloy in terms of wear resistance, particularly adhesive wear [20]. Nazari et al., in their paper, reviewed the advanced manufacturing techniques for fabricating ceramic and bioinspired ceramic composite armors. These techniques include powder-based methods for porous structures and vat polymerization/slurry-based deposition for dense ceramic parts, crucial for cost-effective production and enhanced performance in armor applications [21]. Lamouroux developed a multilayer Si–B–C ceramic matrix to enhance the oxidation resistance and lifetime of carbon-fiber-reinforced ceramic-matrix composites in oxygen environments. Compared to traditional external coatings, this matrix significantly improves the composite's durability under thermomechanical stress, highlighting its effectiveness in protecting carbon reinforcement against oxidation [22].

CMCs have been implemented in numerous applications, including aircraft brake materials [23], gas turbine engines in aircraft to replace previously used superalloys [24], advancements in propulsion systems and space exploration [25], space and aeronautic applications [26], applications involving extreme conditions such as hypersonic flight [27], nuclear applications [28], and biomedical applications [29]. CMCs, categorized into oxide and non-oxide families, offer promising advantages for high-temperature propulsion applications such as aeroengines [30].

This paper aims to provide a state-of-the-art review of CMCs. The different types of CMCs have been categorized according to the raw materials used, including the fiber and matrix systems. A detailed study of CMCs studied by researchers in various experiments has been provided. CMC properties, including mechanical, wear and tribological, thermal and electrical, and biocompatibility, have been studied. As there are various methods of manufacturing CMCs, the most important fabrication processes have been reviewed in detail, along with insights into the current applications of this material. Based on the current research trend and application, an overview of the challenges associated with producing, processing, and implementing CMCs will be studied in this paper, and future directions of CMCs in the industrial sector will be discussed. To summarize, it can be concluded that CMCs have the potential to replace several conventional materials used in the industry because of their desirable properties, such as elevated strength, thermal properties, and frictional behavior. Consequently, this paper aims to put forth the current and future prospects of CMCs in material science engineering.

2. Materials and Processing

CMCs are a subcategory of composite materials which consist of a fiber or matrix system made up of a ceramic material. Due to their very high melting point, low coefficient of thermal expansion, reduced density, superior stiffness, hardness, and chemical inertness, they provide major advantages for structural applications compared to other materials. Although their poor reliability in strength and brittleness limits their widespread application, constant research has played a key role in continuing progress in this field [31].

2.1. Classification of CMCs. The type of CMC used is dictated by the type of matrix present, which includes oxide and non-oxide. Examples of oxide include Al_2O_3, $Al_2O_3SiO_2$, and SiO_2. Examples of non-oxide include BN, SiC, HfB_2, and ZrB_2. Non-oxide CMCs possess greater mechanical strength at elevated temperatures. CMCs, including SiC, have been implemented in high-temperature applications such as aeroplane engines since they have reduced thermal expansion coefficient, density, elevated hardness, and good availability [32]. Commonly used non-oxide-based CMCs include SiC, C/SiC, SiC, ZrB2, and C/C.

In environments involving combustion processes, oxide-based CMCs facilitate better oxidation as well as degradation resistance. Usually, the same ceramic phase is incorporated in both types of CMCs; the difference in the thermal expansion coefficient between different materials during manufacturing will result in the build-up of residual stresses [33]. Potential matrix materials include high-temperature structural silicide such as $TiSi_3$, WSi_2, and $MoSi_2$.

2.2. Raw Materials. Most ceramic matrix reinforcements include nitrides, borides, oxides, and carbides. Usually, the reinforcements are present in whiskers, continuous fibers, short fibers, particulates, and platelets, with each configuration providing a different set of advantages. Continuous fibers increase strength and stiffness, whereas isotropic properties can be imparted with discontinuous fibers. Continuous fibers are a type of polycrystalline material oriented in one direction, and they come in two forms: monofilaments and multifilament. Monofilaments, such as Borsic, SiC, and Boron, have approximately 100–150 μm diameters and are produced using the chemical vapor deposition (CVD) fabrication technique. Multifilaments, including Sumitomo (Al_2O_3), Nicalon (SiC), and Carbon fibers, are created by pyrolyzing organometallic compounds. They exist as tows (bundles of several thousand 3–10 μm diameter fibers) or two or three-dimensional weaves of the tows. Short fibers resemble multifilaments. Whisker-reinforced CMCs use single crystals of SiC and Si_3N_4 that are free of defects. Among the types that are available commercially, SiC whiskers are the most promising for enhancing the properties of ceramic matrices that are brittle in nature, as they have better reinforcement capabilities. Additionally, high purity SiC whiskers have been successfully manufactured using various methods [34].

2.3. Manufacturing Methods. CMC materials in industrial applications predominantly consist of SiC or SiSiC matrices and SiC or Carbon fibers. These materials, commonly called C/C-SiC, C/SiC, or SiC/SiC, are manufactured using distinct process routes. CMC fabrication is predominantly carried out through chemical vapor infiltration (CVI), polymer infiltration and pyrolysis (PIP), or melt infiltration (MI). Table 1 shows a summary of the different manufacturing techniques. Despite commonly used methods in manufacturing, each process inevitably generates variabilities, such as matrix porosity and voids in the microstructure. Volume fraction, morphology, distribution, and the size of the voids generated during the manufacturing process affect the final appearance of the composite material. This makes it challenging to properly correlate the processing technique, microstructure, and final property of the product. Several techniques have been suggested and applied to classify and quantify the defects in CMC material systems. These multiscale models vastly rely on idealized representative volume elements (RVEs), which cannot efficiently consider the shape and dispersal of the scale-dependent defects and the uncertainty in CMC characteristics [40].

2.3.1. Chemical Vapor Infiltration (CVI). The introduction and gradual depositing of gaseous forerunners using the CVI technique can occur under various conditions (such as maintaining a constant temperature, applying temperature or pressure gradients, or using pulsed methods). This process leads to composite materials that possess very good mechanical properties. In contrast, it is faster to infiltrate fiber preforms with liquid ceramic precursor via PIP. However, the overall manufacturing time is still considerable because it necessitates multiple rounds of re-infiltration and re-pyrolysis to decrease porosity to an acceptable level [41]. Gaseous precursors are deposited on the matrix and interphase in CVI. A preform, a porous substrate, the ceramic fibers, is placed inside a high-temperature CVI reactor purged with inert gas. A precursor gas consisting of volatile compounds is introduced into the reactor. The choice of the

Table 1: Summary of numerous infiltration techniques for CMC.

Infiltration techniques	Possibilities of ceramic	Possibilities of reinforcements and matrices	Merits	Demerits	Ref
Chemical vapor infiltration	BN B_4C ZrC SiC Si_3N_4	SiC/SiC SiCw/SiC C/SiC	(i) Matrices of high purity (ii) Low fiber damage (iii) Increased creep and oxidation resistance	(i) High residual porosity (ii) Slow process rate (iii) High capital and production costs	[35]
Polymer infiltration and pyrolysis	Si_3N_4 SiC	SiC/SiC SiCw/SiC C/SiC	(i) Matrices of high purity (ii) Low fiber damage (iii) Increased creep and oxidation resistance	(i) High residual porosity (ii) Slow process rate (iii) High capital and production costs	[36]
Direct oxidation	Al_2O_3 SiC	SnO_2-CNTs ZrC-W Al_2O_3-$TiAl_3$	(i) Simple equipment and raw materials cost (ii) Low shrinkage (iii) Low residual porosity	(i) Fabrication time is too long (2-3 days) (ii) Low productivity (iii) Non-reacted aluminium may be present in oxide matrix	[37]
Slurry infiltration	Mullite Al_2O_3 SiC SiO_2 Si_3N_4	C/SiC-TiC-C C_f/SiC SiC_f/SiC 2D-C_f/SiC TiC/C	(i) Good mechanical properties (ii) Low porosity (iii) Produces denser structure with smaller shrinkage	(i) Requires hot pressing operation (ii) Reinforcing fibers may be damaged (iii) Fabricates small and simple parts	[38]
Sol-gel infiltration	Z_2O_3 Ti_3SiC_2 SiO_2 Al_2O_3	Al_2O_3-B_2O_3-SiO_2 ZrO_2/glass Si_3N_4-SiO_2 SiO_2	(i) Low equipment and manufacturing cost (ii) Less reinforcing fiber damage (iii) Fabricates large and complex parts	(i) Low mechanical properties (ii) Possibility of matrix cracking (iii) High cost of sols	[38, 39]

precursor gas varies on the anticipated CMC. Reactive species are produced and deposited on the preform as the precursor gas decomposes to form the ceramic material. As more precursor gas is introduced and decayed, the ceramic material grows thicker until the desired thickness is achieved. CVI offers several advantages, including the ability to control the duration of constituent infiltration, resulting in better control over the volume fraction of the constituents. Moreover, it allows for introducing an interphase with adjustable thickness, which enables the study of how interphase thickness affects the composite's mechanical characteristics. These characteristics of CVI enable the choice of an optimal interphase thickness and constituent volume fractions, leading to superior mechanical performance.

CVI has gained recognition as an excellent approach for manufacturing high-performance composites that fulfil the requirements of the aviation and aerospace sectors. Zeng et al. conducted a study on a two-dimensional (2D) carbon fiber-reinforced silicon carbide composite (2D C/SiC) to explore the impact on tensile properties by different thermal cycles in air. The composite was prepared using CVI at various heating rates. The test temperature was determined based on aircraft fuel combustion in the air, while the heating rate corresponded to a realistic temperature curve inside an aeroengine. Researchers investigated the damage mechanisms using online acoustic emission (AE) monitoring and offline analysis of fractured morphology. The results revealed that oxidative damage had a crucial effect on the residual properties of 2D C/SiC composites subjected to thermal shocks in an air environment [42]. The traditional isothermal, isobaric CVI method, which uses gaseous precursors at constant temperature and pressure, remains dominant in mass production despite its costly nature and lengthy manufacturing duration. To address these concerns, various rapid densification techniques have emerged in recent years, including thermal gradient CVI, boiling film technique, and forced flow CVI [43]. The different kinds of CVD techniques are demonstrated in Figure 1.

Nagaraja et al. constructed C/BN/SiC mini composites by isothermal, isobaric CVI process. The duration of matrix infiltration and the interphase were varied to alter the interphase's thickness and the constituent volume fraction in various test samples. The tensile response, damage mechanism during and until ultimate failure, and the resulting microstructure were observed to correlate the CMC processing, microstructure, and tensile response [45]. An experiment was carried out to produce CMCs strengthened with SiC whiskers through CVI. Spray drying was carried out in this investigation to enhance printability and flowability. The binder jetting enabled printing of a novel SiC whisker preform, and employing CVI resulted in a dense, pure, and continuous SiC matrix with superior modulus as well as strength [46]. Li et al. assessed the influence of nonuniform microstructures, such as ply orientation and porosity, on the strength of 2D-C/SiC pins produced via CVI. The results revealed a linear correlation between the average shear strengths and total porosity, with values ranging from 85.8 to 134.8 MPa as the average total porosity decreased from 23.2% to 14.5%. When the total porosity was identical, the shear strengths of 2D C/SiC pins closely resembled the in-plane shear strengths of 2D C/SiC composites [47]. To enhance the adhesion between the SiC fibers and matrix in SiC fiber/SiC matrix composites, interfacial coatings of boron nitride (BN) were synthesized using CVI. The synthesis was performed at four different temperatures (843°C, 900°C, 950°C, and 1050°C) with varying times of accumulation. The deposition temperature significantly influenced the microstructure of the deposited BN coatings. Specifically, at 843°C, 950°C, and 1050°C, the coatings exhibited amorphous, polycrystalline, and hexagonal structures, respectively [48]. Choudhary et al. suggested a method to regulate the occurrence of defects caused by grinding in Carbon/SiC composites prepared through CVI. This was achieved by employing high-speed grinding [49]. Tao et al. determined that the tensile strength and flexural strength improved by 11% and 12%, respectively, when Silicon Nitride (Si_3N_4) nanowires densified via CVI were incorporated into two-dimensional Carbon/SiC-CMC [50].

2.3.2. Melt Infiltration. Reaction Melt Infiltration (RMI) is another widely adopted method for fabricating CMCs. In these methods, the fiber tows are firstly coated for protection to ensure a weak fiber-matrix interface. This is important for imparting important CMC characteristics such as superior strength, resistance to thermal shock, and fracture toughness. The fibers are impregnated with a polymer followed by curing and pyrolysis, commonly known as PIP to achieve this. A fiber-reinforced green body of near-net-shape is fabricated, and a porous fiber reinforced with preform is built to contain predominantly Carbon C and SiC. Two primary methods produce near-net-shape green bodies with C- and SiC-fiber reinforcement in specific geometries. The first method involves manufacturing green bodies using polymer matrix-based materials like carbon fiber-reinforced plastics (CFRPs).

On the other hand, the second method relies on CVI primarily for constructing green bodies of SiC fiber-reinforced materials. Finally, the SiSiC matrix is synthesized through the infiltration of the molten Silicon. Different manufacturing processes have been created to produce CMC materials. Some of the names of these processes include C/SiC, SiC/SiC, and C/C-SiC. These processes primarily vary according to the method of fiber protection and incorporation into the SiC matrix, as well as in the methods used to create the initial structure and the porous preform reinforced with fibers [51]. Figure 2 shows the schematic diagram of producing CMCs via melt infiltration.

Arai et al. fabricated ultra-high temperature ceramic (UHTC) matrix composites for various hot structures via the melt infiltration method. Results indicated that in creating high-density composites through Zr-Ti infiltration, the flow through capillaries should be considered during infiltration as alloy's reactivity to preforms [53]. Zhang et al. created C/C-ZrC composites by melt infiltration of eutectic Zr-Si alloyed into C/C composite preforms of different densities. The effect that preform density has on the microstructure of

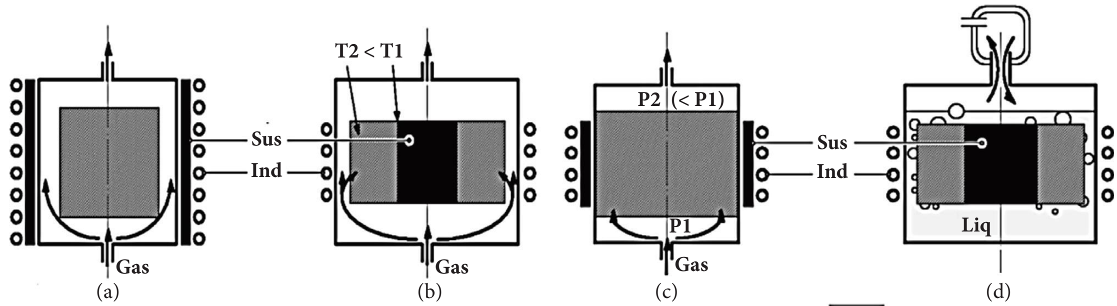

Figure 1: Representation of various types of CVD processes. (a) Isothermal-isobaric CVD. (b) Thermal gradient CVD. (c) Pressure gradient CVD. (d) Film boiling CVD [44].

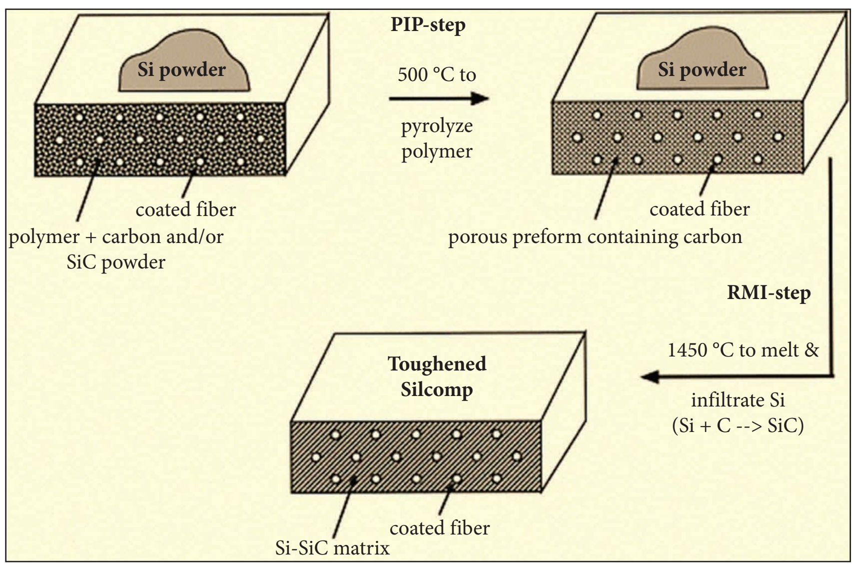

Figure 2: Schematic overview of melt infiltration (MI) [52].

the resulting composite, along with mechanical behavior, was investigated. The composites consisted mainly of the ZrC, Carbon, and Zr_2Si phases. The phase composition and microstructure significantly influenced the preform density. Initially, flexural strength increased with higher preform densities but then reduced. The highest flexural strength achieved was 241 MPa at 1.28 g/cm^3 preform density [54]. The production of SiC-matrix/SiC-fiber CMC, one of the most popular CMC materials, was described in [55]. The process involved CVD of the uncoated fiber tows, followed by impregnation in the matrix and winding on a wet drum. These fiber tows were assembled in plies and cut, stacked in a mold, and subjected to high temperatures and pressures in an autoclave. Afterwards, the preform was introduced into an oven to undergo the process of pyrolysis.

Silicon was then infiltrated into the porous preform through capillary action, resulting in the formation of SiC. Gao et al. prepared Silicon Carbide whiskers (SiC_w) reinforced-SiC CMC with several desirable properties, including isotropic strength, toughness, low cost, and shorter manufacturing process by implementing a combination of gel casting (GC) and RMI method. The SiC whisker preform was prepared by gel casting, a fabricating technique used to manufacture complex structural shapes possessing superior moldability. PIP was done on the SiC_w preform to prepare SiC_w/C as the RMI carbon source. Thermally annealing SiC_w/C materials enhanced the graphitisation level in carbon, making it easier for carbon to react with liquid silicon during the RMI process.

Additionally, by changing the SiC_w content and adjusting the relative proportions of SiC phase and remaining carbon, the carbon content in the SiCw/C composites could be optimized. After the RMI process, this optimization achieved a favourable combination of fracture toughness and bending strength [56]. A CMC fabrication process based on the C/C-SiC system was developed using additive manufacturing. Continuous carbon fibers were placed using automated fiber placement in a polyether ether ketone matrix to create a consolidated printed preform. Pyrolysis converted the polymer matrix into porous carbon, and reactive melt infiltration introduced Si to convert a small amount of carbon into silicon carbide. The resulting C/C-SiC composites had a 10–20% porosity flexural strength of 234.91 MPa, a Weibull modulus of 3.21, and exhibited toughness with significant displacement before failure [57]. Gao et al. utilized RMI to incorporate Si-Y eutectic alloy into a porous C/C preform, fabricating a C/Si-Y-C composite. The distribution and the phase composition within the composites were studied. Considering the reaction between the Si-Y alloy and C/C preform and conducting microstructural observations, a model was suggested to elucidate the microstructure formation mechanism during the reaction process. Additionally, the C/Si-Y-C composite enhanced flexural strength, thermal diffusivity, fracture toughness, and thermal conductivity compared to the C/C-SiC composite [58].

2.3.3. Additive Manufacturing (AM). AM technology is a production procedure for CMCs in which solid parts are created by depositing binders and powders layer by layer, forming a three-dimensional model. This process involves various fields, such as material science, manufacturing technology, computer science, and information technology. In contrast to conventional manufacturing methods, additive manufacturing facilitates the control of microstructures in the manufactured parts and enables the creation of geometric shapes without the need for molds [59]. Additive manufacturing techniques have been applied in many industries such as aerospace, military, electronics, automotive, medical, and more. These technologies offer significant benefits, such as minimizing or eliminating the need for secondary processing of CMCs parts, reducing development time, lowering costs, and enhancing part yield. Due to their hardness and brittleness, fabricating CMCs through conventional methods is challenging. As a result, additive manufacturing has gained popularity in the manufacturing sector [60]. Different kinds of additive manufacturing technologies facilitate exceptional forming capabilities while fabricating CMCs. Some of them have been discussed in this section. The conventional method for 3D printing ceramics involves using a feedstock that comprises organic polymers and ceramic particles. This technique gives researchers more design freedom in customized production for manufacturing complex geometries [61].

(1) Direct Ink Writing (DIW). DIW technology (Figure 3) is better for printing CMCs toughened by particles, short fibers, or whiskers [63]. This simple, adaptable, cost-effective approach can be applied to various materials, including ceramics, polymers, and alloys [64]. It involves extruding a non-Newtonian viscous slurry of liquid and solid phases for printing at room temperature. By utilizing ceramic slurries with viscoelastic properties, it becomes possible to produce parts that can conserve their original shape regardless of the pressure exerted by newly deposited layers. These slurries typically contain a high concentration of ceramic particles and suitable additives and binders. This technique makes manufacturing structures of varying configurations feasible, ranging from complex parts with interconnected cavities to composite materials, filaments with diverse cross-sectional shapes, and solid monolithic components [65]. Franchin et al. used DIW followed by subsequent pyrolysis of preceramic ink embedded with short fibers to fabricate CMCs [63]. Fiber-reinforced ultra-high temperature ceramic matrix composites (UHTCMCs) containing Zirconium diboride (ZiBr2), chopped SiC short fibers, and SiC precursor polymer were manufactured by DIW. DIW enabled complex shapes with preferential alignment of fibers to be fabricated [66].

(2) Selective Laser Sintering (SLS). In SLS (Figure 4), selective sintering of powders to form parts is carried out using a laser. It utilizes a laser beam to create layered 3D objects. It involves fusing powder layers with a high-power laser, removing unfused powder, and achieving a structured formation by melting and fusing the powders [67]. SLS is a widespread technique with significant potential for manufacturing various CMC parts. Despite its advantages, SLS-produced components still have notable drawbacks, such as high porosity, inferior mechanical properties, and relatively low densities.

Nevertheless, the SLS process is relatively speedy due to thick layer printing, making it a reliable additive manufacturing technique for creating porous composite parts suitable for catalyst supports, heat exchangers, and bone scaffolds [61]. SLS can be categorized into direct SLS (dSLS) and indirect SLS (iSLS). The laser was used to sinter composite powders containing ceramic materials with a low melting point in dSLS. However, the ceramic obtained through this process cannot withstand thermal shock. This means that cracks can easily develop when forming parts due to thermal stress caused by high temperatures and rapid cooling. In iSLS, a polymer is employed as the binder for the composite powder. iSLS offers the advantage of using a wider range of forming materials than direct SLS. The processing technology in iSLS is easily manageable but requires a longer processing period and involves several posttreatments. These treatments include pyrolysis, removal of the organic binder, and high-temperature sintering of the parts [68]. Shishkovsky et al. determined that selective laser sintering yielded CMCs with desired dense structure and stabilizing phases with uniform distribution. This composite could be used in various applications, including electrical and thermal insulators and water-resistant coating in crucibles, medical tools, fuel cells, and heating elements [69].

(3) Laminated Object Manufacturing (LOM). LOM (Figure 5) refers to AM technique where layers of paper sheets consisting of adhesive coated on one side are continually joined and shaped into a three-dimensional (3D) object using a laser cutting process. The material used for building is supplied in either roll form or as sheet-stock, and a heated platen or moving roller is used to apply pressure and enhance the bonding between the layers. The primary distinguishing characteristic of LOM is its ability to create complex 3D components with reduced manufacturing requirements and lower expenses for postprocessing [70]. LOM composite fabrication relies on creating composite laminates, which involve the production of particulate or fiber-reinforced sheets. The sheets are then processed further to fabricate composites. Alternatively, composites can be formed via infiltration of the preform after removing the binder through a burn-out cycle. The application of pressure

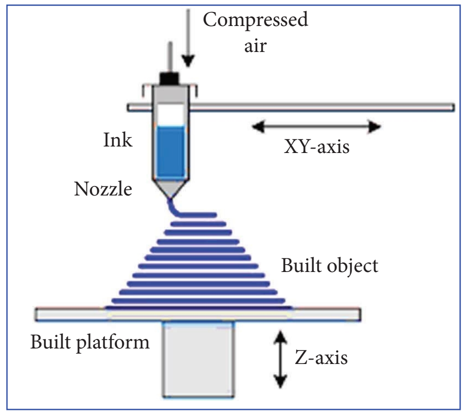

Figure 3: Direct ink writing (DIW) process illustration [62].

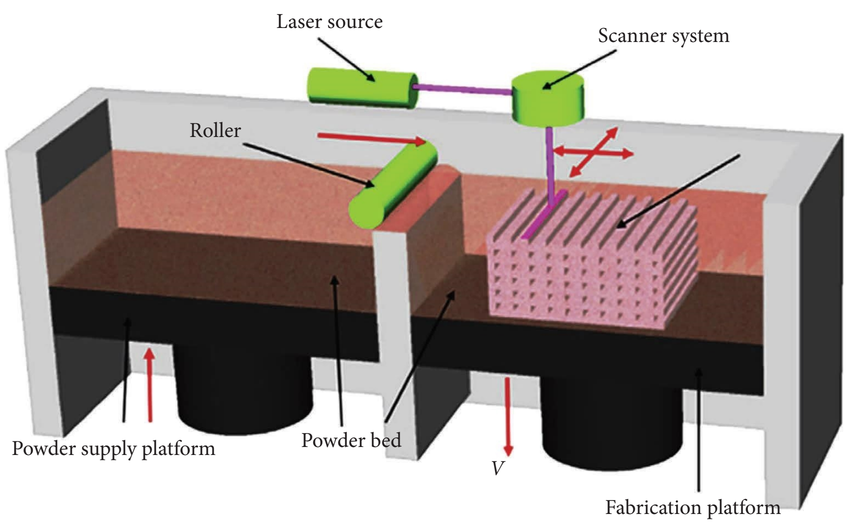

Figure 4: Selective laser sintering (SLS) [67].

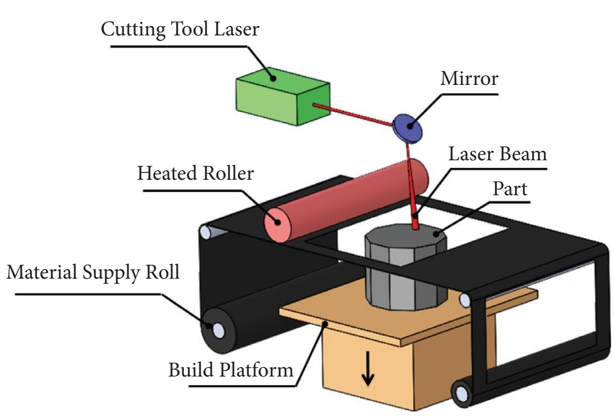

Figure 5: Laminated object manufacturing [70].

during the binder burn-out cycle helps to prevent delamination. This can be achieved by utilizing a uniaxial press within a closed chamber containing LOM parts coated in silica powders. Adding powder aids in distributing pressure uniformly and removing the degraded binder [71]. Zhang et al. used a roll-forming method to create 0.7 mm thick green tape ceramics made of Al_2O_3. They used LOM to shape the green ceramic components. The end products were then generated through a pressure less sintering process [72].

(4) Stereolithography (SLA). Stereolithography (Figure 6), or SLA, utilizes photopolymers which can be solidified using a UV laser. The UV laser is precisely directed along the required path to target the resin reservoir, causing the photocurable resin to undergo polymerization and form a 2D patterned layer. The platform is lowered as each layer is cured, and a new layer of uncured resin is prepared for patterning. Commonly employed polymer materials in SLA include epoxy resins and acrylic. SLA printing technology's key advantage is its ability to produce high-resolution parts.

Furthermore, since SLA is a technique that does not involve nozzles, issues such as nozzle clogging can be prevented reasonably. However, the high cost is the major challenge regarding its application in the industrial sector [74]. A thorough comprehension of the curing reactions during polymerization is crucial for maintaining control over the quality of the printed parts. Printing resolution and the curing time are influenced by laser power intensity,

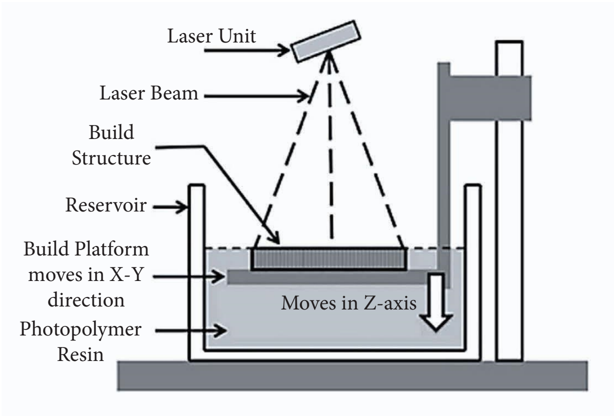

Figure 6: Schematic illustration of stereolithography [73].

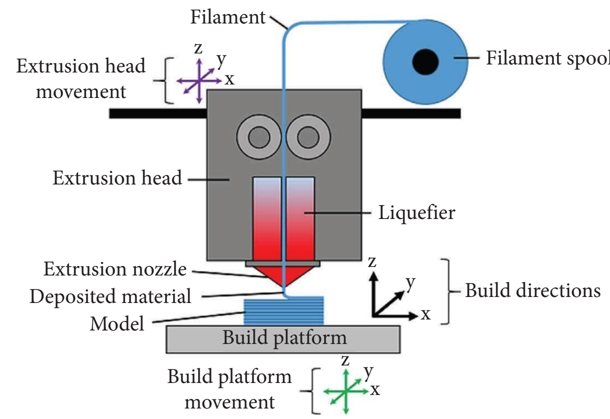

Figure 7: Fused deposition modelling [77].

exposure duration, and scan speed [75]. SiOC polymer-derived ceramic composites filled with SiC microwhiskers were fabricated by Brinckmann et al. using stereolithography to cross-link the resin with the whiskers. It was seen that the hardness and density increased with the incorporation of SiC [76].

(5) Fused Deposition Modelling (FDM). FDM (Figure 7) is a method that is generally implemented for conceptual models, engineering components, and prototypes. Process parameters used in FDM dictate the product's final characteristics such as strength, porosity, and surface finish [78]. The initial stage of producing an FDM object contains creating a computer-aided design (CAD) model of the object, which is subsequently utilized by a printer for printing. The printer's extruder head pulls a spool of printing filament and directs it through the extrusion nozzle, pushing the partially melted filament onto the printer platform. The extruder head can move along the *x*, *y*, and *z* axes. After completing each two-dimensional layer, the extruder moves vertically (*z*-direction) to add another layer. The partially melted state of the filament enables the adjacent layers to merge, forming a solid 3D structure [77]. Singh et al. used FDM to develop Al_2O_3-based functionally graded material with a relatively harder surface and soft core inside [79].

The characteristics of different additive manufacturing techniques are summarized in Table 2.

3. Properties of CMCs

Ceramic matrix composites possess many advantageous properties such as high-temperature stability, high thermal shock resistance, high hardness, high corrosion resistance, light weight, non-magnetic and non-conductive properties, and versatility in providing unique engineering solutions. The combination of these characteristics makes ceramic matrix composites attractive alternatives to traditional processing industrial materials such as high alloy steels and refractory metals.

Some of the properties of ceramic matrix composites have been described in the sections below.

3.1. Mechanical Properties. Although CMCs are not equal to MMCs in the case of mechanical characteristics like hardness and strength, many of their mechanical qualities came to light in various complex conditions where they were more helpful than metal matrix composite. For example, their weight-to-strength ratio made them both durable and lightweight, and their high stiffness made them eligible for dimensional stability type operation. From time to time, these qualities were studied and were changed, enhanced, or reduced for other research or industrial purposes.

Ran Mo et al. tested the mechanical efficiency of SiC_f/Si_3N_4 composite and found a greater bending strength of 380 MPa, whereas fracture resistance was 12.9 $MPa{\cdot}m^{1/2}$ [87]. GNPs being used as supports can successfully increase the mechanical characteristics of CMC ingredients, including resilience to strain, fracture, and strength. This is accomplished by relying on processes for toughening [6].

With increased SiC concentration in SiC-reinforced nano-Al-matrix composites, sintered composites' relative density dropped but rose with increased firing temperature. The mechanical characteristics, particularly the fracture strain, improved due to the increased SiC concentration and sintering temperature. Composite Al-8wt% SiC sintered at 570°C had a hardness, compressive strength, and bulk modulus of 885.4 MPa, 276.2 MPa, and 135.9 GPA, respectively [88]. Arai et al. found that fracture toughness rises when carbon fibers are added to ceramic composites with carbon fiber reinforcement for extremely high temperatures. A weak interphase must occur to boost the composites' ability to withstand fracture. This is because touch causes fractures to deflect, avoiding the concurrent fracture of the matrix and fibers [89]. New composites have been designed to enhance the application and simplicity of hard-to-machine CMCs. They may be fabricated using the B_4C, Si_3N_4, and SiC matrices without significantly sacrificing their other good features. In situ generated CNTs initially caused a minor reduction in mechanical characteristics in SiC-based materials. However, this reduction was negligible. Due to persistent porosity, Si_3N_4-GNP composites also saw a drop in hardness. Hardness in B_4C-GNP composites was mostly unaffected by the GNP

Table 2: Characteristics of different additive manufacturing techniques.

Additive manufacturing technique	Characteristics	Ref
Direct ink writing	Accuracy and reliability: DIW supports the production of complex structures without the need of additional masks or dies. However, it takes a long time to fabricate large and complex structures The resolution of printed fibers and patterns is constrained by printing parameters like nozzle diameter and the maximum flow path of the nozzle. DIW also suffers from low processing efficiency, low precision, and significant anisotropic properties.	[80, 81]
	Mechanical properties: DIW-printed structures often demand postprocessing treatments such as drying or sintering in order to enhance their mechanical properties.	[80]
	Tribological properties: The properties of the ink used in DIW play an influential role in determining the mechanical and tribological properties of the final product. The inks should possess good rheological properties, mechanical strength, and mechanical stiffness.	[81]
Selective laser sintering	Accuracy and reliability: Limited research has been conducted to develop a method for producing dense ceramic parts without cracks using selective laser sintering (SLS). This is primarily due to the considerable challenges posed by ceramic materials, such as their exceptionally high melting point, limited thermal shock resistance, and lack of plasticity, which complicates the application of SLS technology in comparison to polymers and metals.	[82]
	Mechanical properties: It is challenging to prevent easy cracking in parts fabricated via direct SLS because of thermal stresses occurring during sintering, resulting in subpar mechanical properties in the final products. Hence, opting for the indirect SLS method could be a suitable approach for creating crack-free samples.	[82]
Laminated object manufacturing	Accuracy and reliability: LOM ensures superior printing resolution compared to other additive manufacturing techniques. Unlike other additive manufacturing (AM) methods, LOM can handle a diverse range of raw materials without the need for toxic chemicals or intricate chemical reactions.	[83]
	Mechanical properties: Previous studies indicate that items manufactured using LOM exhibit a capacity to endure greater deflections compared to items produced using alternative layer manufacturing methods. Predicting the final surface roughness of LOM components is relatively straightforward, making it a notable advantage in comparison to other additive manufacturing methods.	[84]
Stereolithography	Accuracy and reliability: SLA technology not only delivers a smoother surface finish but also enhances precision during production. Additionally, it has a relatively fast build-up speed.	[61, 85]
	Mechanical properties: the utilization of 3D printed structures through SLA is constrained by imprecise dimensional control and subpar mechanical properties.	[86]
Fused deposition modelling	Accuracy and reliability: FDM is a very popular additive manufacturing method across diverse manufacturing sectors due to its dependable nature, cost efficiency in creating 3D objects with high resolution, stable dimensions, extensive material customization, straightforward fabrication process, and capability to safely produce complex geometric parts within favourable conditions. FDM technology exhibits great flexibility and seamless integration with computer-aided design (CAD) software packages.	[78]
	Mechanical properties: a comprehensive examination of process parameters and their interplay, along with the correlation between multiple parameters, is essential for enhancing understanding regarding the mechanical and material characteristics of parts produced through FDM.	[78]

concentration and was controlled by residual porosity. The figures below show CNT and GNP's effect on the composite [90].

3.2. Thermal Properties. Several uses make CMCs appealing such as gas turbines, aerospace constructions, thermal management systems, and high-temperature processing machinery due to their thermal characteristics. Remembering that specific attributes may change based on the composite's composition, processing strategy, and particular ceramic fiber and matrix types is vital.

The composition of the SiC matrix and fiber is exactly stoichiometric and has grains close to 500 nm in size. So, there should not be a problem with their innate strength and microstructural stabilities under no stress spanning hundreds of hours at temperatures that exceed no less than

1600°C. A SiC/SiC component will deform or creep because particles in the underlying microstructures will begin to move through under stress. Depending on the grain boundaries' impurity phases, this creep might begin as early as 1100°C [91]. Wang et al. saw that when an Al alloy is present in the spaces between the SiC CMCs, the thermal stress is reduced, which stops fracture nucleation and uses up the propagation energy to stop cracks from spreading [92].

As the fiber volume percentage rises, the thermal conductivities of Cmil/UHTC (milled carbon fiber = C_{mil}) and Csf/UHTC (short carbon fiber = Csf) composites fall in the direction through the thick. This was due to the matrix's fiber interface's function as a thermal conduction barrier. Anisotropic thermal characteristics are demonstrated using 2D-woven C_f/UHTC composites. In-plane and out-of-plane 3D-braided Cf/UHTC composites have somewhat different heat conductivities [89]. Reza et al. experimented with Al composite reinforced with SiC content and found that increasing amount of SiC of 20 wt% vol. reduced both thermal expansion coefficient and thermal conductivity by 14.8 ppm/K and 61.5 W/m·K for crystalline defects enhanced in phase boundaries [93].

3.3. Electrical Properties. CMCs are better known for their thermal attributes than any other matrix composite. But much research has been conducted to exploit their various electrical capabilities, such as electrical resistivity, dielectric constant, dielectric strength, and piezoelectricity. Due to the ceramic's materials, CMCs have high dielectric strength and constant. These electrical characteristics of a ceramic matrix can vary in the presence of any special composition of other materials or coatings.

Researchers found that compared to the SiC/C/SiBC composite, the initial resistivity of the SiC/BN/SiC-Si composite is ten times lower, most likely due to the substantial fraction of conductive silicon present in the matrix as opposed to the amount of C in the case of the SiC/C/SiC composite. In line with what was predicted based on the values of its components, the resistivity of the C/C/SiC composite is 105 m lesser than that of the other two materials [94]. Pavol et al. summarized several ceramic samples and concluded that a functionalized conducting ceramic could be created from an insulator by adding small amounts of CNFs or CNTs, greatly increasing the electrical conductivity. The separation happened at 1% CNF in ZrO_2, but 3%–5% CNT in Si_3N_4 and 2–5% CNT in Al_2O_3 were required. This suggests that higher CNFs were more effective here [95]. The SiC_f/Si_3N_4 composite exhibited outstanding EMW absorption capabilities regardless of its extremely poor conduction (its conduction loss makes up around 33% of the total dielectric loss), having an RC of 0.7 less than −7.2 dB for the whole X band and a relative intricate permittivity of about 9.2–6.4 at 10 GHz. Its great polarization relaxation loss ability and low comparative complex permittivity better match the impedances of composites and air, allowing it to take up more EM wave energy [87]. Although SiC-reinforced nano-Al-matrix composites exhibited much enhancement in mechanical efficiency, the conductivity of the composites decreased as the SiC particle fraction in the Al matrix rose, depicted in Figure 8, such as when the SiC concentration increased from 0.0 to 8 wt%, the conductivity of the composites burnt at 400°C reduced from 3.41×10^7 to 2.62×10^7 S/m. However, it increased with cumulative sintering temperature to 500 and 570°C [88].

Due to the interfacial polarity and dipole caused by the stuffing and the thermal growth of the PVDF (poly (vinylidene fluoride)) matrix and ceramic, the dielectric constant increased with temperature and ceramic filler quantity. According to the results, the PVDF matrix's inclusion of ceramic filler atoms considerably impacts the polarization response. However, the piezoelectric coefficient rose when more ceramic filler was added [96]. Two crystalline forms of boron nitride (BN) are hexagonal boron nitride (h-BN) and cubic boron nitride (c-BN) where structure and properties of h-BN are similar to those of graphite, with adjacent layers bonded together by weaker van der Waals forces and boron and nitrogen atoms bonded together by strong sp2 covalent bonds. This crystal structure of h-BN possesses multiple qualities, such as strong thermal conductivity, oxidation resistance, low dielectric coefficient, and great thermal shock resistance [97].

3.4. Wear and Tribological Properties. CMCs are used in challenging circumstances. Therefore, their resistance to friction, wear, and lubrication is crucial. Friction slows relative motion and produces energy loss in the system. Lubrication is commonly utilized in tribological systems to provide a material with reduced shear strength between surfaces, decreasing friction and wear while preserving load. Ceramic wear is significantly influenced by factors such as normal load, motion velocity, and the atmosphere [98]. The characteristics of the interfaces involved have a direct impact on CMC behavior. Damage in CMCs, for example, manifests as microcracking in the matrix [99].

Furthermore, fracture toughness is key to determining engineered ceramics' tribological features. Ceramics' friction coefficient reduces as fracture toughness increases. Fracture increases friction by providing a different mechanism for energy dissipation at the sliding contact.

Ceramics, as compared with metals, are more prone to brittle fracture in response to stress. Crack formation in ceramics containing oxide substances is subject to environmental variables that influence the plastic flow by impacting surface dislocation through the mobility of wear. This kind of chemical-mechanical effect is called the Rehbinder effect [100]. Interacting ceramic-based composites with the surroundings to produce tribochemical oxides is a key factor influencing tribological behavior. This is especially essential in ceramics with no oxygen compound like TiB_2. Tribochemical corrosion in ceramics is a form of oxidative wear closely related to the tribological process's surface chemistry and physics [101].

Zirconia (ZrO_2), alumina (Al_2O_3), and silicon nitride (Si_3N_4) are the most utilized ceramic materials. For ceramics to be used successfully as triboelements, a complete

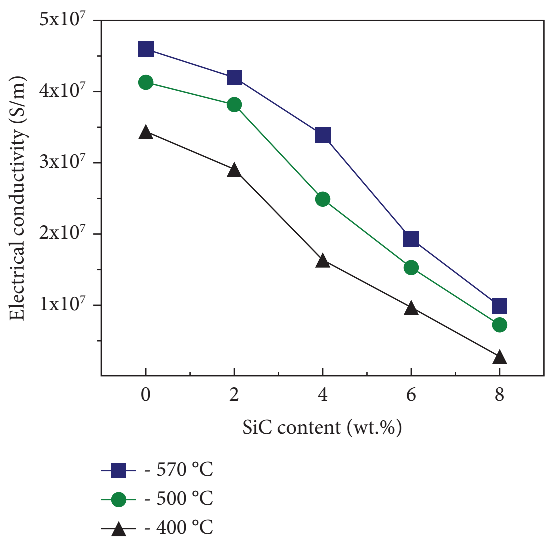

Figure 8: Al-SiC composites deposited at various sintering temperatures in terms of electrical conductivity [88].

understanding of their tribological behavior is essential. Ceramic materials offer great thermal strength and stability, making them appropriate for high-temperature technical applications. However, their high friction poses a challenge. Lubricating CMCs are being researched to enhance efficiency in engines with ceramic components at extreme temperatures [102]. Kong et al. developed a zirconium oxide that is a self-lubrication matrix composite by incorporating eutectic BaF_2/CaF_2 and Mo as lubricants. They tested from ambient temperature to 1000°C. The results revealed that eutectic 5 wt% BaF_2/CaF_2 and 10 wt% Mo (ZFM10) had the best self-lubrication and wear-preventing features [103]. Using spark plasma sintering, tribological characteristics were observed by Ouyang et al. The same matrix composites are prepared by doping them with various solid lubricants. The gamut of temperature varied from ambient to 800°C, and the composites containing $SrSO_4$ had a less than 0.2 steady-state friction coefficient and a $10^{-6}\,mm^3/Nm$ wear rate. Lu et al. investigated two distinct techniques for producing $ZrO_2(Y_2O_3)$-Al_2O_3-graphite composite powder. The results revealed that mechanical milling was superior to direct powder doping milling for wear and tribological properties [104].

Zhou et al. observed that fiber orientation affects the tribological behavior of CMCs. Reinforced CMCs spot the tribological performance with carbon fibers (C/C-SiC). The 45° fiber orientation of the brake pads yielded the highest performance among others [105]. Wei et al. [106] compared the tribological response of C_f/SiC composite with the varied direction of fibers (Figure 9). They also sought ZrO_2 behavior on polished and ground surfaces. The sliding behavior was more efficient at each fiber orientation than on polished surfaces. The most excellent tribological property is 90° oriented fiber sliding against the pad's ground surface material in disc brakes, which affects the tribological features of this type of composite. The form of the pad material influences the friction coefficient. The coefficient of friction can be affected by even minor alterations in the pad material composition [98].

Ceramic composites with aluminium as matrix material have enhanced mechanical and chemical characteristics. The tribological characteristics of these composites supplemented with alumina material (Al_2O_3) are remarkable. However, the lubricating qualities of aluminium-based ceramic composites must be improved. Zhang et al. used graphene platelets to strengthen a WC-Al_2O_3 ceramic composite. Utilizing ball-on-disc dry sliding, this modification lowered the friction coefficient by 40% under 40 N and 33% under 60 N and the specific wear rate (from 1.21×10^{-5} to $1.32 \times 10^{-6}\,mm^3 \cdot N^{-1} \cdot m^{-1}$, under 40 N; from 2.18×10^{-5} to $6.72 \times 10^{-6} mm^3 \cdot N^{-1} \cdot m^{-1}$, under 60 N) [107]. Aluminium ceramic composites with 5% alumina (Al_2O_3) and 5% molybdenum disulphide (MoS_2) produced by powder metallurgy showed considerable increases in tribological performances. However, adding more MoS_2 to the compound composite does not necessarily boost its tribological properties [108]. The thickness and spacing parameters of Al_2O_3/Mo laminated composites affect their sliding friction and wear characteristics. These composites exhibit a friction coefficient like pure Mo, enabling a layer of oxide lubrication (MoO_3) generation. Additionally, friction stability tends to improve with the thicker layer of structural molybdenum [109].

Ceramic silicon nitride can be used as turbine and engine combustion section structures. Its application is valid due to its high strength and toughness during high temperatures. These properties of silicon nitride allow them even to replace metals for structural applications for high efficiency. Adding graphene nanoplatelets to silicon nitrite matrix-based nanocomposites improves their wear and friction characteristics. The wear resistance of materials is maximum when large nanoplatelets of graphene are used [110]. Carbon fibrous phases in CMCs benefit through a reduced coefficient of friction (COF). However, for Si_3N_4, a certain quantity of carbon (5 wt%) is required for wear resistance [89]. Adding hBN to Si_3N_4/hBN ceramics did not affect the friction coefficient. However, the wear resistance improved when the micro-hBN powder was introduced to the Si_3N_4 matrix [111]. SiC ceramic tribology can be categorized into sliding and erosion wear. It is commonly recognized that deflection in fractured or cracked sections in the reinforced phase decreases material loss during SiC composite sliding wear. Furthermore, the brittleness index, a ratio of hardness to fracture toughness, is discovered to provide a qualitative estimate of wear for SiC ceramics. The erosion wear of ceramics mainly depends on second-phase features such as physical layout, energy dissipation, and durability [112].

3.5. Biocompatibility. CMCs have several biocompatible features that allow them to be implemented on various biomedical tools. Their chemical inertness, low toxicity, and biostability make them appropriate for various applications [113]. Ceramic minerals, particularly HA, are the primary inorganic elements of natural bone. CMCs have significantly

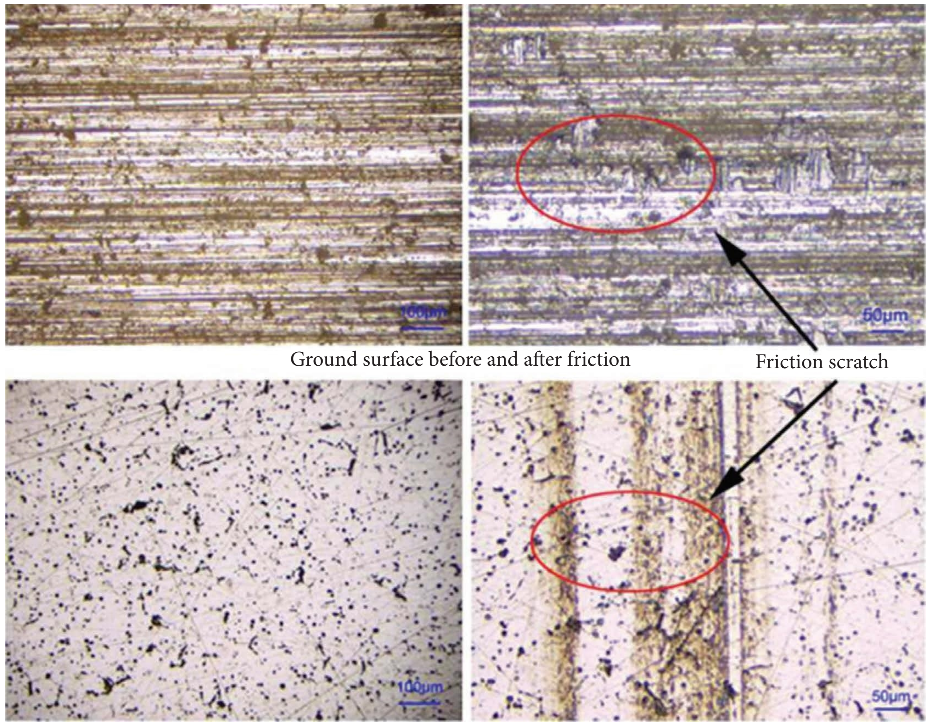

Figure 9: Surface microstructures of the disc before and after friction [106].

advanced bone tissue engineering scaffolds [114]. Bioceramic HA implants only bind to bone and bond thickness of bone implants less than 1 μm. Because of the narrow bonding surface of HA implants, the elastic modulus gradient between biological and non-living materials is substantially higher [115]. Several studies have attempted to reinforce HA with GNPs to enhance HA's poor mechanical characteristics, particularly its low fracture toughness [116]. Because of their exceptional biocompatibility, carbon/carbon composites can be installed in the human body to repair bone fractures. Their elastic moduli are similar to human bones, making them extremely promising for hard bone tissue replacement. Nonetheless, their applicability is restricted due to their biological inertness, hydrophobic nature, and carbon debris leakage while implanted in human bodies. Several investigations have shown that a bioceramic coating such as Ca-P on the C/C matrix may elude previously discussed limitations [117].

4. Joining and Machining of CMCs

Due to their innate hardness and abrasiveness, CMCs can be difficult to machine conventionally. Advanced ceramic materials reinforced with fibers, or CMCs, are frequently employed in high-temperature, high-performance applications where conventional metals are not appropriate.

There are various material removal processes (Figure 10) used in mechanical machining, such as drilling, milling, and grinding. During the cutting of orthotropic brittle materials, they significantly impact the external environment by producing varied break signs and a mix of brittle and ductile behaviors. The laminated structure of CMCs could result in the delamination of the sample's internal water jet. Hence, safety measures, such as ramping the pressure in the setup, may need to be initially researched [33].

4.1. Conventional Machining. Conventional machining is the standard method employed for reshaping CMCs to achieve specific geometric or assembly specifications. In this segment, various machining techniques that involve mechanical material removal using a tool are examined. The grinding, milling, and drilling procedures are elaborated upon in distinct sections.

4.1.1. Grinding. CMC is an example of a material that is challenging to manufacture. Harder cutting tools are needed because of the material's high hardness and great resistance to wear. Grinding with a diamond wheel is the most popular method for achieving the appropriate surface polish and dimensional accuracy for ceramic and CMC items. Such a machining procedure can be quite expensive, which raises the cost of production. The schematic diagram for the grinding procedures is shown in Figure 11. A dynamometer that was attached beneath the workpiece and above the surface grinder's worktable was used to measure the grinding forces. The analogue signal was amplified and converted into a digital signal via a charge amplifier and a collection card. The computer eventually recorded and presented the grinding signals [1].

In addition to diamond, other materials used as grinding and turning tools include ceramics, coated and polycrystalline cBN (PcBN), tungsten carbide, and cubic boron

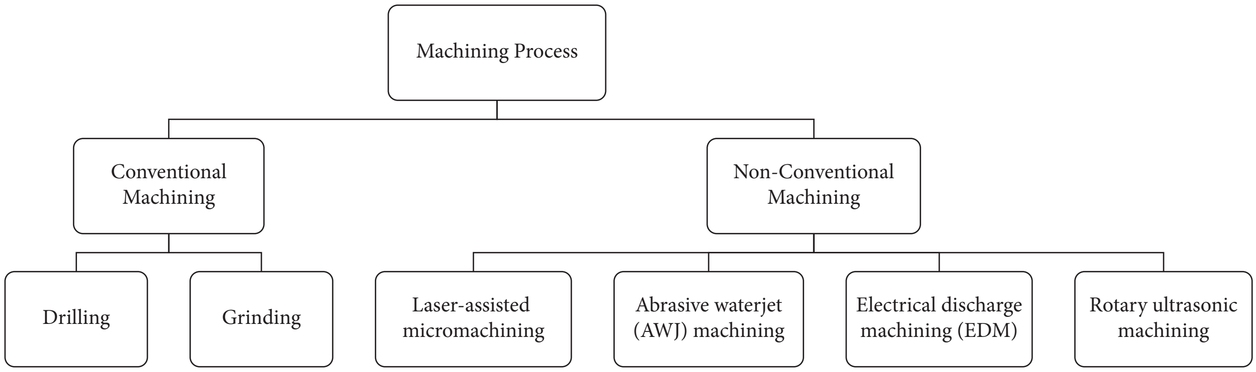

FIGURE 10: Various machining processes of ceramic matrix composites (CMCs).

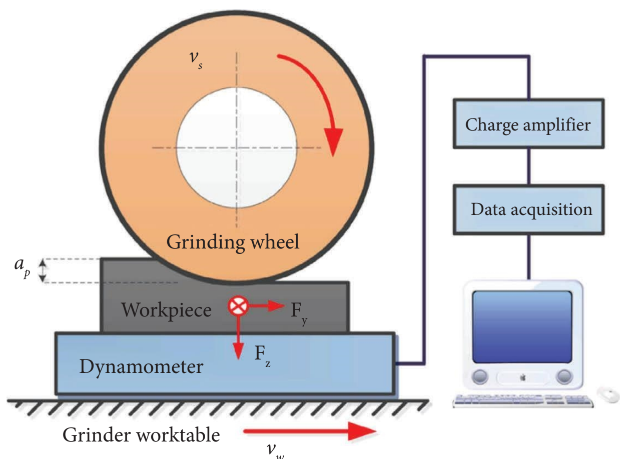

FIGURE 11: Schematic of diamond grinding process [118].

nitride [119]. Researchers are now concentrating on the grinding force, fiber removal mechanism, and surface quality in CMC grinding. As shown in Figure 12, brittle fracture is the main material removal mechanism in grinding based on fiber direction. Zhang et al. studied the experimental examination of the surface grinding procedure for woven unidirectional CVI-C/SiC composite in three typical orientations. The findings demonstrate that the reinforced fiber orientation significantly impacts the grinding of the woven CMC. The surface roughness and grinding force of woven composites can be anticipated based on the results. The feed speed and depth of cut during the grinding operation affect the grinding force and surface roughness [118].

Burrs, microcracks, and residual stress are defects that frequently occur during the cutting and grinding process, reducing the processing effectiveness and output rate of CMC components [60]. Weinert et al. reported that the C/C-SiC substantially under examination exhibits quasi-ductile actions. This indicates that compared to other ceramics, this ceramic exhibits more ductile behavior under stresses, yet the same material is brittle during machining and grinding. Some studies have focused on the machining defects depicted in Figure 13, caused by material removal on carbon fibers. The advantages of employing a tool with electroplated coatings were also demonstrated [99]. Qinglong et al. found machining defects where 0-degree needled fibers had a brittle lamellar fracture, while 90-degree fibers had a brittle fracture and other failure mechanisms such as pull out of fiber, which all generated craters on the fabricated surface of the 3D needled C_f/SiC composites [100].

When grinding along and transverse to the fiber longitude direction, low-speed grinding does not show any promising result as fibers get ploughed and covered in the smearing of the matrix. When the speed increases, fibers show brittle nature and matrix is torn off, showing an improved surface finish. It also improves the material removal rate of SiC_f/SiC [121]. Figures 14(a) and 14(b) depict the impact of grinding speed on the surface of SiC ceramic matrix composites. The quality of the machined surface was unsatisfactory due to the presence of numerous long matrix cracks, and the surface morphology appeared rugged [120].

4.1.2. Drilling. Drilling uses a drill or reamer tool to enlarge holes in mold pieces on a drilling machine. Several academics have studied the drilling force and quality of drilled holes to machine ceramic-reinforced composites. Some commonly used diamond drills are shown in Figure 15. Pertinent theoretical drilling force and torque research has been involved in this context. Some specifically designed electroplated diamonds are suggested for drilling these composites to improve the quality of drilled holes and compensate for the deficiencies of other cutting tools. Because of their low hardness, conventional tools like cemented carbide drilling tools cannot be used to drill C/C-SiC. Additionally, drilling of CMCs procedure is not appropriate for tools with particularly hard polycrystalline diamond (PCD) cutting edges. This is due to rapid wear of the tools, which makes the hole quality inconsistent. In CMC machining, a metallic-bonded tool exhibits greater resistance to friction than a resinoid-bonded tool.

In drilling unidirectional C/C-SiC using brazed diamond drills, Xing et al. explained the impacts of machining parameters on axial force, tool wear, and machined quality, as illustrated in Figure 16 [122].

When combined with their respective analyses, the delamination of the hole entry and the quality of the

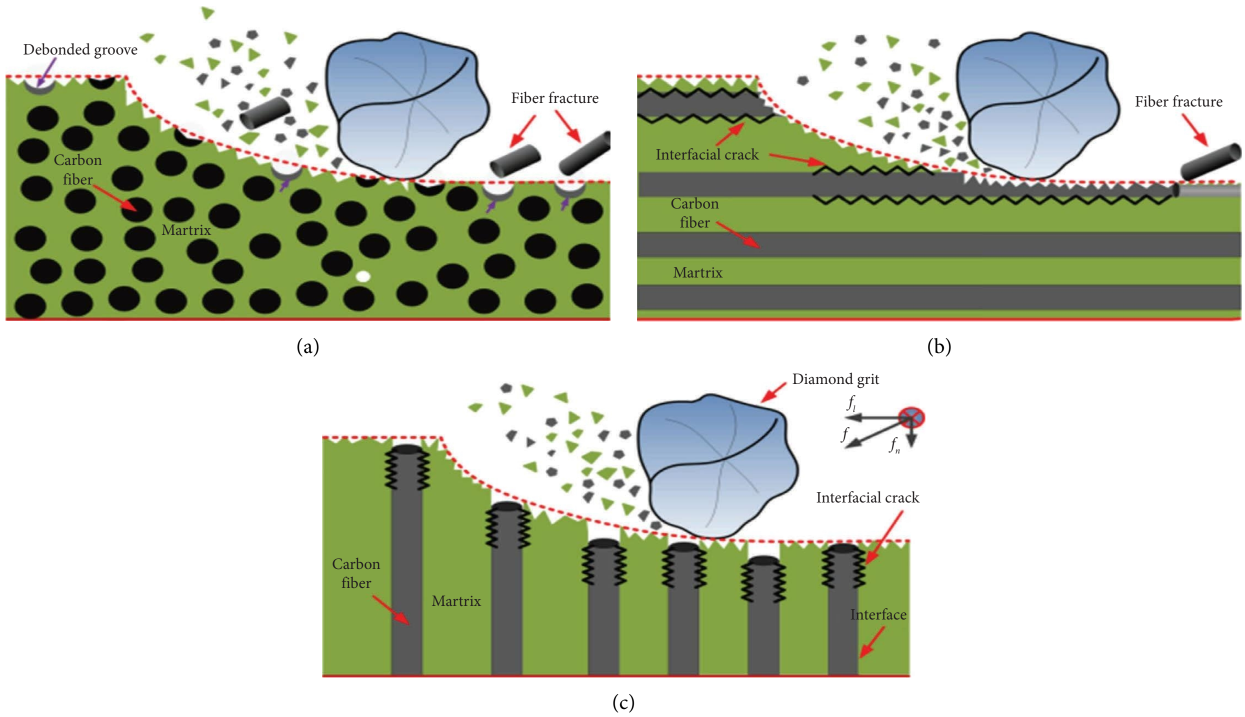

Figure 12: Illustration of the various fiber orientations when grinding CMCs: three types of fibers—(a) longitudinal, (b) transverse, and (c) cross fibers [9].

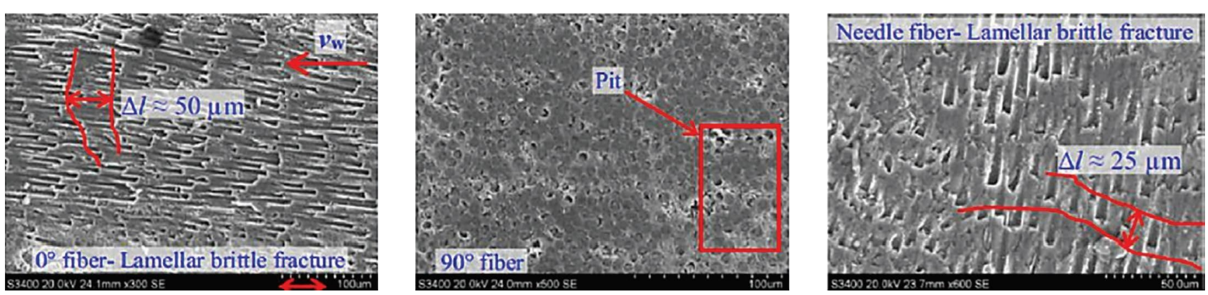

Figure 13: Grinding errors on the surface of 3D needled Cf/SiC composites [9].

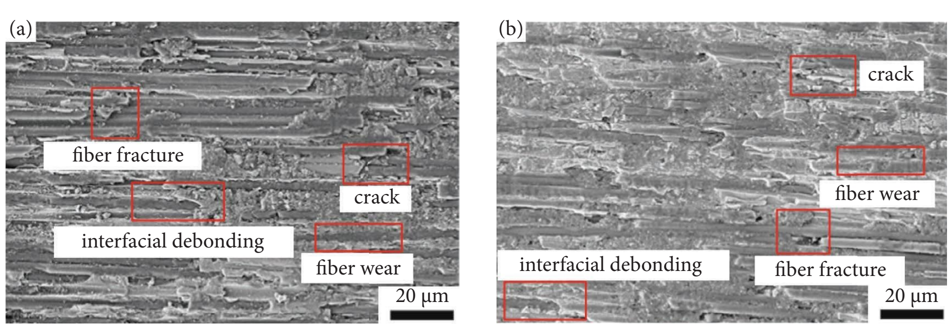

Figure 14: (a, b) Surface morphology SEM photos of parallel/perpendicular direction with the different values of grinding speed [120].

drilled hole had a significant bearing on the drilling direction and fiber orientation. Based on the experimental findings of Xing et al., a graphite plate was used to enhance the quality of the hole exit. It can prevent the workpiece from bending and eliminate damage flaws of the hole exit. The effects of spindle speed, feed rate, feed quantity, and drill diameter on axial force are crucial to the drilling process [123].

The dependability of C/SiC-CMC manufacturing is hampered by tearing errors at the hole exit caused by

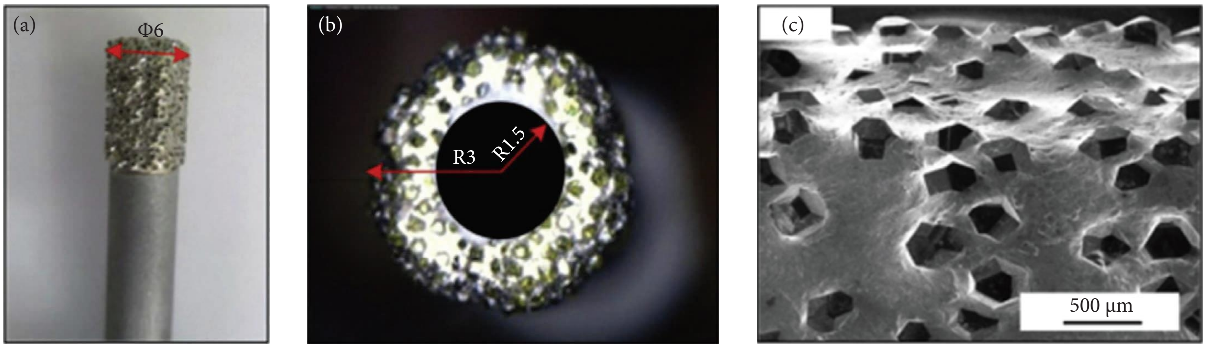

FIGURE 15: Brazed diamond drills [122].

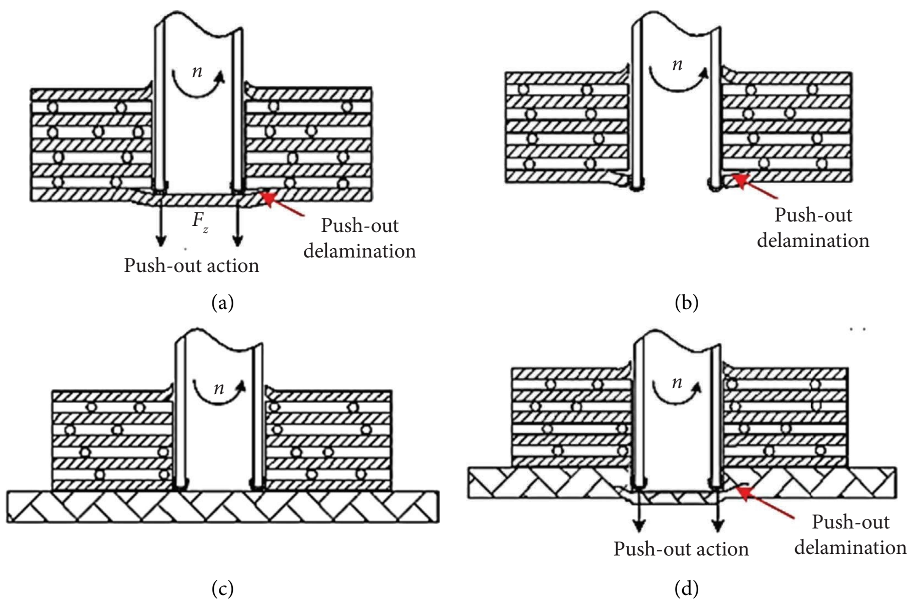

FIGURE 16: The effect of supported graphite plate in drilling: (a) no support, (b) with support, and (c, d) with supported graphite plate [122].

drilling. Figure 17 shows a typical image of hole entrance (to the left) and hole exit (to the right). The drilling-induced tearing faults in rotary ultrasonic machining of C/SiC composites were quantitatively examined in this work by Du et al. They suggested that tearing defects can be further minimized by raising the ultrasonic amplitude and the spindle speed or lowering the feed rate [110].

4.2. Non-Conventional Machining. To get around the problems with traditional machining of composites made of CMCs, unconventional processing methods, also known as quirky or sophisticated machining techniques, are frequently used. These processes remove substances from the workpiece using energy in various ways, and they provide benefits, including decreased tool wear, improved finish on the surface, and the capacity to work with complicated shapes [125].

4.2.1. Abrasive Waterjet (AWJ) Machining. AWJ machining holds promise for cutting tough ceramics like SiC and reinforced materials. The research explored its potential for a mix of ceramic TiB2/SiC, finding it effective for hard

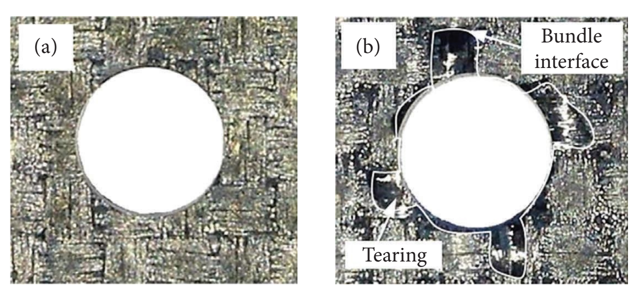

FIGURE 17: Drilling image of C/SiC. (a) Hole entrance. (b) Hole exit [124].

ceramic composites, despite some surface quality issues near the jet exit due to the way the cut tapers and the material's brittleness when thick [126].

In ceramics with long reinforcing fibers, like 2D-woven CMCs, machining becomes more difficult due to their specific fracture properties. Starting the jet within the material (Figure 18(a)) can lead to challenges due to potential cracking or delamination, making edge features more favourable (Figure 18(b)) [33].

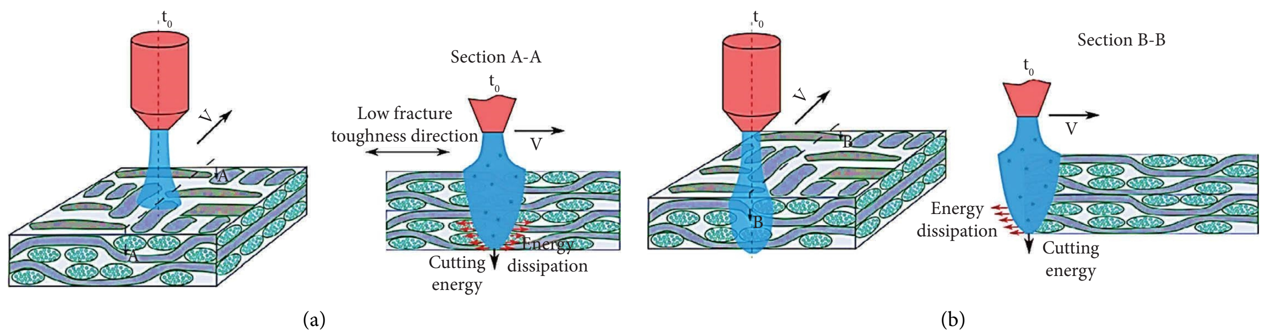

Figure 18: Illustration of how the abrasive water jet (AWJ) behaves while machining tough CMCs. It demonstrates the difference between (a) starting the jet in the center of the workpiece and (b) starting it at the edge [33].

Yet, studies revealed that AWJ could effectively machine slots, holes, and cuts in SiC/SiC and Al_2O_3/Al_2O_3 CMCs if operating parameters are optimized, despite the complexities of CMCs, possibly leading to process-related flaws [127].

4.2.2. Laser-Assisted Machining (LAM). CMCs are quite tough to work with due to their hardness and brittleness. These characteristics make applying strong cutting forces and high temperatures necessary during machining, which can harm both the material and the cutting tools. Additionally, CMCs do not conduct heat well, so it builds up near the tool's tip, damaging the tool. Traditional coolants can also mess up the material, so a more expensive cooling method involving chilled air is used. The integrated hardware is shown in Figure 19.

Because CMCs cannot handle high cutting forces and temperatures, they cannot be machined quickly. A method called LAM is used to improve the process and speed things up. This technique involves using a laser to heat up the top layer of the CMC before cutting it with a regular tool. Doing this makes the materials brittle and more flexible, so less force is needed to cut it, allowing for faster material removal and production [129].

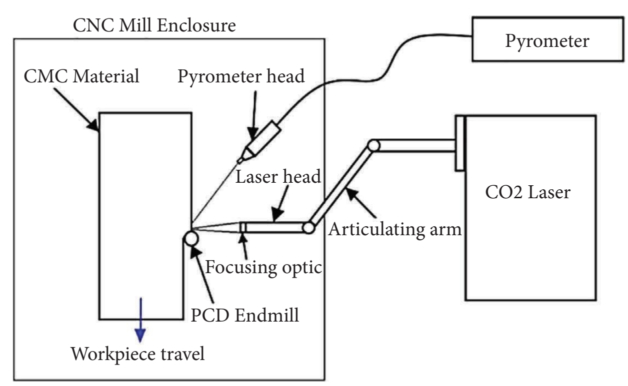

Figure 19: Laser-assisted machining process [128].

4.2.3. Rotary Ultrasonic Machining. FRCMCs (fiber-reinforced ceramic matrix composites) like SiC/SiC, C/C, and C/SiC have emerged as strong candidates due to their superior mechanical and physical properties. In experiments, these materials have shown better crack propagation resistance than pure ceramics. Thanks to their ability to withstand high temperatures, these materials find valuable purposes in parts like jet engine exhaust ducts and nose cones, which face much heat [130].

However, when machining these materials for machine components, their hardness and brittleness present challenges for traditional machining methods. For example, drilling holes in FRCMCs can lead to issues like chipping at the hole exit and concerns about tearing due to the material's internal variations. The intricate ceramic nature of FRCMCs makes conventional drilling methods unsuitable [131].

Experiments confirm that Rotary Ultrasonic Machining (RUM) effectively works for FRCMCs. RUM blends a diamond cutting tool with ultrasonic vibrations, as shown in Figure 20. The tool is hollow with diamond abrasives, vibrating and cutting while cooled by coolant. RUM success relies on parameters like cutting depth, feed rate, spindle speed, vibration frequency, and amplitude. Cutting force in RUM impacts output quality [132].

In simpler terms, RUM is a process that uses both a special vibrating tool and a regular tool to cut tough materials effectively. The vibrations make the tool work better, especially when drilling holes, and this method is carefully controlled to achieve the best results.

4.2.4. Electrical Discharge Machining (EDM). EDM is commonly used for cutting and making holes in materials that are tough to work with using regular methods. Studies identify that EDM shows potential as a technique for machining C-C composites. Experiments on C/C composites found that wear rate and material removal rate (MRR) are crucial factors affecting the machinability of these composites, with significant economic implications. Therefore, there is a need for further exploration and optimization of these factors by considering additional process variables [133]. Figure 21 represents a schematic for the EDM process.

Lower pulse currents prevent fiber breakage and delamination. The main material removal mechanisms are melting and evaporation, causing more damage along fibers [135]. Copper deposition from the electrode can arrest crack propagation [133]. Comparisons on SiC/SiC revealed that

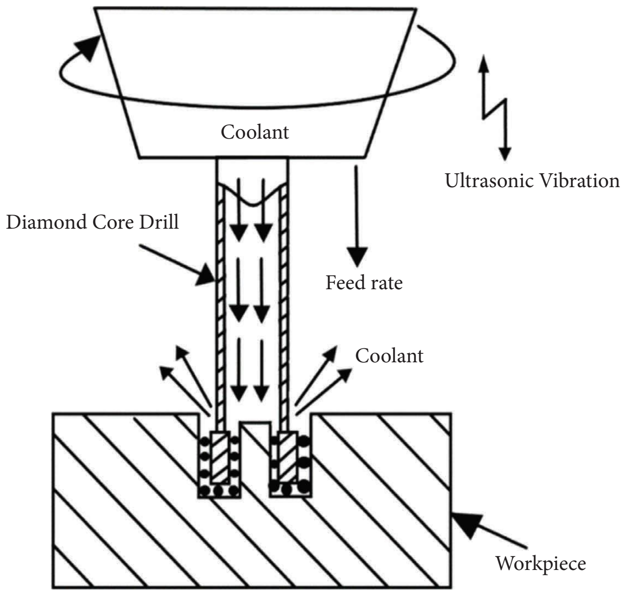

Figure 20: Rotary ultrasonic machining [132].

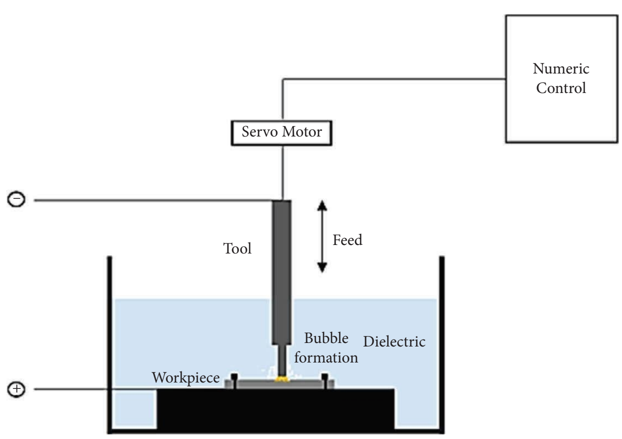

Figure 21: Schematic diagram of electric discharge machining (EDM) [134].

efficient debris removal improves surface quality [136]. The matrix was cracked and stripped, and fibers broke due to the thermal effects of sparks. Some non-conventional machining processes are depicted in Table 3.

In summary, various machining techniques have been tested on CMCs, but no clear method guarantees a damage-free surface when dealing with these ultra-hard composite structures.

5. Applications of CMC

CMCs possess applications (Figure 22) in a wide variety of sectors, which will subsequently be discussed in this section.

5.1. Automobile and Aerospace Industries. The automobile and aerospace sectors must reduce exhaust gas emissions, fuel consumption, and vehicle weight for advancement to enhance the vehicle's safety and performance. New contemporary materials with improved attributes instead of conventional materials can meet these tough and mutually competing needs. CMCs are emerging modern materials with vast potential for application in various demanding fields. These composites exhibit extraordinary properties, encompassing mechanical, electrical, and electronics. CMCs have enormous promise in various industries, including shielding from heat, nozzle material in aerospace sectors, nose cones and missiles for the military, braking systems, engine valves and liners for automobiles, and many more.

CMCs, with their basic characteristics (moderate density, elevated melting point, strong mechanical capabilities, and chemical resilience), are perfect replacements for conventional metals, with their ordinary fracture toughness addressed by fiber reinforcement and customized fiber/matrix bonding. As shown in the Figure 23, in 2016, the CMC market was worth $2.2 billion and is predicted to grow at a 13.74% rate through 2024. CMC manufacturing is expanding due to increased transportation, aviation, military, and electronics demand. According to market research, oxide, SiC, carbon, and various minerals are matrix materials in CMC materials. As the applicability of CMCs has increased, the proportion of different elements utilized to fabricate these matrix materials. SiC had the highest market share in 2017 (more than 25%) of all materials considered above.

The driving performance of an automobile is influenced by key factors such as (i) achieving higher speeds, (ii) achieving quick and efficient braking, and (iii) maintaining stability while navigating curves. These aspects are closely linked to the performance of various internal components (engines, tyres, and brakes) and the overall physical structure of the vehicle. In the automotive industry, among the benefits of using these materials are being able to manufacture highly complicated forms, minimizing the running cost of components, the ability to connect the components during the fabrication, durability in extreme conditions, the ability to resist corrosion, simpler maintenance, a higher lifetime, work-up efficiency, and recycling ability [141].

One of the most essential units of contemporary automobiles is disc brake as it causes the vehicle to brake under significant mechanical and thermal stress. CMCs can be used in place of traditional cast iron braking discs. Their weight and temperature resistance prevent them from being used in wheels performing sports, racing, and luxurious applications, where braking performance is more vital than cost. Carbon ceramic brakes are preferable in these instances because these substances are not as heavy as cast iron brakes. Moreover, they are up to 50% stronger and resilient to high temperatures and have endured a longer lifetime [142]. Besides that, numerous ceramic usages, which are knock detectors, oxygen detectors, and exhaust gas catalysts in automobile engines, have been effectively employed in automobiles. The use of ceramic turbochargers composed of silicon nitride instead of typical nickel-based superalloys could substantially boost performance. The ceramic rotor requires 36% less time to reach 10,000 rpm reducing turbo-lag [143].

Table 3: Advantages and disadvantages of different types of machining processes.

Type of machining	Advantages	Disadvantages	References
Abrasive waterjet (AWJ) machining	Avoids processing without tool contact, hence no tool wear Not affected by heat during processing, so deeper holes for processing are possible	Problems such as nozzle wear and micro- and macrowear may occur Workpiece surface may be susceptible to burr and chipping	[137]
Laser-assisted machining (LAM)	Comparatively faster cutting tool speed Low cutting force, prolonged tool life, high machined surface quality	Immature technology, expensive, complicated equipment upgrades	[138]
Rotary ultrasonic machining	No free abrasives Drilling deep holes is made easier without creating abrasive slurry	Relying on diamond tools	[9]
Electrical discharge machining (EDM)	Can be implemented on all types of materials The workpiece used in the EDM is titanium which allows it to provide any shape to the materials	Uses thermal energy and reduces mechanical forces As electrode wear is present, sharp edges can be hard to obtain	[139]

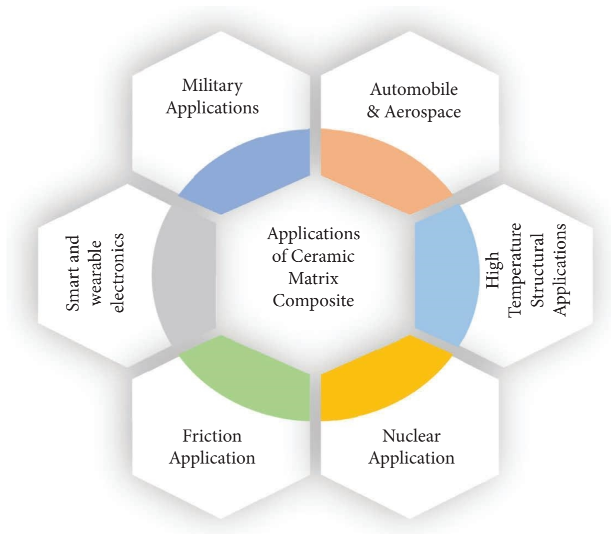

Figure 22: Applications of CMCs.

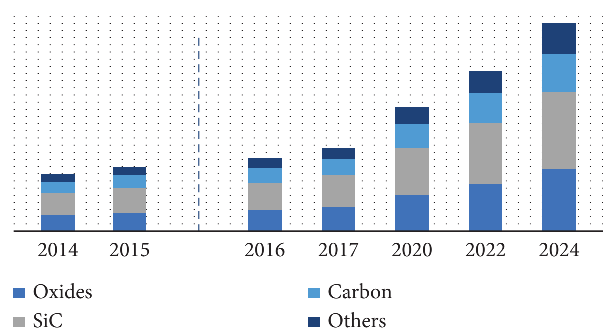

Figure 23: Ceramic matrix composites market, by product [140].

In power transmission automotive function, high-powered clutches and sporty and racing wheels have used C/SiC friction plates. The primary benefit over predictable organic or sinter metallic counterparts is their ability to superior temperature resistance and durability, which results in elevated torque capacity and energy storage, as well as a low-weight and solid design [144]. In heat exchanger tubes, the primary use sectors for CMCs are for energy recovery. Such applications use components that might be basic or complex and are often shorter in size. The commercial availability of thick, resistant-to-wear CMCs reinforced with particle and whisker for applications including wear, cutting tool inserts, and combustion engines is not unusual [145]. Alumina, called aluminium oxide, is a common fine ceramic material with good chemical and physical stability. These qualities make it a good material for spark plugs [146]. However, because CMCs increase the longevity of the parts used in turbine engines and other aeroengine components, the aerospace industry needs them. Reimer et al. examined the fatigue properties of both short and long CMCs. Its potential applicability in the aerospace industry, where vibration is always present, is limited by tests conducted under vibrating conditions, which indicate an abrupt fall of the resonance frequency, indicating a quick loss of the material's elastic resistance, limiting its application in these industries where vibration is associated [147].

CMCs can improve aerospace vehicles such as aeroplanes, helicopters, missiles, re-entry vehicles, and future hypersonic aircraft. For applications involving aircraft jet engines in turbine section, the NASA Environmentally Responsible Aviation (ERA) Project focuses on evaluating CMC parts and environmental barrier coatings (EBCs). The project aims to examine and develop alternative aircraft designs and technologies to reduce fuel consumption, noise, and pollution. This initiative uses CMCs to construct various components, including combustor liners, highly pressurized turbine vanes, and exhaust nozzles [148]. Most materials used for heat protection in reusable aircraft are CMCs, which can withstand high temperatures. Space shuttles have metallic wings and fuselages to offer thermal insulation upon re-entry into Earth's atmosphere [149]. CMCs have shown promise in aircraft radome applications. A radome must be electromagnetically clear, structurally sturdy, and weather resistant. For combative purposes, for example, a fighter jet moving at Mach 3 or an improved hypersonic missile of Mach 5, ceramics are the only plausible choice. The best candidates for this role include silicon nitride-based radome materials with great rigidity, electromagnetic transparency, and temperature stability up to 1400°C [150].

5.2. High-Temperature Structural Applications. Modern aircraft and spacecraft must provide enhanced performance for various applications. It includes lowering the structural weight of the engine and protecting components in high temperatures. The total impulse per unit mass is a crucial parameter for propulsion technology operation at temperatures beyond 1500°C. A higher ratio of this parameter is much desired in aviation technology. Currently used superalloys and metals resistant to decomposition can be substituted by ceramic materials as the new breed of structural materials due to their excellent ability to survive high temperature, moderate density, elevated specific modulus and strength, and shielding against oxidation and ablation.

Jet engines, nuclear furnaces, gas turbines, and wheels requiring rapid brakes with operating durations of thousands of hours are all excellent applications for C/SiC composites ranging from 700 to 1650°C. They are ideal for ramjets, thermal insulation systems, and liquid rocket engines with working durations of several to tens of hours. They operate between 2200 and 2800°C, making them perfect for solid rocket engines [151]. With suitable reinforcement and coating, UHTCMCs can endure the extreme aero-thermo-chemical conditions of hypersonic flight. Due to their moderate density of 1.5 g/cm^3, carbon fiber-reinforced carbon matrix (matrices of Zr- or Hf-based UHTC composites) is regarded as prospective heat-resistant materials [89].

Turbine blades incorporated in aircraft engines need to exhibit exceptionally good mechanical properties, especially at high temperatures. Previously, the low-speed blades used in turbines were manufactured with alloys. As the weight and speed of an aircraft increases, the blade's ability to withstand high temperatures needs to increase as well. To improve this property in second and third generation engines while using alloys as turbine blade materials, thermal barrier coatings (TBCs) are used, which provide limited thermal resistance. This is where CMCs prove to be superior in comparison to traditional materials. SiC CMCs provide enhanced thermal stability and high temperature resistance at a relatively small density, making them well suited for aircraft engines with high thrust to weight ratio [92]. Ceramics offer great thermal stability and excellent stiffness while delivering low density, but their brittle property prevents them from being used as structural materials. Carbon nanotubes may be utilized as ceramic reinforcement due to their resilient tensile strength. The coupling of these nanotubes with a ceramic matrix can produce composites with great thermal stability, remarkable toughness, and creep resistance [152, 153]. Ceramic matrix nanocomposites combine ceramic qualities with nanofiller properties. Whiskers, fibers, and platelets are nanofillers that improve ceramic fracture toughness, reducing the brittleness required for many multifunctional applications [153]. CMCs can offer exceptional durability as a protective layer to serve thermal insulation requirements. Their properties of lightweight extended melting point and moderate conductivity against thermal conditions make open foams, silicon carbide, and other ceramics to be used as the main materials in preventive extreme temperature conditions [154]. Silicon carbide with reinforcement of continuous SiC fiber ceramic composites is also being studied as possible materials for high-temperature components in recent jet engines.

Environmental barrier coatings (EBCs) must be employed on the outer layer of ceramic composites like SiC_f/SiC because of their environmental exposure and proneness to rust and deterioration at high temperatures. This allows for replacing turbine section nickel-based superalloys [155]. Ceramics are good for high-thermal applications, but they have low toughness. Walker et al. were among the first to explore Si_3N_4 system with the addition of graphene, achieving a far better increase in the effectiveness of fracture toughness with 1.5 vol.% multilayer graphene inclusion. On top of that, GNPs have also been found helpful in several other structural ceramics, including AlN, SiO_2, ZrO_2, and ZrB_2 [156].

5.3. Smart and Wearable Electronics. Due to their unique features, ceramics are appropriate for various applications. However, the brittleness nature of ceramics limits their uses. Ceramic materials possess excellent thermal and dielectric properties, making them highly suitable as substrate materials. Three kinds of ceramic substrates that are often utilized are aluminium oxide (Al_2O_3), beryllium oxide (BeO), and aluminium nitride (AlN). Low dielectric constants, losses, high thermal conductance, and chemically balanced characterize these ceramic substrates. The superconducting properties of several ceramics have captivated much notice, which are applied in electrical and magnetic systems. Aluminium nitride ceramics offer good dielectric characteristics and are used in semiconductor components and electrostatic chucks. For more general electronics applications, enhanced mechanical qualities and control over thermal and electrical characteristics are desired [157]. Ceramic materials with unique electrical characteristics can be employed in portable gas sensors. Ferrites with spinel structures, for example, are used as gas detection materials as a form of electronic signal. They are systems providing much affordability, are relatively straightforward and flexible, and can be modified via changes of structural and compositional aspects [113]. Sensor applications generally monitor and convert non-electrical elements, including pressure, temperature, electron flow, gas concentration, acceleration, distance, and moisture content, into electrical impulses carried forward in subsequent electronic devices. One particularly unique characteristic is developed by researchers using anisotropic piezoelectric ceramic composites having a paper-cut construction, and it could play a role in joint mobility and guard against joint conditions. These piezoelectric ceramic composite sensors with a paper-cut setup can detect joint movement while identifying various movement patterns [158].

The toxic substances found in the ceramics used in wearable electronic devices have recently become a concern in this field. There are several efforts to utilize nanomaterials in various sectors these days. The nanoparticles in the materials could be hazardous to humans, animals, and plants. Most piezoelectric ceramics provide great properties to be utilized; however, it lacks flexibility, limiting its applicability in practical wearable components. As a result, ceramic composites compounded with various environment-friendly polymers have been examined as potential non-conducting materials. Several polymer/ceramic nanocomposites have recently gained popularity in energy storage and sensing because of their easy and attainable production processes, cost-effectiveness, and accurate piezoelectric characteristics [159].

5.4. Nuclear Application. CMCs have emerged as a game-changing material for nuclear applications. With their remarkable high-temperature resistance, exceptional mechanical properties, and inherent radiation tolerance, CMCs offer unprecedented advantages in the nuclear industry. High corrosion resistance is a major requirement for nuclear applications. Stainless steel is therefore suitable as it possesses good corrosion resistance, weldability, enhanced strength, and toughness. However, it suffers from the limitation of insufficient wear resistance as well as radiation tolerance. This issue can be addressed by incorporating ceramic reinforcements into the metal matrix to enhance the strength and wear resistance while maintaining the corrosion resistance. Boron Carbide-reinforced composites are an ideal candidate for nuclear applications because Boron Carbide can absorb neutrons. It also possesses low density, good chemical stability, and high strength [160].

5.4.1. CMC Fusion Application. CMCs are being considered for development in nuclear fusion reactors, specifically in Plasma-Facing Components (PFCs). PFCs include the diverter, first wall, and blanket. The diverter removes impurities from the plasma, extracts heat, and controls plasma density. The first wall is the first material facing the plasma, while the blanket is positioned behind the first wall and contributes to energy recovery, tritium production, and neutron shielding. Figure 24 shows the two designs (flat tile and monobloc) under consideration for the shape of the CMCs, although the monobloc configuration is considered mostly.

For these PFCs, CMCs have been considered, particularly SiC/SiC and carbon/carbon (C/C) composites. CMCs offer potential advantages because of their elevated temperature capabilities, resistance to thermal shock, low activation, erosion resistance, and hydrogen retention. The application of SiC/SiC composites, mainly, has gained attention for their performance under low activation and irradiation properties [161].

5.4.2. CMC Fission Application. The Fukushima Daiichi accident has raised unease about the safety of current and future fission reactors, highlighting the limitations of existing materials under severe accident conditions. The search for new core materials for CMCs has gained importance in developing intrinsically safe reactors. CMCs offer improved refractoriness and reduced reactivity during accidents, enhancing reactor safety. The Generation IV Nuclear Energy Systems Initiative was launched to strengthen protection, resource management, and waste reduction in nuclear power [161].

5.4.3. CMCs for Structural Materials. CMCs find potential applications in structural components and fuel cladding, particularly in Gas-Cooled Fast Reactors (GFRs), Sodium Fast Reactors (SFRs), and Very-High Temperature Reactors (VHTRs). The advancement of materials with high-temperature resistance, like CMCs, is crucial for successfully deploying these advanced reactor designs.

(1) Very-High Temperature Reactors (VHTRs). VHTRs require high-temperature-resistant materials for structural components. CMCs are studied for their applications in VHTRs, particularly in control rods. Challenges include mechanical and thermomechanical failure, irradiation-induced dimensional changes, absorber swelling, and corrosion. SiC/SiC composites are favoured for control rods because of their superior dimensional stability. International collaborations, like the I-NERI program, aim to develop suitable SiC/SiC composites for VHTR control rods. These efforts enhance VHTRs' safety and efficiency [8]. VHTR is a thermal-spectrum reactor using a graphite moderator and gaseous helium coolant as shown in Figure 25.

(2) Sodium Fast Reactors (SFRs). A recent patent proposes using SiC/SiC-type CMCs for the hexagonal tube fuel-assembly body in SFRs as shown in Figure 26. Currently, the body is made of steel alloys. The CMC body would provide structural integrity and rigidity and guide the coolant flow. The patent suggests a composite assembly with metal end components and a central CMC cylinder to reduce adverse effects on neutronic reactions. The CMC material should be chemically compatible with sodium, have low swelling, withstand neutron flux, and be thermochemically in line with the alloy employed for the structural body. Detailed specifications are still under research for this application [161].

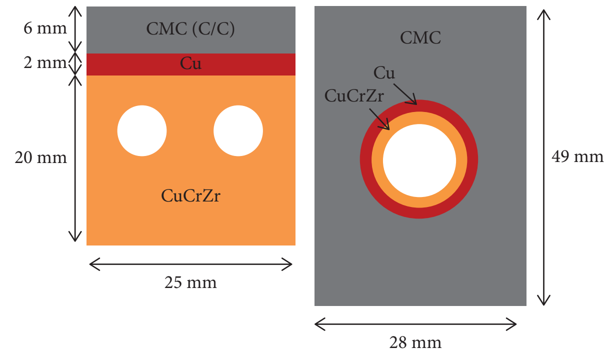

Figure 24: Geometry of plasma-facing components (PCFs) [161].

5.4.4. CMCs for Pin Cladding Materials. CMCs are recently being researched for their potential use as fuel cladding materials in light-water nuclear and gas-cooled fast reactors. This is due to their exceptional strength at high temperatures and ability to resist corrosion when exposed to hot steam during severe accident scenarios.

(1) Gas-Cooled Fast Reactor (GFR) Applications. SiCf-SiC composites show promise as cladding materials for the fuel assemblies within nuclear reactors. These composites comprise SiC fibers, a loosely bonded interphase consisting of PyC, and a SiC matrix, which can be chemical vapor infiltrated or may incorporate a dense outer layer of CVD SiC. Their exceptional high-temperature resistance makes them an attractive choice for use in GFRs [161].

(2) Light Water Reactor (LWR) Application. In the wake of the Fukushima Daiichi Nuclear Power Station accident in 2011, extensive research has been undertaken to enhance the safety of LWRs by improving accident-tolerant fuel (ATF) claddings. Among the various explored options, SiC has emerged as a highly promising candidate [162].

SiC/SiC composites, specifically continuous SiC fiber-reinforced SiC matrix ceramic composites, offer unique radiation resistance, high-temperature stability, mechanical strength, and enhanced safety features. They can withstand high temperatures and have slower oxidation kinetics than zirconium alloys, reducing the risk of catastrophic failure. SiC/SiC composites also provide passive safety features during severe accidents, such as low hydrogen generation and limited fission product release. These numerous advantageous characteristics make it well suited for nuclear applications [163].

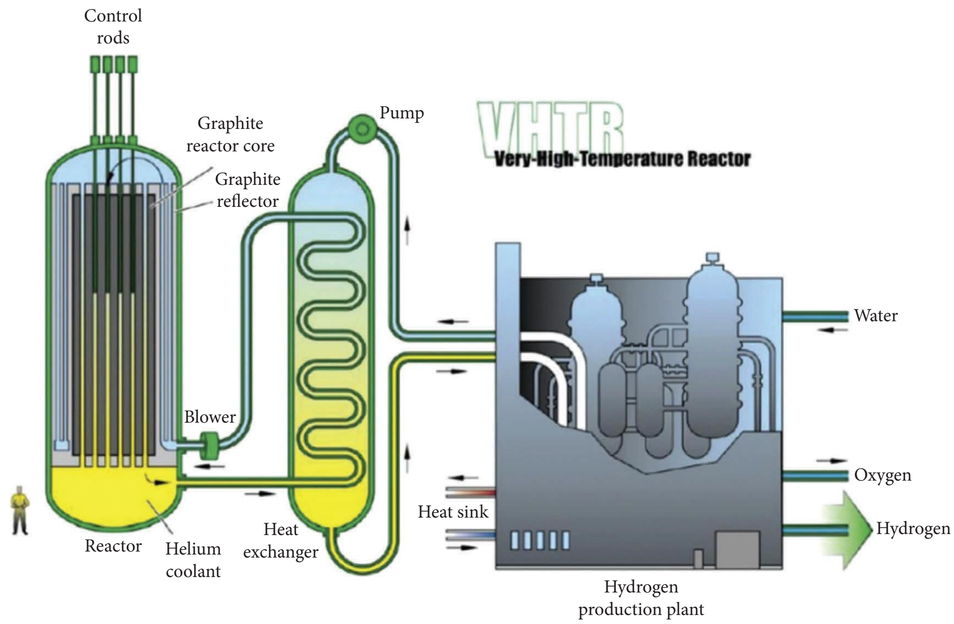

Figure 25: Schematic diagram of VHTR [161].

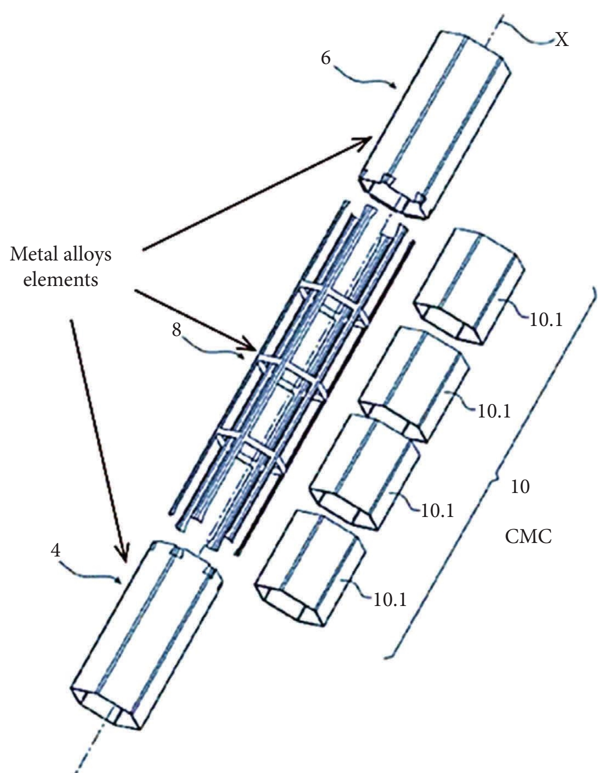

Figure 26: Hexagonal composite (metal alloy/CMC) structural body for SFR [161].

5.4.5. Boiling Water Reactor (BWR) or Pressurized Water Reactor (PWR) Applications. The Fukushima accident emphasized the necessity for advanced materials in BWRs and PWRs. SiC-based cladding, including SiC/SiC composites, is being considered as a replacement for zirconium alloys due to its better resistance to high temperatures and oxidizing conditions. The goal is to reduce heat release and hydrogen generation during accidents and maintain fuel integrity [164].

Although CMCs show great potential for nuclear applications, their application is constrained by their response to irradiation, limiting their use to scenarios with radiation doses below 10 displacements per atom (dpa) or approximately 1×10^{26} neutrons per m^2 [161].

5.5. Friction Application. CMCs have emerged as a revolutionary material with immense potential in friction applications. With their exceptional combination of high strength, temperature tolerance, and wear resistance, CMCs offer promising solutions to address the challenges associated with friction and wear in various industries.

5.5.1. C/SiC (Carbon/Silicon Carbide) Brake Discs. In 1999, DaimlerChrysler and Porsche introduced C/SiC brake discs at the International Motor Show in Germany. These brake discs were first used in the Mercedes CL 55 AMG F1 Limited Edition in 2000. Large-scale production began in 2001, featuring the Porsche 911 GT2. The technology, known as Porsche Ceramic Composite Brake (PCCB), is now an option for all Porsche models and is a standard feature on special edition vehicles. Carbon Ceramic Brakes, including CMC components, are also offered by various automobile manufacturers, such as Aston Martin, Ferrari, Bugatti, BMW, Corvette, Audi, AMG, Bentley, and Lamborghini. These high-performance brake systems utilize CMC materials to enhance braking performance and durability. Formula One racing cars still use pads on disc configuration (Figure 27).

C/SiC brake discs, incorporating Carboxymethyl Cellulose CMC, offer weight savings and improved performance. CMC reduces friction, enhancing braking response,

Figure 27: Racing car brakes: ventilated discs and pads [165].

smooth operation, and increased driving comfort. It also improves wear and corrosion stability, providing long service life [166].

5.5.2. C/SiC (Carbon/Silicon Carbide) Friction Rings. C/SiC friction rings, like those from BSCCB (Brake Steer Control Cornering Brake), which is based on LSI (Lane Steering Intervention), are employed in top-tier sports and racing cars, including Audi R10 TDI and Porsche Carrera GT, and in rally racing cars like Volkswagen Race Touareg 3. These rings offer advantages over conventional materials, with higher temperature stability, strength, and lower wear. They enable lightweight, compact clutch designs with increased torque capacity [161].

5.5.3. Emergency Brakes in Elevators. Emergency brakes are crucial in advanced elevators to prevent freefall in the improbable event of cable malfunction. Controlled emergency braking is initiated when the elevator car exceeds a set speed. This involves metallic springs applying friction pads against steel guide rails. Considering the substantial loads carried (up to 45 tons) and high velocities reached (up to 10 m/s), the brake pads reach temperatures exceeding 1200°C. Organic or metallic friction pads cannot withstand these conditions because they are significantly large. Therefore, they are substituted with heat-resistant and lightweight C-SiC materials [165]. High-speed elevators are generally equipped with C/C-SiC brake pads for emergency braking (Figure 28).

5.5.4. C/C-SiC Friction Pad Rings. Propeller brakes in large cargo aircraft rapidly stop the propellers upon landing and prevent unintended movement in strong winds during parking or maintenance. The A 400M aircraft utilizes a compact multidisc propeller brake with four C/C-SiC friction pad rings. Despite their small outer diameter as small as 120 mm, these friction pads effectively bring the rotation of the eight-blade propeller to a halt, from 650 rpm to a complete stop in under 8 seconds [168].

Nevertheless, the carbon/ceramic composites encounter a constraint when transitioning from a low to high friction coefficient (μ) with increasing temperature. In the context of passenger cars, where brakes are typically cold, the braking

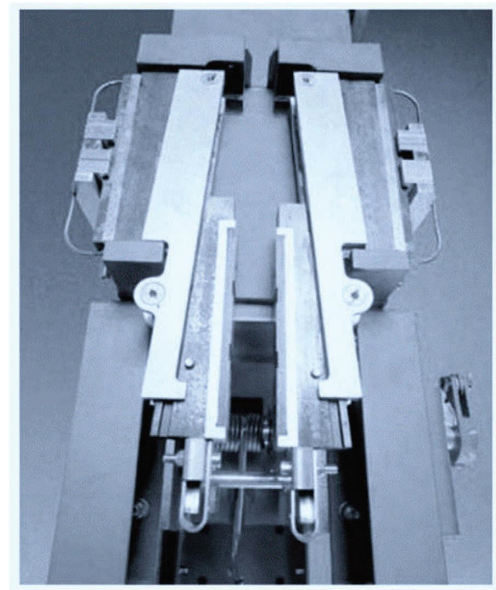

Figure 28: Emergency braking system for high-performance elevators utilizing C/SiC brake pads [167].

efficiency starts off low, necessitating high pressure for effectiveness. Subsequently, as the temperature rises, the shift to high μ takes place, but not uniformly across all wheels. This uneven braking efficiency poses a potential hazard to road grip and proves disadvantageous for the utilization of C/C brakes in regular cars and trucks [165].

5.6. Biomedical Application. CMCs are highly desirous for biomedical applications for their excellent biocompatibility, impressive strength, and exceptional fracture toughness. These materials are sought after for their ability to withstand mechanical stresses and promote successful integration with biological tissues. In biomedicine, CMCs hold great potential for various applications, including tissue engineering scaffolds, implantable devices, and drug delivery systems. Their superior properties make them promising candidates for advancing biomedical technologies and improving patient outcomes [169]. CMCs find diverse applications in the biomedical industry, including the following.

5.6.1. Orthopaedic Application. CMCs are used in orthopaedic procedures to create bone grafts, joint replacements, and many more. These biocompatible and durable materials offer superior aesthetics, strength, and longevity. CMCs promote bone tissue regeneration and offer excellent load-bearing capabilities for joint replacements. Their biocompatibility ensures successful integration with surrounding tissues, improving patient outcomes.

Ceramics have proven effective in orthopaedic prostheses, serving as surfaces that meet ceramic or polymer components. Compared to metallic materials like titanium, stainless steel, and chromium-cobalt alloys, ceramics exhibit advantages such as lower friction coefficient and reduced wear rates. Zirconium and Aluminium oxides are widely acknowledged as biomaterials suitable for joint prostheses. Ceramics have proven effective in orthopaedic prostheses, serving as surfaces that meet ceramic or polymer components [170]. Figure 29 shows the use of a CMC for orthopaedic applications.

CMC materials, such as alumina and alumina matrix composite (AMC), are increasingly used in hip implants and other orthopaedic applications. The utilization of ceramic ball heads alongside highly cross-linked polyethylene has shown potential benefits such as reduced wear rates and minimized risks of corrosion and fretting. While concerns about ceramic fracture and the associated rise in implant expenses, research indicates that the fracture risk is relatively low, and advancements in manufacturing and materials have further enhanced the dependability of successive generations of ceramic components [170].

5.6.2. Dentistry. In dentistry, CMCs are extensively utilized to create natural-looking synthetic teeth and promote tissue generation due to their excellent mechanical properties derived from ceramic-based materials and their ability to withstand high temperatures. CMCs exhibit characteristics like natural teeth, such as stiffness and brittleness. Among the various ceramic compositions used in dental ceramic composites, alumina-zirconia-titania is a commonly employed combination [172]. Metal-ceramic crowns were used very frequently in dentistry to treat a compromised tooth. The presence of metal provides good strength against fracture but at the expense of compromising aesthetics. Ceramic materials, such as zirconia, possess good fracture strength, and they can be designed to have the appearance of normal teeth, making them a good candidate for use as dental material [173].

5.6.3. Heart Valves. CMCs are increasingly used to manufacture biocompatible heart valves essential for cardiac valve replacement surgeries. These CMC-based heart valves offer significant advantages over traditional materials. They provide superior biocompatibility, reducing the risk of adverse reactions and promoting successful integration with the surrounding tissues. CMCs also exhibit excellent mechanical properties, including high strength and durability, ensuring long-term performance and functionality of the implanted valve. Additionally, CMCs can withstand demanding hemodynamic conditions within the cardiovascular system, maintaining their structural integrity and minimizing wear and tear [170].

5.6.4. Drug Delivery. Bioceramics, such as ceramic composites, have emerged as successful solutions for various medical applications, particularly in drug delivery. These materials, including silica, CaPs, zirconia, titanium dioxide, and alumina, exhibit bioactive properties on human body tissues. Biomedical uses of calcium phosphate- (CaP-) based materials range from bone reconstruction and orthopaedic implant coatings to dental applications and drug delivery. With their demonstrated effectiveness and bioactive effects, bioceramics have revolutionized the field of drug delivery in recent decades [174].

For drug delivery, silica-based glasses and bioactive CaPs are extensively used in ceramic composites. Their superior biocompatibility and enhanced biological effects have made them highly attractive in the field. They can be synthesized through different methods and offer versatile forms such as granules, powders, porous scaffolds, and coatings for specific clinical applications [175].

The inherent brittleness of CMCs, however, poses a significant challenge for various applications, particularly in the production of medical devices for hard tissues, such as orthopaedic and dental prostheses that demand precise mechanical performance [176].

5.6.5. CMC for High-Energy X-Ray Generation. CMC based on molybdenum and aluminium nitride (AlN) has been developed as a substrate designed for high-energy X-ray targets. This composite is covered with tungsten using dc blown arc plasma spraying. This CMC improves the performance and lifespan of X-ray tubes in CT scanners, resulting in more efficient and reliable high-energy X-ray generation for enhanced imaging capabilities [177].

6. Limitations and Challenges

CMCs are achieving popularity as a preferred material for various high-value and safety-critical components. As a result, there is a growing demand to comprehend the impact of different machining processes on these materials [33]. Despite their widespread usage, several drawbacks must be addressed, as mentioned below.

FRCMCs-SiC, or continuous fiber-reinforced SiC CMCs, are widely used in energy, transportation, and aerospace for high-value components. However, machining these materials is a challenging task. Machining CMCs is particularly challenging due to their complex characteristics, such as anisotropic thermal and mechanical behavior, heterogeneous structure, and the inherent hardness of at least one of the constituents (such as the fibers or matrix) [129].

The demand for high-quality, miniaturized products with complex features has expanded to include CMCs as a promising engineering material. Micromilling, a common subtractive manufacturing process for such products, presents effective means to generate intricate surfaces and challenging features. However, machining CMCs using traditional mechanical micromilling methods has severe tool wear, low production efficiency, anisotropic characteristics, and high cutting temperatures [178].

The inherent characteristics of ceramic materials, such as hardness, porosity, and brittleness, often necessitate implementing strategies to address the challenges linked with these traits. Ceramic materials typically exhibit ionic or

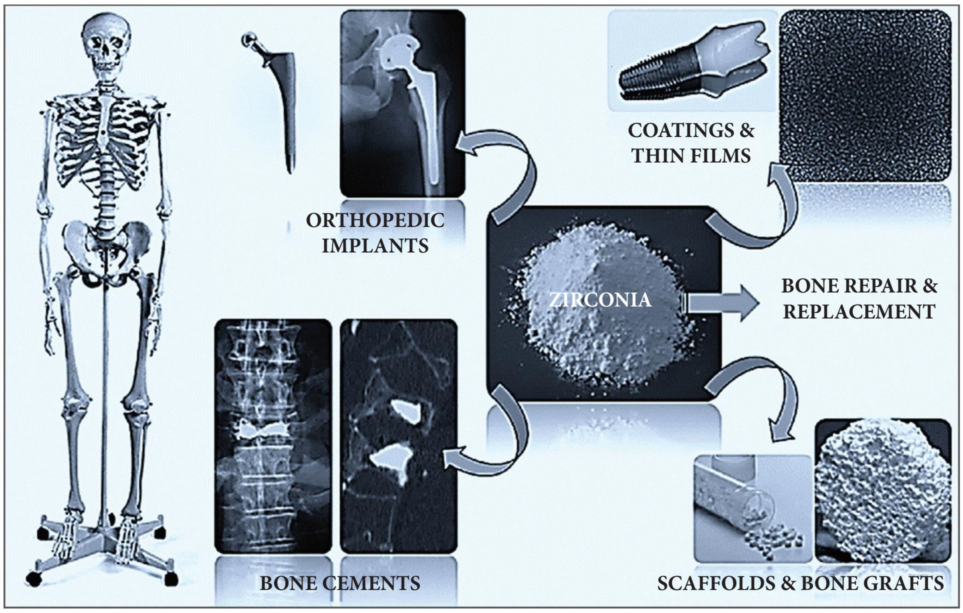

Figure 29: Use of ceramic composite, namely, zirconia, in orthopaedic applications [171].

covalent bonding and are crystalline or amorphous. Due to their specific electronic bonding, ceramics tend to fracture rather than undergo plastic deformation. Consequently, they typically have low tensile strength, material toughness, and poor machinability [145].

More research is required to advance CMCs. Researchers must focus on low-cost mass production and enhance the high-temperature mechanical characteristics of CMCs, such as high toughness, ultra-high temperature resistance, and the long-term effects of SiC CMCs. Moreover, ceramics designed for high-temperature structural applications, like SiC CMCs, are challenging to restore after experiencing partial failure, and there is currently a dearth of research focused on remanufacturing CMCs. Therefore, efforts should be directed toward improving the high-temperature mechanical properties of ceramics while exploring possibilities for their remanufacturing [92].

CMCs find application in manufacturing various structures that must tolerate high temperatures, including brake discs, turbine blades, turbine bearings, heat shields, and nozzles. However, due to the particular nature of CMCs, they cannot be efficiently compacted like conventional materials. Hence, developing processing technologies that can quickly and cost-effectively fabricate complex structures with high efficiency and dependability is of utmost importance.

On the other hand, the composite's most used raw materials are usually Carbon or SiC, which either involve using hazardous materials or high energy-consuming production processes. Owing to their complex structure, the recycling and disposal of CMCs is another challenge that needs to be confronted. However, researchers are making several attempts to create more environmentally friendly composites. Bagheri et al. developed a CMC to remove the toxic dyes present in wastewater [179]. The inorganic matter was used as a coating material in the chitosan-starch-CMC-Na-PVAL composite to enhance thermal stability and hydrophobic properties and obtain superior crystallinity and roughness [180]. To manufacture lithium-ion batteries with low environmental impact, Mancini et al. made a CMC that could be used for replacing the binder material in cathodes and anodes in batteries, thus replacing N-methylpyrrolidone (NMP) and thereby reducing the hazards and cost of battery production [181].

7. Future Direction of Research

Despite the numerous advantages CMCs possess, it is desirable to further enhance their toughness, thermal shock resistance, and resistance to wear and high temperatures. Future work can be dedicated into exploring methods that support this measure. For example, there are several methods for enhancing the performance of SiC CMCs: improving the ceramic's performance, adding a sacrificial phase or reinforcement, or enhancing the compatibility of the interface between the ceramic matrix and reinforcement. In addition to improving the existing characteristics of CMCs for different applications, more focus should also be drawn into the low-cost production of CMCs. Structural ceramics implemented in high-temperature applications (such as SiC-CMC) are challenging to repair after partial failure. This issue can be addressed through carrying out research in the possibility of remanufacturing CMCs [143]. Figure 30 depicts the future scope of CMCs.

In order to fully utilize the potential of CMCs, a comprehensive understanding of the impact of adding different reinforcements is necessary. This could be done through exploring different methods of incorporating reinforcements (such as nanoparticles) and other manufacturing technologies.

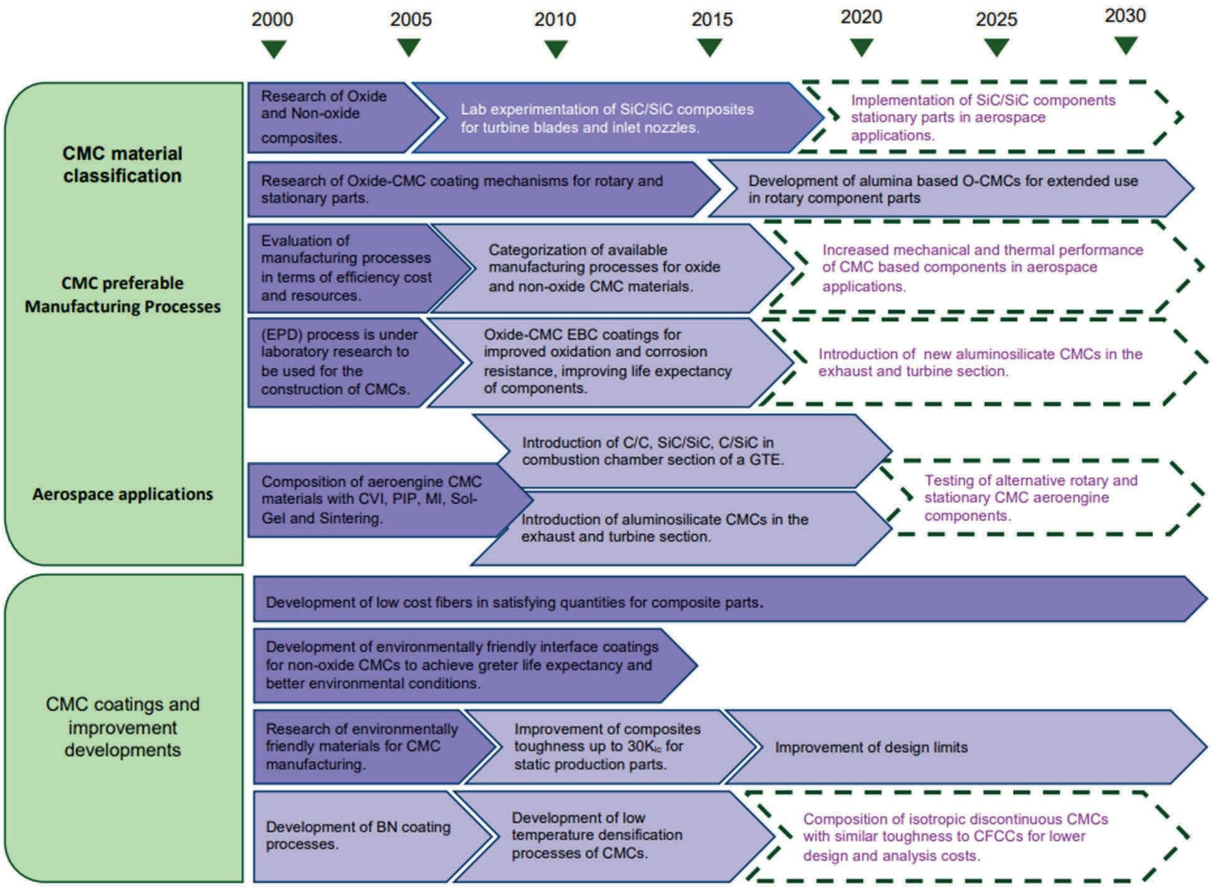

Figure 30: Future scope of CMCs [30].

8. Conclusion

To conclude, CMCs are a highly adaptable and multifunctional category of materials capable of being utilized in many potential applications. They possess a multitude of desirable properties which include but are not restricted to exceptional strength, good resistance to corrosion, resistance to high temperatures, and lightweight. As a result, they have gained popularity in many industries and sectors.

CMCs offer numerous opportunities for aerospace, nuclear, automotive, biomedical, friction, electronics, and beyond. They have been frequently used in the aerospace sector, including aircraft engines, enabling higher efficiency and performance due to their exceptional strength, high-temperature resistance, and lightweight nature. CMCs hold promise in the nuclear industry for advanced reactor design owing to their capacity to endure very high temperatures. With low weight, CMCs can enhance fuel efficiency and overall performance in an automotive vehicle. In biomedical applications, CMCs have the potential to be used in implants and prosthetics due to their biocompatibility and strength. CMCs can also find applications in brake friction materials, offering improved durability and heat resistance. In the electronics industry, the electrical insulation properties and high-temperature performance of CMCs render them suitable for incorporating heat sinks, substrates, and packaging materials for power electronics and high-temperature electronic devices.

The prospects of CMCs are equally versatile. Ongoing research and development efforts focus on improving manufacturing techniques, enhancing temperature resistance, optimizing mechanical properties, tailoring material characteristics, incorporating multifunctionality, reducing costs, and promoting sustainability. The unique combination of properties offered by CMCs positions them as a key material in addressing the challenges and requirements of high-performance industries.

In the coming years, we can expect CMCs to play a significant role in shaping the future of aerospace, energy, automotive, defence, electronics, and other sectors, enabling innovative solutions that deliver improved performance, efficiency, and sustainability. With their remarkable properties and ongoing research, CMCs can provide opportunities for advancing technology and driving progress in various fields.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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