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Review

Advances in Sintering Technologies for SiC Ceramics: Mechanisms, Challenges, and Industrial Applications

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ABSTRACT: Silicon carbide (SiC) ceramics have become critical materials for high-temperature engineering applications because of their exceptional mechanical strength, thermal conductivity, and chemical stability. In order to meet the diverse needs of industrial applications, various sintering methods have been developed. These include traditional methods such as pressureless sintering, reaction-bonded sintering, hot pressing, and recrystallization, as well as advanced technologies like spark plasma sintering, oscillatory pressure sintering, and flash sintering. This review provides a systematic analysis of both traditional and advanced sintering techniques for SiC ceramics. It highlights their mechanisms, critical process parameters, and impacts on the final material properties. Key challenges, including high sintering temperatures, additive selection, microstructural control, and scalability, are examined. Strategies for balancing cost-efficiency with performance are also discussed. In addition, recent advancements in SiC-based composite materials for applications ranging from aerospace components to catalytic filtration systems are presented. Finally, future research directions are proposed. These focus on precise additive engineering, microstructure tailoring, and innovative sintering methodologies to speed up the transition of high-performance SiC ceramics from laboratory prototypes to large-scale industrial implementation.

Keywords: Silicon carbide (SiC); Sintering; Microstructure; Properties; High-temperature applications

1. Introduction

SiC is a covalent compound and a fundamental material for high-performance ceramics. Its exceptional properties, such as high flexural strength, excellent thermal conductivity, outstanding oxidation resistance, and superior chemical corrosion resistance, make it essential in high-temperature engineering applications [1–3]. SiC is widely used in extreme environments. In nuclear reactors, it can be used as first-wall materials [4,5]; In the aerospace industry, it can be employed in engine rotors and mirrors [6,7]; In steel production, it can serve as refractories and arbors [8–10]; In the photovoltaic and semiconductor sectors, it can be utilized as wafer carriers and mechanical seals [11,12]; moreover, in chemical catalysis, it can be used for exhaust gas filtration [13,14] (Figure 1). Additionally, SiC exhibits tunable bandgap widths across its various polytypes [15,16], making it a promising material for wide-bandgap semiconductors in high-temperature electronic devices [17–20].

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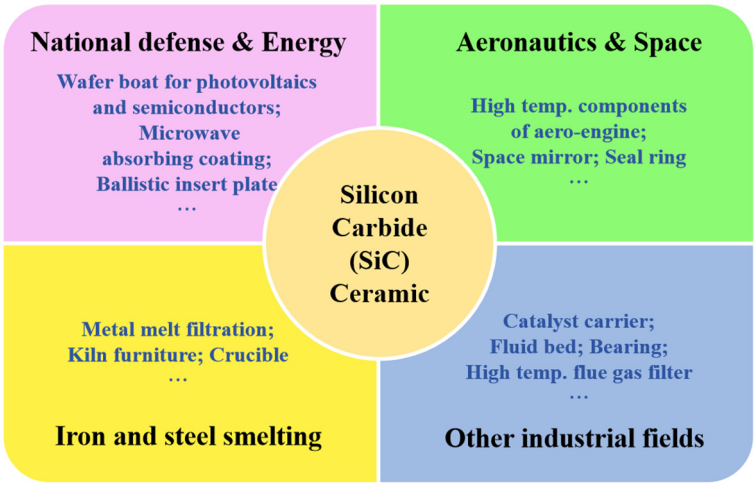

Figure 1. Applications related to silicon carbide ceramics.

However, the sintering of SiC ceramics poses significant challenges due to its strong covalent bonding and the inherently low self-diffusion coefficient between silicon and carbon atoms [21]. These characteristics result in high sintering temperatures and limited densification under normal conditions, necessitating the development of tailored sintering strategies to achieve precise microstructural control and optimize material performance. Over the years, diverse sintering techniques have been developed for polycrystalline SiC ceramics, ranging from traditional methods such as pressureless sintering (solid-state and liquid-phase sintering), reaction-bonded sintering, hot-pressing, and recrystallization sintering, to advanced methods like spark plasma sintering (SPS), oscillatory pressure sintering (OPS), and flash sintering (FS) [22–29]. These methods differ in their densification mechanisms, sintering temperatures, and resulting microstructural properties, as illustrated in Figure 2. Achieving a balance between performance and cost remains a critical challenge for the industrial application of SiC ceramics in high-temperature environments. The service temperature, service performance, and production cost of SiC ceramics are closely related to the sintering process employed.

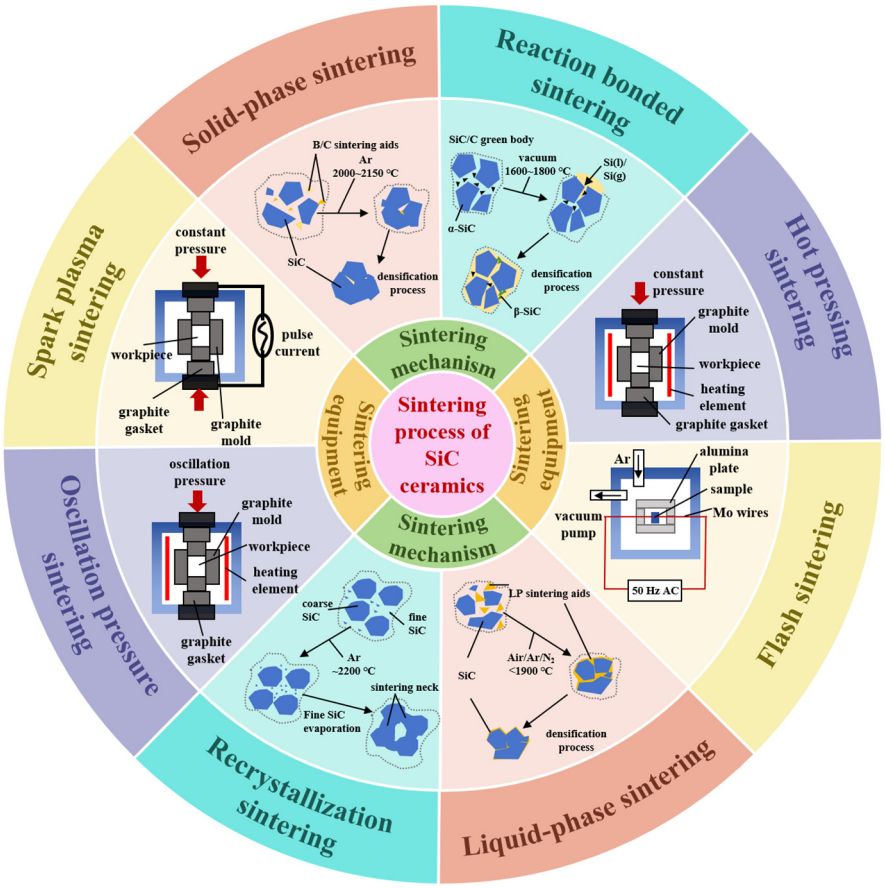

Figure 2. Common sintering process of silicon carbide ceramics.

For instance, reaction-bonded SiC (RB-SiC) ceramics often contain residual free silicon because of the incomplete reactions between SiC/C preforms and infiltrated silicon. When the temperature rises above 1400 °C (close to the melting point of silicon at 1410 °C), this residual silicon becomes soft, and this leads to a considerable decline in the mechanical performance of RB-SiC ceramics [30,31]. To address this problem, recent research efforts have been centered on reducing the free silicon content to improve the high-temperature properties of RB-SiC ceramics. In contrast, pressureless solid-state sintering (SS-SiC) utilizes boron and carbon-based sintering aids. This method can produce SiC ceramics with clean grain boundaries and no residual glass phase, enabling these ceramics to withstand service temperatures up to 1600 °C [32]. Current studies in this area are mainly focused on investigating the effects of sintering aids, reinforcing phases, and forming techniques on the microstructural control and performance of SS-SiC ceramics [33,34]. For applications such as high-temperature filtration and catalyst carriers, porous SiC ceramics, like recrystallized SiC (R-SiC), are widely employed. These materials depend on unique sintering mechanisms to achieve controlled pore structures and optimal mechanical properties [35,36]. Nevertheless, diverse filtration scenarios impose different requirements on pore size, permeability, and thermal stability. As a result, research has been directed towards tailoring the pore structure and enhancing the overall performance of R-SiC ceramics by adjusting sintering parameters and using additives [14,37].

Achieving a balance between performance and cost is a crucial challenge for the industrial application of SiC ceramics in high-temperature environments. When the service environment temperature is below 1380 °C, the production cost of RB-SiC ceramics is much lower than that of SS-SiC and R-SiC ceramics. SS-SiC ceramics have distinct advantages under high-temperature and high-load conditions, while R-SiC ceramics are a more suitable choice when higher purity or specific pore structures are required. Therefore, engineers need to prioritize selecting appropriate sintering processes based on the specific service environments, taking both production costs and performance characteristics into account. This paper offers a comprehensive review of the latest advancements in sintering technologies for SiC ceramics. It evaluates the impact of different sintering methods on industrial applications, explores the underlying connections between sintering processes, and provides insights into future directions for the development of SiC materials.

2. Sintering Process

2.1. Pressureless Sintering

Pressureless sintering (PS) is a commonly used and cost-effective method for producing dense SiC ceramics. It can be broadly classified into solid-state sintering and liquid-phase sintering (LPS) according to the type of sintering aids employed [22,23]. The choice of sintering aids plays a crucial role in determining the densification mechanisms and has a substantial influence on the final SiC microstructure, including factors such as grain size and the composition of the grain boundary phase. Consequently, the overall mechanical, thermal, and chemical properties of the fabricated SiC ceramics vary depending on the sintering method. Solid-state sintering primarily relies on boron-carbon-based additives to facilitate densification, while liquid-phase sintering makes use of oxide systems that create transient liquid phases, enabling densification at relatively lower temperatures. This section focuses on solid-state sintering due to its simplicity and widespread industrial application, with a particular emphasis on recent progress and challenges in this area.

2.1.1. Solid-State Sintering

Solid-state sintering of SiC ceramics utilizes boron-carbon (B/C) series additives, including B, B + C, and B_4C + C, Al_3BC_3 to facilitate densification. The densification process is governed by two complementary mechanisms. Boron segregates at grain boundaries, thereby reducing the interfacial energy (γ_{GB}). Carbon removes the native SiO_2 layer on SiC particles through carbothermal reduction, which enhances the surface energy (γ_{SV}). The combined effect of these sintering aids lowers the γ_{GB}/γ_{SV} ratio to a subcritical value, rendering densification thermodynamically advantageous [38]. In solid-state sintering, sintering temperatures usually exceed 1900 °C, guaranteeing sufficient diffusion activity.

Recent studies have explored the effects of different additives and processing parameters on the thermal and mechanical properties of SS-SiC ceramics [22,32–34,39–41]. Zhao et al. [22] investigated the addition of β-SiC nanoparticles (β-SiC_{np}) to enhance the thermal conductivity of solid-state sintered SiC ceramics. The introduction of β-SiC_{np} resulted in the homogeneous encapsulation of α-SiC particles, filling microstructural voids and enabling grain growth. These structural changes promoted longer phonon mean free paths, improving thermal conductivity. The optimized β-SiC_{np} additions achieved >100 $W \cdot m^{-1} \cdot K^{-1}$ in thermal conductivity, a marked improvement over conventional formulations. Additionally, for the aerospace applications of SiC ceramics, maximizing specific stiffness

is critical to minimizing structural weight. Yeom et al. [42] investigated the effect of B_4C content on specific stiffness and found that the specific stiffness reached a maximum of 144.4 × 10^6 $m^2 \cdot s^{-2}$ at a B_4C content of 20 wt.%. Meanwhile, the study also revealed that when the B_4C content was 10 wt.%, the flexural strength (~520 MPa) and fracture toughness (~4.2 $MPa \cdot m^{1/2}$) reached their highest values, while the thermal conductivity decreased due to the formation of amorphous intergranular phases when the B_4C content exceeded 20 wt.% (Figure 3). These observations emphasize the trade-offs between mechanical strength, fracture toughness, and thermal performance when optimizing additive contents.

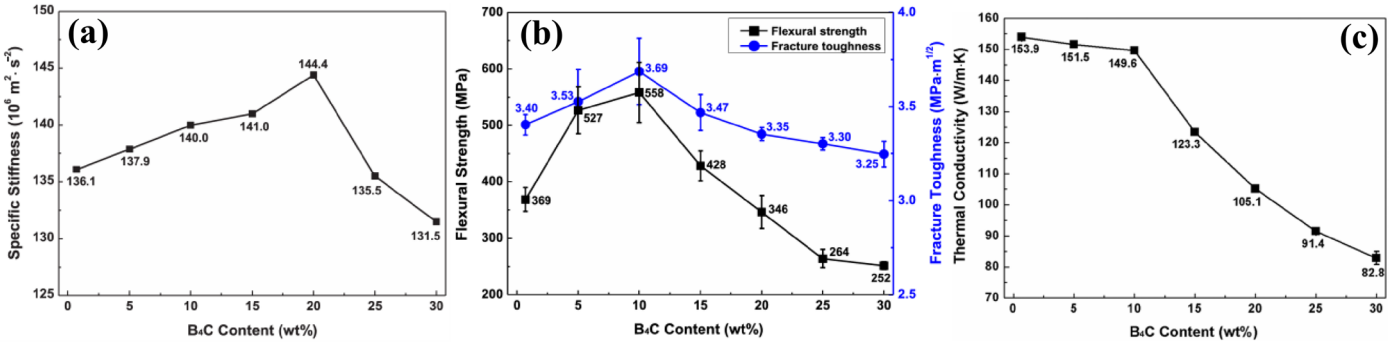

Figure 3. (**a**) Specific stiffness of SiC ceramics as a function of the B_4C content; (**b**) Flexural strength and fracture toughness of SiC ceramics as a function of the B_4C content; (**c**) Thermal conductivity of pressureless-sintered SiC ceramics as a function of the B_4C content [42]. Reprinted with permission from Ref. [42] Copyright 2023, Elsevier.

In addition, SS-SiC ceramics find applications in those requiring intermediate mechanical performance and wear resistance, such as kiln furniture, ballistic armor, and structural components for mechanical systems [43]. SiC ceramic ballistic armor has received significant attention from scholars in the defense sector. Dong et al. [43] suggest that the key challenge in developing SiC ballistic armor lies in optimizing the types and proportions of raw materials and additives to sinter silicon carbide ceramics. This optimization is crucial for balancing the hardness and fracture toughness of the ceramics, enabling them to withstand both high-penetration impacts and the shocks from multiple weapon types. The future development of ballistic armor is expected to focus on lightweight, composite structures with high hardness and toughness.

Despite its simplicity, the solid-state sintering of SiC ceramics encounters multiple challenges. The high sintering temperature (~1900–2100 °C) required for effective densification is associated with substantial energy consumption and potential grain coarsening, leading to degraded mechanical properties [22,34]. As a result, expanding their industrial applicability requires advancements in additive optimization and process innovations. To illustrate, researchers have proposed utilizing multi-step heating profiles to limit grain coarsening and optimize thermal gradients during sintering [44]. Future work may also involve integrating solid-state sintering with secondary phases, such as SiC whiskers, graphene nanoplatelets, or other reinforcements, to enhance fracture toughness and thermal conductivity [22]. In summary, although pressureless solid-state sintering remains a fundamental technique in SiC fabrication due to its simplicity and scalability, the high sintering temperature limitations create challenges. Continued innovation in sintering aid chemistry and process design is essential for addressing these barriers and meeting the needs of emerging high-performance applications.

2.1.2. Liquid-Phase Sintering

Aiming at the high preparation temperature of SS-SiC ceramics, liquid-phase sintering (LPS) provides a low-temperature sintering approach. It mainly achieves the densification of silicon carbide ceramics at a lower temperature (~1800 °C) by using low-melting-point sintering aids such as SiO_2, Al_2O_3, AlN, and rare-earth oxides [23]. These additives play a crucial role in forming transient liquid phases during sintering, which facilitate mass transport and densification through enhancing grain boundary diffusion and particle rearrangement [13,45–49]. However, although LPS-SiC ceramics achieve near-theoretical densities (>98%), their mechanical and thermal properties at elevated temperatures are often compromised by the presence of amorphous intergranular phases. These films tend to soften and weaken at high service temperatures (>1200 °C), posing challenges for LPS-SiC ceramics, particularly in long-term high-temperature applications where thermal stability is essential [50–53]. Therefore, enhancing the high-temperature resistance of LPS-SiC ceramics has become a main focus in this field.

Recent studies have demonstrated the effectiveness of these approaches in improving LPS-SiC properties. Seo et al. [52] reported that optimizing rare-earth oxide additives (such as Y_2O_3 and Sc_2O_3) during LPS facilitated the

formation of crystalline intergranular phases, achieving maintained 93% of its room temperature (RT) strength up to 1600 °C, a marked improvement compared to conventional LPS-SiC with amorphous boundaries. Similarly, studies have shown that by using an extremely small amount of sintering aids (2000 ppm Y_2O_3), it is possible to maintain an extremely high flexural strength (981 ± 128 MPa) at 2000 °C by reducing the residual amorphous phases [53]. Additionally, since the viscosity of Si-O-C glass is strongly influenced by the contents of Al, O, and N, AlN and various rare-earth oxides are also added as sintering aids to LPS-SiC [54].

SiC ceramics exhibit exceptional chemical resistance and thermal stability in high-temperature corrosive environments, making them promising candidates for applications such as light-water reactor components. A recent comparative study [55] evaluated the hydrothermal corrosion resistance of SS-SiC and LPS-SiC ceramics under extreme conditions (360 °C and 18.6 MPa). The results revealed that SS-SiC exhibited concentrated void formation around residual sintering additives (e.g., B and C). These voids functioned as stress concentrators, accelerating crack propagation and delamination in specimens with pre-existing flaws. In contrast, in the absence of prefabricated cracks, LPS-SiC ceramics experienced higher weight loss due to the hydration of intergranular amorphous phases, which compromised their structural integrity (Figure 4). These findings emphasize the importance of optimizing the composition and purity of sintering aids to reduce the vulnerability of LPS-SiC to hydrothermal attack.

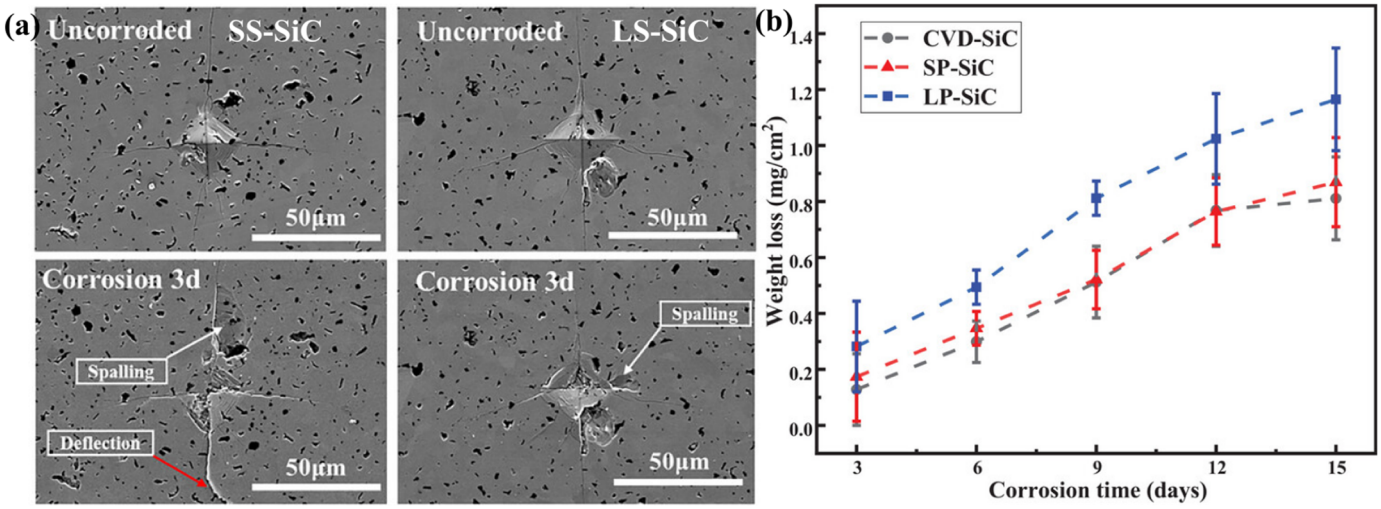

Figure 4. (**a**) Microstructure of SiC specimens with prefabricated cracks after exposure to high-pressure steam erosion; (**b**) Weight loss data of the SiC samples without the prefabricated indentation-induced cracks during the 15-day hydrothermal corrosion test process at 360 °C and 18.6 MPa [55]. Reprinted with permission from Ref. [55] Copyright 2025, American Ceramic Society.

Despite its advantages, liquid-phase sintering has its challenges. The presence of amorphous intergranular films limits the high-temperature mechanical reliability of LPS-SiC ceramics. Moreover, shrinkage and residual stress during cooling require precise control to ensure dimensional accuracy, particularly for large-scale components. Additionally, the susceptibility of amorphous grain-boundary phases to hydrothermal degradation in aggressive environments remains a major concern. To address these issues, future research should focus on developing new sintering aids that either minimize amorphous phase formation or promote their crystallization during sintering. Furthermore, combining liquid-phase sintering with advanced post-processing methods, such as isostatic pressing, could potentially enable the production of large-scale components with superior mechanical properties.

2.2. Reaction-Bonded Sintering

Reaction-bonded sintering (RB-SiC) is one of the earliest industrial sintering processes developed for silicon carbide ceramics, characterized by its low sintering temperature, short processing time, and close to the final shape capability [5,8]. In the traditional reaction-bonded silicon carbide process, ceramics are manufactured by blending silicon carbide powder with a small amount of carbon powder, followed by high-temperature infiltration of molten silicon. This reaction forms a dense SiC matrix through an in-situ process [56]. Due to its scalability and cost-effectiveness, RB-SiC has been widely adopted in industrial applications. However, with increasing demands for more complex geometries and high-performance components, traditional RB-SiC no longer meets the stringent requirements of modern engineering. Current research on RB-SiC is focused on advanced forming techniques such as injection

molding, tape casting, and additive manufacturing, as well as brazing technologies and the effects of additives and particle size distribution on the microstructure and properties of the final ceramics [24,56–65].

One critical limitation of traditional RB-SiC is the presence of residual free silicon. The incomplete reaction between infiltrated silicon and carbon results in unreacted free silicon, which compromises the material's mechanical strength, thermal stability, and maximum operating temperature. As such, RB-SiC is often limited to applications below 1380 °C [30,31,66]. Reducing the free silicon content has thus become a central objective in RB-SiC research [67–73]. Strategies employed to reduce free silicon content include optimizing the pore characteristics and carbon content of SiC/C preforms, enhancing silicon infiltration efficiency, and employing customized sintering conditions. Park et al. [63] demonstrated that using high-density diamond as the primary carbon source allowed for optimal pore channel design, which improved silicon infiltration into high-carbon SiC/C preforms. This resulted in RB-SiC ceramics with bending strengths exceeding 200 MPa at 1500 °C (Ar). These advancements highlight that careful control of preform properties and sintering dynamics is critical to improving the performance of RB-SiC ceramics. Low-cost, high-performance RB-SiC with reduced free silicon content represents a promising direction for industrial-scale applications.

In advanced applications requiring lightweight and complex geometries, such as large-scale structural components, heat exchangers, and catalyst carriers, traditional forming methods for RB-SiC have limitations in producing intricate designs. Additive manufacturing (AM), combined with liquid silicon infiltration, has emerged as a transformative technology enabling the fabrication of complex RB-SiC ceramics with unprecedented design freedom and enhanced material utilization. This approach allows the integration of intricate features, such as internal channels and lattice structures, which are challenging to achieve using conventional methods [1,58,59,74,75]. Figure 5 illustrates RB-SiC specimens fabricated using additive manufacturing technologies, showcasing their potential for lightweight and complex structural designs.

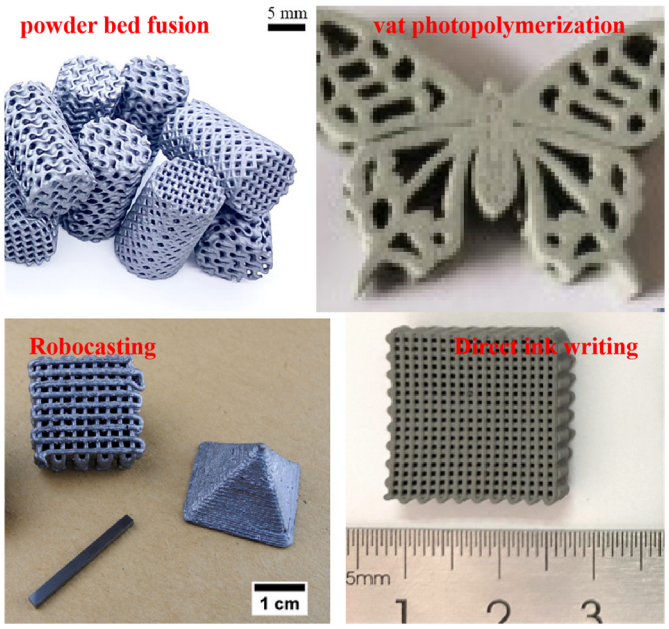

Figure 5. Samples prepared by partial additive manufacturing process [58,59,74,75]. Reprinted with permission from Ref. [58] Copyright 2022, Elsevier; [59] Copyright 2020, Elsevier; [74] Copyright 2024, Elsevier; [75] Copyright 2024, American Ceramic Society.

Recent advancements in additive manufacturing for RB-SiC focus on material and process optimization. Wang et al. [74] explored the shape retention and defect control of silicon carbide whiskers (SiC_w) during de-binding in light-curing molding techniques. By optimizing de-binding and sintering protocols, they successfully developed SiC whisker-reinforced RB-SiC ceramics (SiC_w/RBSiC) with bending strengths of 352.2 MPa and Vickers hardness of 17.54 GPa. Pelanconi et al. [75] employed polyamide powder bed fusion technology to fabricate green compacts, followed by ceramic precursor polymer infiltration, pyrolysis, and liquid silicon infiltration, yielding helical SiC ceramics with a maximum compressive strength of 24.7 ± 2.2 MPa, a skeletal density of 3.173 ± 0.022 g/cm^3, and a relative density of 93.5%. The results demonstrate the effectiveness of this approach in fabricating complex ceramic structures for engineering applications such as heat exchangers and catalyst supports. These studies fabricate SiC green compacts by sintering/melting binders in raw materials and obtain sintered bodies through debinding and subsequent sintering processes, which may lead to deformation or shrinkage. However, SiC lacks a molten phase under normal atmospheric

conditions, making it extremely challenging to prepare SiC products in a one-step process using direct additive manufacturing methods such as Laser Powder Bed Fusion (L-PBF) or Selective Laser Sintering/Melting (SLS/SLM) [76]. How to simplify the process and fabricate high-performance SiC ceramics will become one of the research priorities in the field of SiC additive manufacturing. Meyers et al. [77] investigated selective laser sintering using SiC and Si powders as starting materials, where silicon is melted and resolidified to bond the original silicon carbide particles. However, to fabricate RB-SiC components with higher performance, researchers still employed post-processing techniques such as resin impregnation, pyrolysis, and liquid silicon infiltration.

In addition, RB-SiC ceramics have been applied in the photovoltaic field. High-temperature carriers produced from silicon carbide, such as boat supports, uniform flow plates, silicon wafer boats, etc. (Figure 6, the picture is sourced from Science X (Huangshi, Hubei) New Material Technology Co., Ltd.), are increasingly replacing quartz and becoming crucial high-temperature devices in the thermal processing/thermal coating processes of photovoltaic production. Their complex geometries pose higher requirements for the additive manufacturing process. Such developments affirm the potential of additive manufacturing in producing high-performance RB-SiC composites with controlled microstructures. Additionally, customizing printing parameters, raw material formulations, and sintering systems has proven critical to achieving defect-free, high-density RB-SiC components.

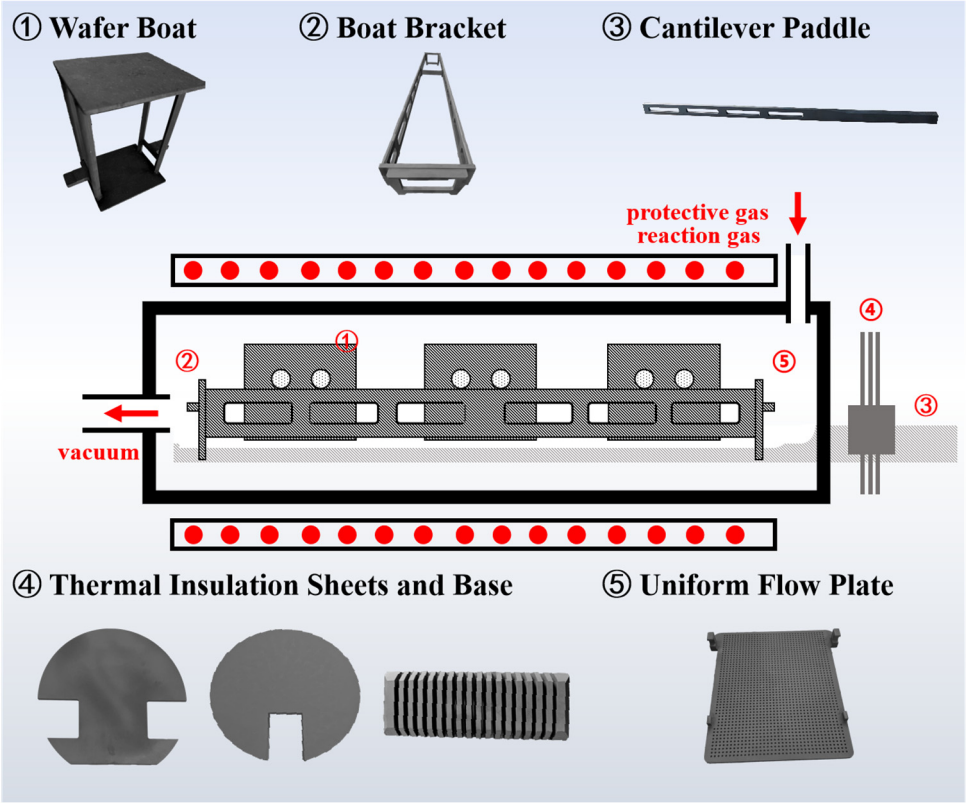

Figure 6. High-temperature carriers for photovoltaic field (①: for loading photovoltaic cells; ②: for carrying wafer boats; ③: for carrying wafer boats and boat bracket; ④: for ensuring the uniformity of furnace temperature; ⑤: for ensuring the uniform flow of reaction gases).

2.3. Recrystallization Sintering

Recrystallization sintered silicon carbide (R-SiC) is a unique sintering method that primarily employs SiC powder as the raw material. During the sintering process, evaporation, condensation, and recrystallization occur within a high-temperature and controlled-pressure protective atmosphere, leading to the formation of a sturdy SiC sintered body. In contrast to other sintering methods, R-SiC does not rely on external additives or binders to achieve densification. Instead, the recrystallization mechanism generates a sintered structure with minimal dimensional shrinkage. Throughout the sintering process, the distance between the centers of large SiC particles remains nearly constant, thereby preserving the overall volume stability of the material [14,37,78]. A notable feature of R-SiC is the presence of continuous gas pores within its structure. These pores are formed as a result of the limited densification and interconnected porosity during the recrystallization process. This distinctive pore structure confers R-SiC with unique properties, making it highly suitable for applications in high-temperature flue gas filtration, catalyst carriers, and diesel particulate filters [14,35,36].

Recent research has focused on optimizing the sintering parameters of R-SiC and investigating their impact on physical and mechanical properties, with particular emphasis on pore structure, permeability, and mechanical strength [26,35,76,77]. For example, Wang et al. [79] utilized the Dinger-Funk particle packing model to design optimized particle size distributions for SiC powders. This facilitated the fabrication of an R-SiC ceramic membrane with remarkable permeability. Figure 7 illustrates the relationship between the structural evolution of silicon carbide ceramic membranes and different sintering temperatures, as well as its sintering mechanism. The prepared membrane achieved a permeability of 1210 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$, demonstrating excellent performance in carbon black wastewater treatment. This study highlights the crucial role of particle packing and sintering neck formation in adapting the transport properties of R-SiC for filtration applications.

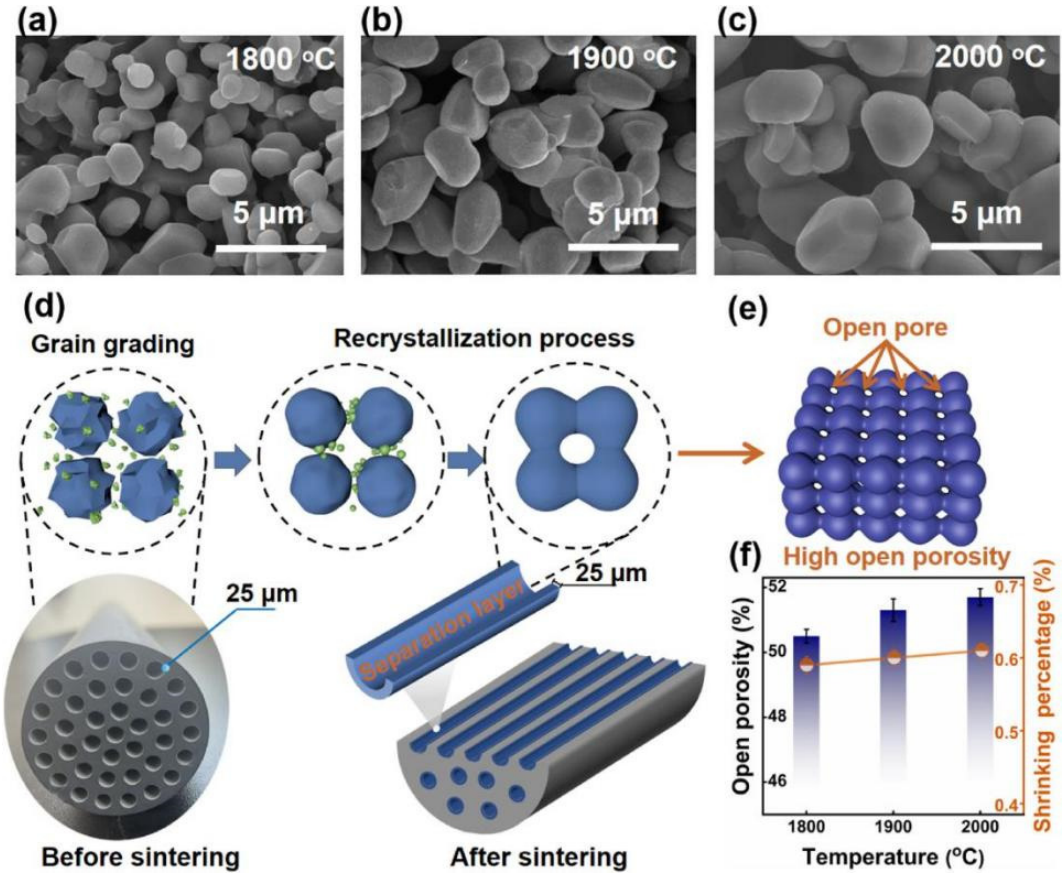

Figure 7. Structural evolution of sample sintered at (**a**)1800 °C, (**b**)1900 °C and (**c**) 2000 °C. (**d**) Schematic diagram of a green compact (**left**) featuring a bi-modal particle size distribution and its corresponding sintered body (**right**) under the conditions of an evaporation/condensation mechanism. (**e**) Opening structure schematic with high porosity, and (**f**) Open porosity and shrinking percentage of sample particle grading sintered at 1800–2000 °C [79]. Reprinted with permission from Ref. [79] Copyright 2024, Elsevier.

In another study, Yu et al. [14] introduced Al_4SiC_4 as a sintering additive to prepare R-SiC honeycomb ceramics via a two-step sintering process. The research explored the solubility behavior of AlN at various temperatures and its impact on sintering neck parameters and the mechanical properties of the honeycomb structures. Figure 8 shows the micro-morphology and the diagram of the high-temperature reaction mechanism of the nitrided-recrystallized SiC ceramics prepared at different sintering temperatures. The results revealed that uniform sintering necks with optimal connectivity were crucial for enhancing mechanical strength while maintaining sufficient porosity. The addition of Al_4SiC_4 enabled precise control over the pore structure and mechanical properties of the R-SiC ceramics, making them suitable for tailored industrial applications. Through continuous advancements in pore structure optimization and sintering techniques, R-SiC ceramics are expected to make significant contributions to industries that demand high-temperature filtration, catalysis, and environmental protection.

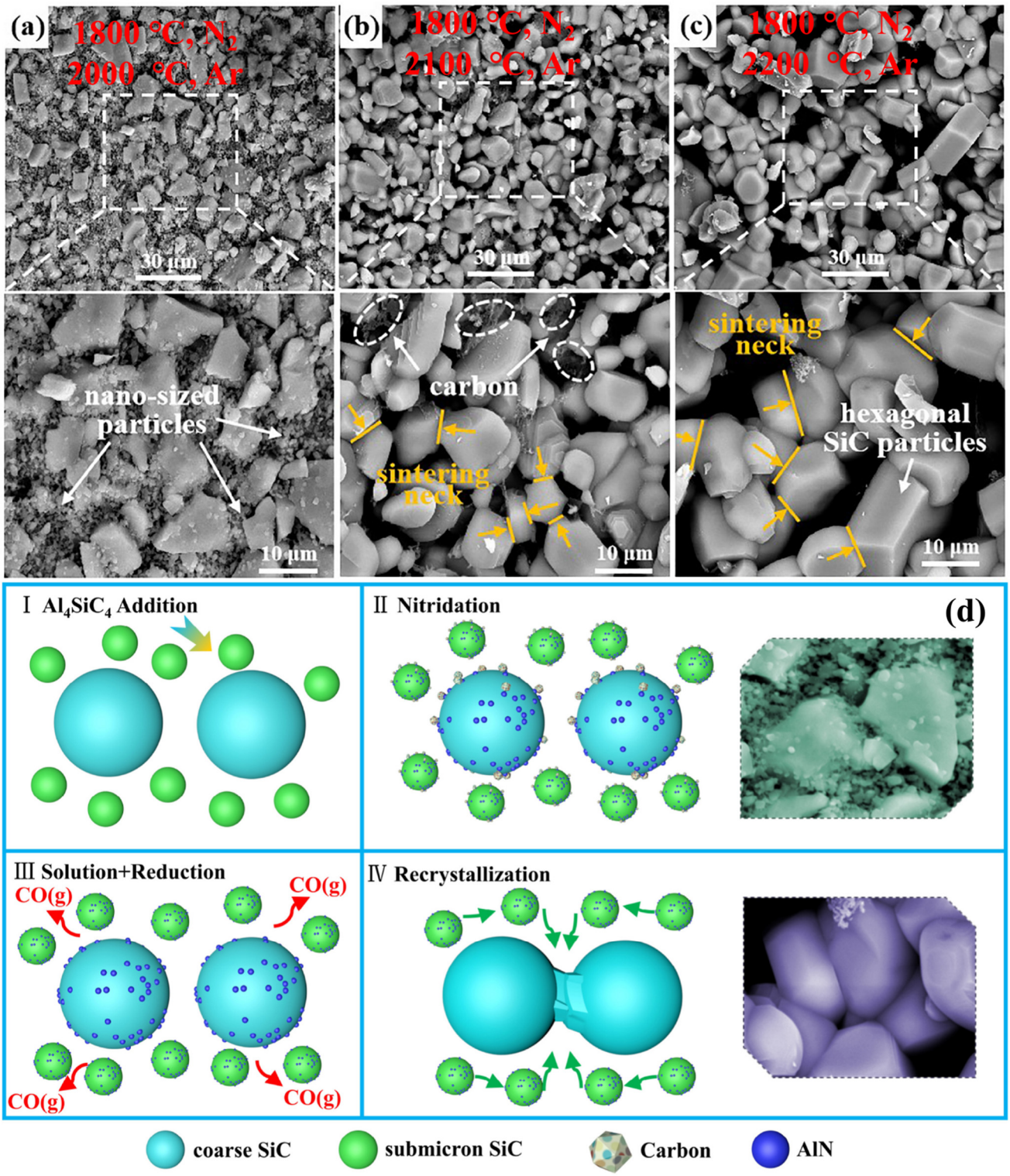

Figure 8. The micro–morphology of R-SiC ceramics sintered at different temperatures (**a**–**c**); Schematic of high–temperature reaction and sintering process (**d**) [14]. Reprinted with permission from Ref. [14] Copyright 2023, Elsevier.

2.4. Pressure-Assisted Sintering

2.4.1. Hot-Pressing Sintering

Hot-pressing sintering (HP) is a mechanical pressure-assisted sintering method (Figure 9). In this process, ceramic powders or green compacts are placed inside a die cavity and then subjected to uniaxial pressure at elevated temperatures. The external pressure enhances the densification process by promoting particle rearrangement and reducing pore size, allowing for the production of fine-grained and uniform microstructures within a relatively short sintering period. This method exhibits several advantages, including yielding superior mechanical properties, reducing both the sintering time and temperature required, lowering the requirements for sintering aids, and improving the high-temperature

performance of the final material [80–82]. However, there are limitations to hot-pressing sintering. Due to the constraints imposed by uniaxial pressing, this method is generally applicable only to simpler geometries. For example, it is well-suited for fabricating disk-shaped components, as well as other flat or axisymmetric parts such as chip carriers and sealing rings [9,25].

Hot-pressing sintering is extensively employed for the fabrication of high-melting-point ceramic composites, covering carbides and borides [83–86]. However, the strong covalent bonding within SiC poses a challenge in achieving complete densification without the aid of sintering additives, even when subjected to the high pressures and temperatures characteristic of hot pressing. As an example, Lee et al. [87] managed to prepare high-purity SiC ceramics via hot pressing at 2350 ℃ and 50 MPa, yet the relative density obtained was merely 92%. This clearly illustrates the difficulty in attaining full densification in SiC ceramics without sintering aids, which presents obstacles for industrial-scale production.

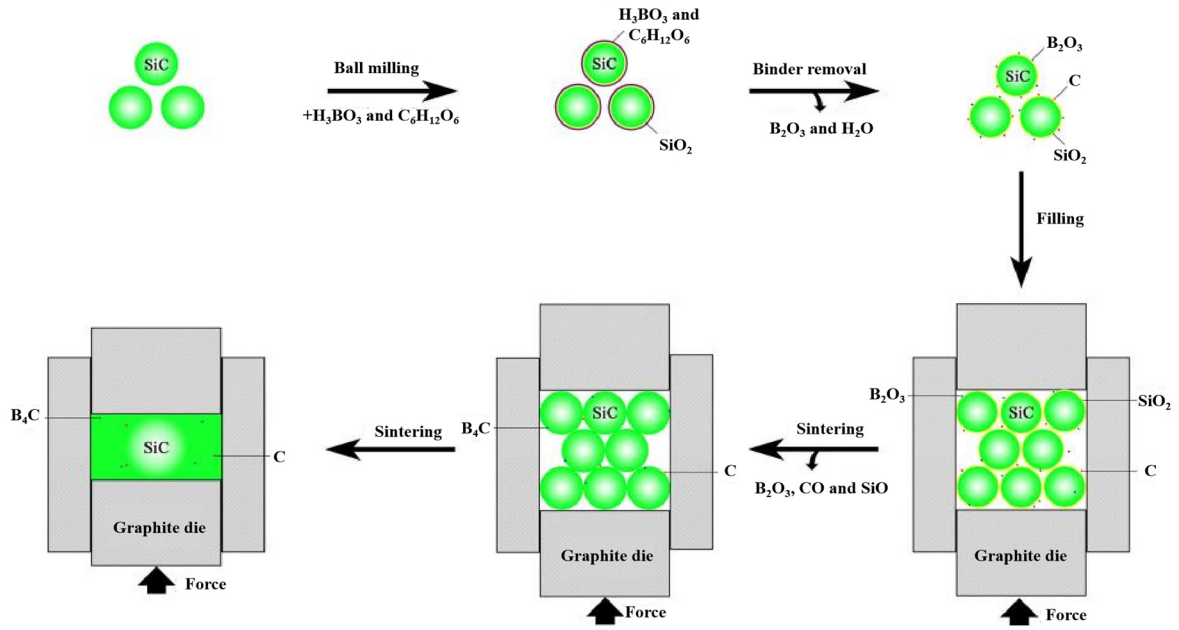

Figure 9. Schematic of preparation of SiC ceramics by HP sintering [25]. Reprinted with permission from Ref. [25] Copyright 2022, Elsevier.

To overcome these limitations, researchers have delved into the utilization of sintering aids to promote densification and enhance the mechanical properties of hot-pressed SiC ceramics. Tao et al. [88] employed aluminum powder, boron powder, and carbon black as sintering aids to produce silicon carbide nanofiber-reinforced silicon carbide (SiC_{nf}/SiC) composites through slurry impregnation and hot-pressing sintering. Under sintering conditions of 1950 ℃ and 30 MPa, the in-situ formation of an $Al_8B_4C_7$ liquid phase substantially facilitated the densification process, yielding a bending strength of 548 MPa and a fracture toughness of 15.86 MPa·m½. Likewise, liquid-phase sintering aids like Al_2O_3, Y_2O_3, and metallic Mg have also been demonstrated to foster densification in hot-pressing sintering by generating transient liquid phases that lower grain boundary energy and assist in grain rearrangement [9,89].

In addition to liquid-phase sintering aids, recent investigations have showcased the efficacy of employing smaller amounts of highly dispersed sintering aids to obtain high-purity hot-pressed SiC ceramics. As a representative example, boric acid and fructose have been utilized as sintering aids in high-pressure sintering to yield SiC ceramics with a residual boron content as low as 556 ppm and a relative density of 99.5% [25]. Owing to the low sintering temperature during HP sintering and the fact that the applied axial pressure suppresses grain growth, the grain size of high-purity ceramics is relatively small (Figure 10). This approach not only reduces the amount of sintering additives required but also minimizes the impact of residual impurities on the material's high-temperature performance, making it a promising strategy for producing high-purity SiC ceramics.

Despite its merits, hot-pressing sintering requires considerable equipment and process constraints. In particular, it necessitates meticulous control of temperature, pressure, and mold design. These stringent requirements restrict its applicability to relatively straightforward geometries and small-scale production. Moreover, the high pressures and temperatures implicated in hot pressing demand the employment of sturdy and costly equipment, which can inflate

production costs. Consequently, the application of hot-pressed SiC ceramics is frequently confined to high-value components where exceptional mechanical properties and thermal stability are imperative.

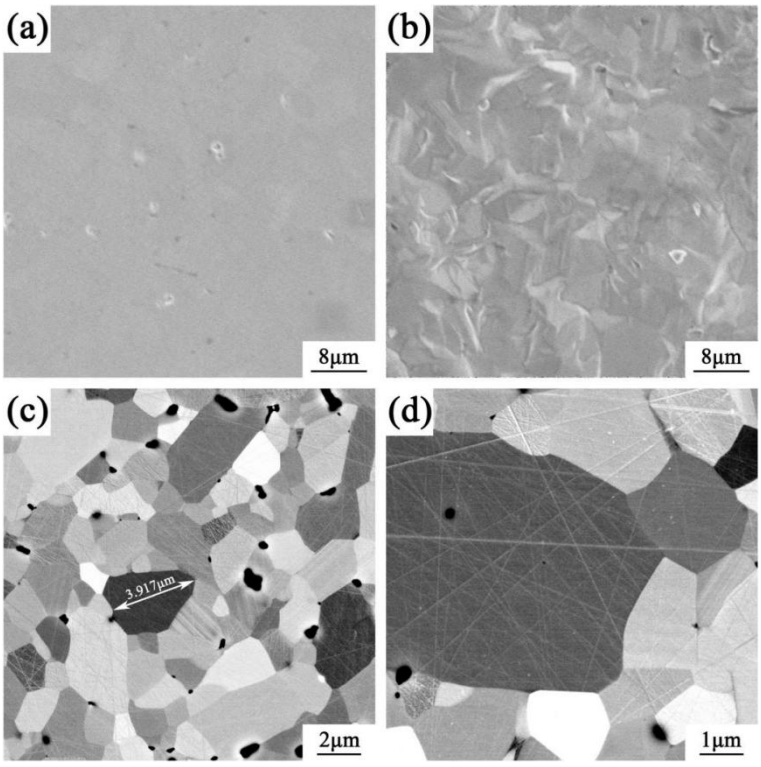

Figure 10. Microstructures of high-purity SiC ceramics: (**a**) SEM image of polished surface; (**b**) SEM image of fracture; (**c**,**d**) BSD image of polished surface (usually, larger and regular black areas were holes which was formed after small SiC grains had been ground away during polishing, and smaller oval black areas were pores.) [25]. Reprinted with permission from Ref. [25] Copyright 2022, Elsevier.

2.4.2. Gas Pressure Sintered and Hot Isostatic Pressing

Gas Pressure Sintering (GPS) and Hot Isostatic Pressing (HIP) are sintering processes for ceramic powders, green compacts, or sintered bodies. These processes use gas as a pressure medium to apply isotropic pressure during high-temperature and high-pressure sintering, achieving densification through the combined effect of high temperature and pressure. Both GPS and HIP are important for eliminating porosity, refining grain size, and increasing density, which makes them particularly suitable for producing complex-shaped ceramic components [90–96].

In Gas Pressure Sintering, N_2 is mainly used as the pressure medium and reactive gas. The sintering pressure is relatively low, so it is commonly used in the production of nitride ceramics or ceramics containing nitride compounds [96,97]. Research on the gas pressure sintering of SiC ceramics often relates to SiC composite ceramics or ceramics with reinforcing phases formed in situ by nitridation [92,97]. For example, Wu et al. [98] used Al_4SiC_4 as the raw material and produced a new type of AlN-SiC-C composite ceramic by sintering at 1700 °C under a nitrogen gas pressure of 20 atmospheres. The product had a relative density of 75.8%, a volume density of 2.20 g/cm^3, and a flexural strength of 120.9 MPa. The material had a cellular microstructure composed of interlocking worm-like SiC and C particles along with AlN ceramic boundaries (Figure 11).

On the contrary, Hot Isostatic Pressing (HIP) generally uses an inert gas like Ar as the pressure medium, which does not participate in reactions. HIP applies higher sintering pressures and is usually used for densifying ceramics or metal/ceramic composite materials [94,99–101]. For instance, Lv et al. [93] used nanoparticulate β-SiC powder, Si powder, C powder, and microparticulate TiH_2 powder as raw materials to in situ synthesize SiC-32%TiC composite ceramics through a hot isostatic pressing process at 1600 °C, 120 MPa for 4 h. The resulting SiC-32%TiC composite ceramics showed the best densification, hardness, flexural strength, and good fracture toughness, with a density of 98.7%, hardness of 21.2 GPa, flexural strength of 428 MPa, and fracture toughness of 5.5 MPa·m$^{1/2}$

However, the equipment costs for Gas Pressure Sintering and Hot Isostatic Pressing are high. Especially, it is difficult to manufacture equipment for ultra-high temperatures and pressures, which further limits their widespread industrial application. Controlling equipment costs and integrating with additive manufacturing and computer

simulations to accurately predict the effects of factors such as pressure, temperature, and time on material density and porosity changes could be key directions for the future development of GPS and HIP processes. This would enable the optimization of process schemes before actual production, reduce trial and error, and lower research and development costs.

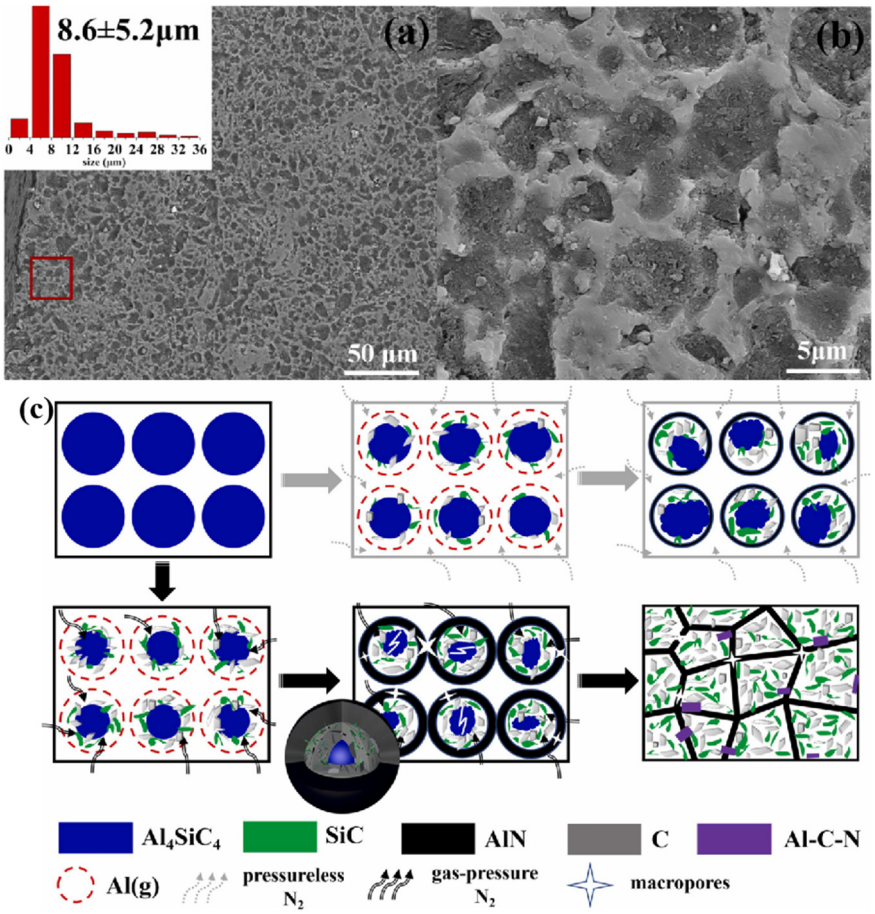

Figure 11. BSE images of specimens heat-treated at (**a**,**b**)1700 °C and Reaction model illustration for the formation of AlN-SiC-C (**c**) [98]. Reprinted with permission from Ref. [98] Copyright 2022, Elsevier.

2.4.3. Spark Plasma Sintering

Spark Plasma Sintering (SPS) is an advanced powder consolidation technique that has gained significant attention in the field of ceramic materials due to its ability to achieve rapid densification and fine-grained microstructures (Figure 12). The SPS process involves the application of high-energy, rectangular direct current pulses, which generate resistive heating and activate the powder surface through the formation of spark plasma in the interparticle gaps. This unique combination of electrical and thermal effects accelerates densification and promotes the formation of strong interparticle bonds, making SPS a highly efficient sintering method [27,102–105].

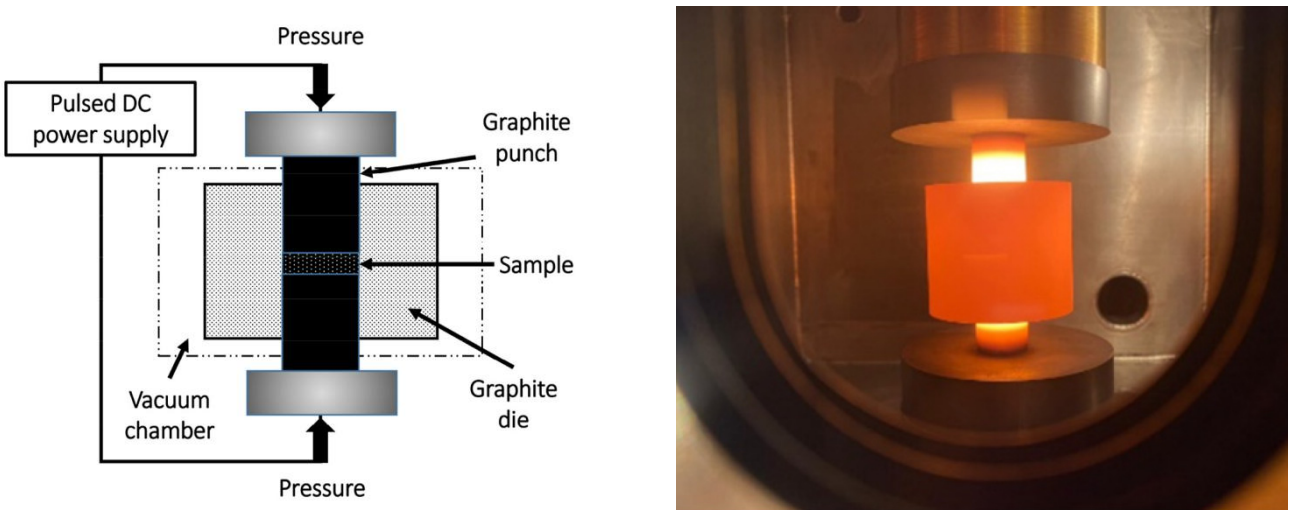

Figure 12. Principle of spark plasma sintering equipment [27,105]. Reprinted with permission from Ref. [27] Copyright 2023, MDPI; [105] Copyright 2023, Elsevier.

Despite its advantages, the densification temperature of silicon carbide (SiC) ceramics in SPS remains above 2000 °C in the absence of sintering aids, primarily due to the strong covalent bonding in SiC that limits atomic diffusion [103]. To address this, recent research has focused on exploring various sintering aids. These include oxide-based liquid phase additives like Al_2O_3 and Y_2O_3, which form transient liquid phases during sintering to facilitate grain boundary sliding and improve densification [27,104]; B-C system solid phase additives such as boron and carbon-based ones that reduce grain boundary energy and enhance diffusion for densification at lower temperatures [105–107]; MAX phases like Ti_3SiC_2, which are ternary carbides and nitrides with unique layered structures that promote grain refinement and improve mechanical properties [89,108]; and graphene and carbon nanostructures, whose incorporation not only enhances the electrical conductivity of SPS-SiC ceramics but also improves fracture toughness and thermal conductivity [109].

In addition to sintering aids, researchers have also investigated the influence of sintering parameters, including the sintering regime, powder layer thickness, and applied pressure, on the densification behavior and physical properties of SPS-SiC ceramics. Optimizing the heating rate and holding time can affect grain growth and pore elimination, thereby improving the mechanical and thermal properties of the final product [110–112]. Moreover, precise control of powder thickness during sintering has been shown to impact the uniformity of densification, particularly in large-scale components.

Another promising application of SPS technology is in the bonding of SiC ceramics. Employing the localized heating and high pressure essential to SPS, researchers have developed techniques for joining SiC components. This enables the fabrication of complex ceramic structures that are otherwise challenging to produce using conventional methods. This approach offers a novel strategy for manufacturing advanced SiC devices, such as heat exchangers, turbine components, and structural parts for aerospace applications [113,114]. The ability to bond SiC ceramics with minimal residual stress and high joint strength further highlights the versatility and potential of SPS technology.

In summary, Spark Plasma Sintering represents a cutting-edge sintering technology with significant potential for the fabrication and bonding of SiC ceramics. While challenges remain in reducing the densification temperature and optimizing sintering parameters, advancements in sintering aids and process control are paving the way for the development of high-performance SPS-SiC ceramics. Future research should focus on exploring novel sintering aid systems, integrating SPS with other advanced techniques, such as additive manufacturing [115], and scaling up the process for industrial applications, particularly in the fields of energy, aerospace, and electronics.

2.4.4. Oscillatory Pressure Sintering

Oscillatory pressure sintering (OPS) is an advanced pressure-assisted sintering technique. In this technique, oscillatory pressure is applied at a specific frequency during the ceramic sintering process (Figure 13). This creates a dynamic pressure environment. Compared to conventional constant-pressure sintering methods such as hot pressing and spark plasma sintering, OPS introduces additional driving forces for densification, resulting in several notable advantages. These include a reduction in sintering temperature, improved material density and densification rate, and enhanced mechanical properties of the sintered ceramics [28,116–119]. The densification mechanisms in OPS combine traditional processes—such as grain boundary diffusion, lattice diffusion, and evaporation-condensation driven by

surface energy—with unique mechanisms induced by oscillatory pressure. These new mechanisms include particle rearrangement, grain boundary sliding, plastic deformation, grain movement due to deformation, and the expulsion of pores [118]. At the same sintering temperature, OPS-SiC ceramics exhibit smaller average grain sizes, indicating that in addition to the lower sintering temperature, the oscillatory pressure applied during OPS also inhibits grain growth. Furthermore, compared with HP-SiC, the grain size-relative density curve of OPS-SiC shifts toward higher relative density, which also demonstrates that oscillatory pressure can effectively suppress grain growth. The dynamic pressure environment created by OPS thus accelerates sintering kinetics and improves the microstructural homogeneity of the final product.

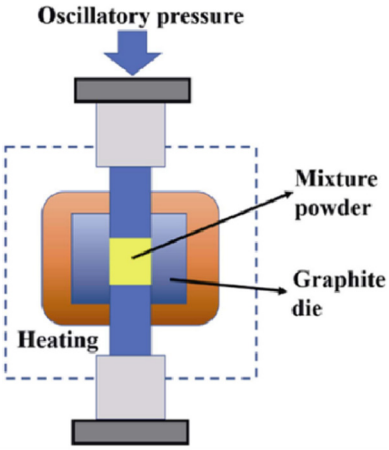

Figure 13. Principle of oscillatory pressure sintering equipment [117]. Reprinted with permission from Ref. [117] Copyright 2024, The Author(s).

OPS technology has been particularly effective in the sintering of SiC-based composite materials reinforced with one-dimensional (e.g., silicon carbide whiskers, SiC_w) and two-dimensional (e.g., graphene nanoplatelets (GNP_s)) reinforcements [6,116,120,121]. Notably, researchers have successfully used OPS to fabricate SiC-GNP composites with higher density and superior mechanical properties compared to those produced under constant-pressure sintering at the same temperature [120]. The incorporation of reinforcements such as SiC_w and GNP_s enhances the strength and toughness of SiC-based ceramics through mechanisms such as crack deflection, crack bridging, interfacial bonding between reinforcements and the SiC matrix, and strong bonding at SiC/GNP_s and SiC/SiC_w interfaces (Figure 14) [116]. These mechanisms not only improve the fracture toughness of the composite but also contribute to its ability to resist crack propagation under mechanical stress.

In addition to mechanical improvements, OPS also positively affects the tribological properties of SiC-based ceramics. Researchers have investigated the effects of external factors, such as applied load and sliding speed, on the wear behavior of SiC ceramics fabricated using OPS. It was observed that the addition of GNP_s and SiC_w altered the wear mechanism from brittle fracture-dominated abrasive wear to adhesive wear and micro-cutting, reducing wear rates. This transition in wear behavior highlights the ability of OPS to enhance both the strength and wear resistance of SiC-based ceramics, making them suitable for demanding applications [122].

The unique advantages of OPS technology make it highly promising for applications in fields such as aerospace, where components like engine blades and rotors require exceptional strength, toughness, and thermal stability at high service temperatures. However, the widespread industrial adoption of OPS is currently limited by high equipment costs, challenges in scaling up the process, and the complexity of manufacturing large-sized or intricately shaped SiC components. Future developments in OPS technology should focus on reducing sintering costs through innovations in equipment design and process optimization. Additionally, the development of scalable OPS systems capable of fabricating large and complex SiC structures will be critical for expanding its industrial applications. In summary, Oscillatory Pressure Sintering represents a novel and effective method for producing high-performance SiC-based ceramics. By leveraging dynamic pressure mechanisms to enhance densification, microstructural uniformity, and mechanical properties, OPS has the potential to address the stringent requirements of advanced engineering applications. Continued advancements in process scalability and cost reduction will be essential for unlocking the full potential of OPS in industrial manufacturing.

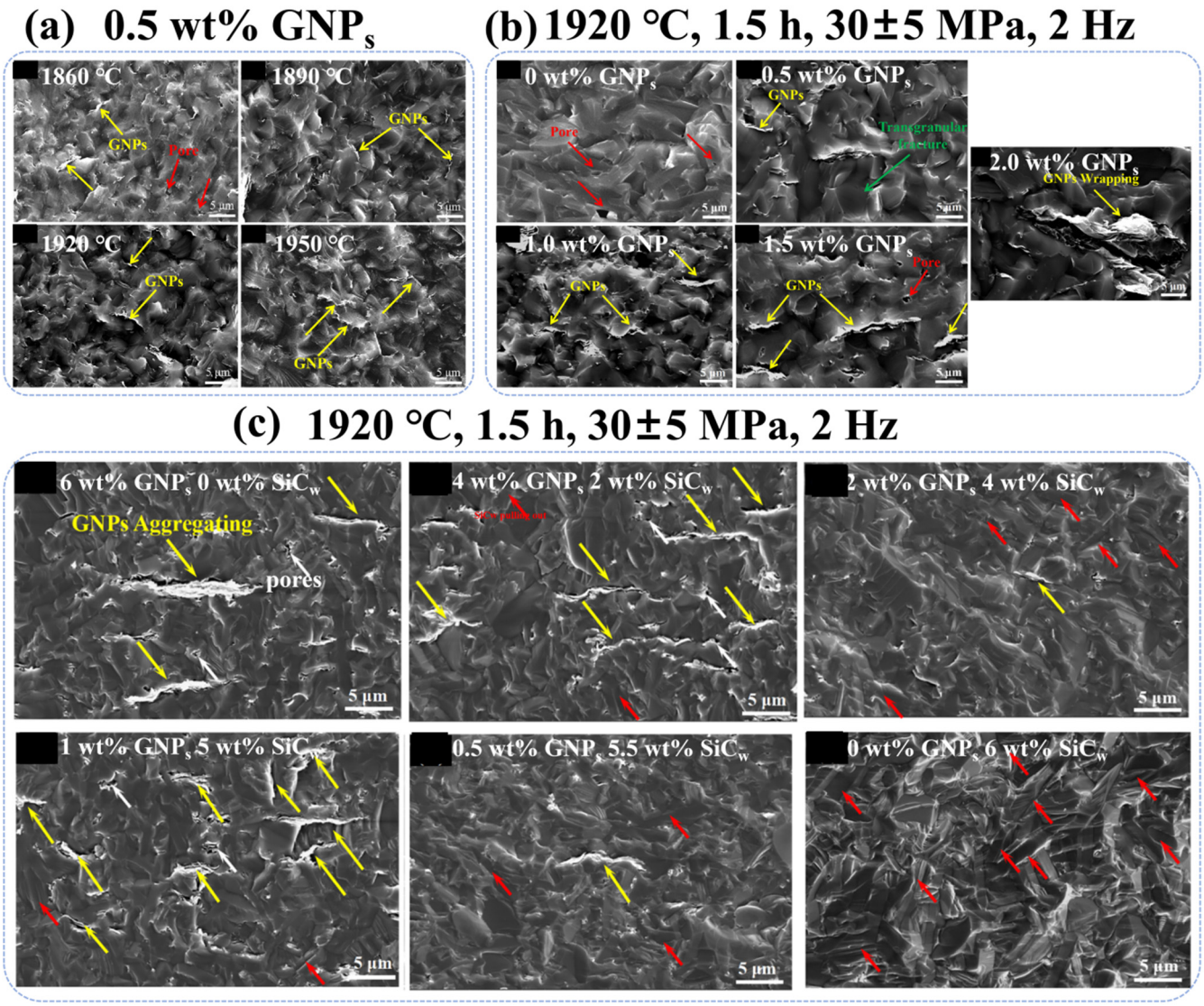

Figure 14. Micromorphology of SiC matrix composites reinforced by one-dimensional (SiC_w) and two-dimensional (GNP_s) reinforcements [116,120,121]. Reprinted with permission from Ref. [116] Copyright 2024, Elsevier; [120,121] Copyright 2022, Elsevier.

2.5. Flash Sintering

Flash Sintering (FS) is a groundbreaking electric field-assisted rapid sintering technique first introduced by Cologna et al. in 2010 [123]. The core principle of this method involves applying an external electric field to the ceramic sample, generating intense Joule heating effects within the material (Figure 15). This enables rapid densification, often accompanied by a characteristic "flash" phenomenon, representing a sudden surge in current and temperature. Flash sintering has acquired significant attention due to its ability to achieve ultra-fast sintering rates and substantial energy savings compared to conventional sintering methods.

One of the most notable advancements in flash sintering was achieved by Gibson et al. [124], who successfully demonstrated pressureless flash sintering of SiC ceramics for the first time using B and C as sintering aids. This approach produced SiC ceramics with a density of 94.4%, an average grain size of 5.9 ± 0.5 μm, and a Vickers hardness of 24.7 ± 0.5 GPa. Compared to traditional pressure-assisted sintering, flash sintering reduced the processing time by over six hours and lowered the furnace temperature by 700 °C, highlighting its potential for energy-efficient and time-saving ceramic manufacturing. In another study, Shin et al. [125] utilized high-purity silicon scrap derived from semiconductor manufacturing waste, combined with Y_2O_3 as a sintering aid, to fabricate β-SiC ceramics via flash sintering. The addition of Y_2O_3 enabled sintering at a lower furnace temperature of 1133 °C while enhancing the densification of the β-SiC ceramics. This study not only demonstrated the feasibility of recycling industrial byproducts for high-performance ceramic fabrication but also highlighted the role of sintering aids in optimizing flash sintering parameters. Their research also found that the porosity in the area near the surface of FS-SiC ceramics is higher than that in the interior, while the grain size is smaller than that in the interior region. This indicates that a gradient

temperature field occurs in the green compact during sintering, with the position close to the electrode being lower in temperature. The inhomogeneous microstructure poses challenges for the improvement of sintering processes and the application of materials.

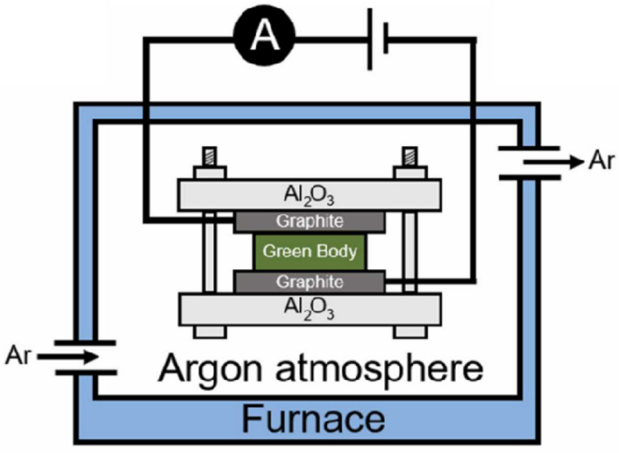

Figure 15. Principle of flash sintering equipment [125]. Reprinted with permission from Ref. [125] Copyright 2024, Elsevier.

Further innovations in flash sintering have focused on improving current pathways and enhancing localized heating effects. Lu et al. [126] developed a method to create thermal pyrolytic carbon (PyC) "bridges" between SiC particles through the carbonization of phenolic resin. These PyC bridges provided abundant conductive pathways, reducing the sintering time and facilitating rapid densification. The transformation of PyC from amorphous carbon to oriented graphite carbon during the sintering process indicated the successful generation of localized ultra-high-temperature environments. This technique also shows potential for localized repair of matrix damage in SiC ceramic-based composites, further expanding the applicability of flash sintering technology (Figure 16).

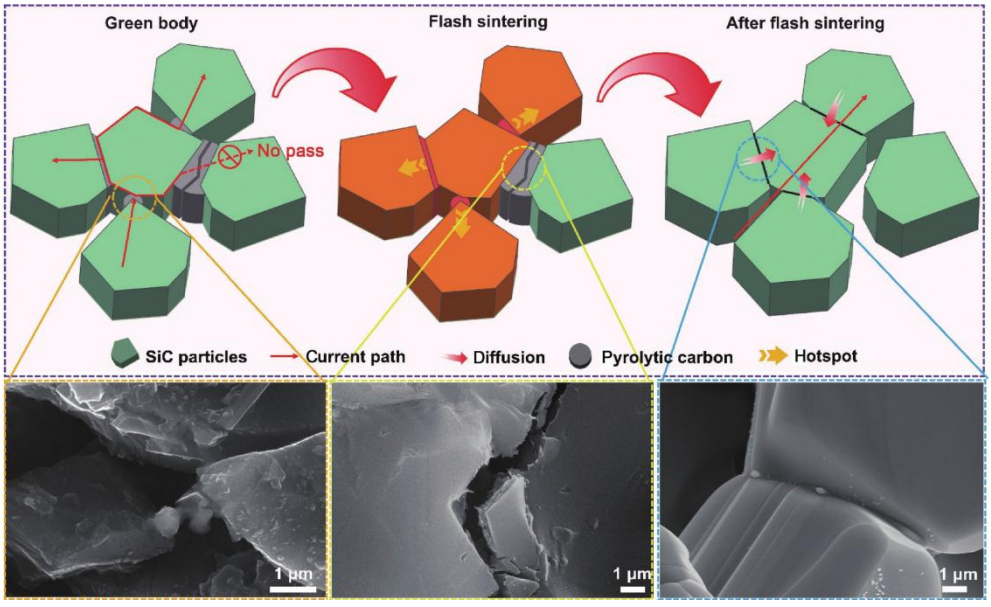

Figure 16. Diagram of optimal current path formation during FS [126]. Reprinted with permission from Ref. [126] Copyright 2024, The Author(s).

Flash sintering offers several advantages, including reduced energy consumption, shorter production cycles, and lower furnace temperatures, making it one of the most advanced energy-efficient technologies for densifying SiC ceramics [127]. However, despite these promising developments, several aspects of the underlying sintering mechanisms remain poorly understood. Key uncertainties include the precise roles of the applied current and electric field during the flash phenomenon, the mechanisms governing material transport and densification, and the chemical reactions occurring within the ceramic matrix. These knowledge gaps limit the broader adoption and optimization of flash sintering for industrial applications.

Future research should focus on elucidating the fundamental mechanisms of flash sintering, particularly the interplay between electrical and thermal effects during densification. Additionally, developing advanced models to predict the evolution of microstructures and properties under flash sintering conditions will be critical for process optimization. Efforts to integrate flash sintering with other advanced techniques, such as additive manufacturing or hybrid sintering methods, could further expand its industrial applications. By addressing these challenges, flash sintering has the potential to revolutionize the fabrication of SiC ceramics, offering a sustainable and efficient pathway for producing high-performance materials in fields such as aerospace, energy, and electronics.

3. Summary and Outlook

The advancements in SiC sintering technologies have established a firm basis to meet the growing demands of high-temperature industrial applications. The main conclusions of this review are as follows.

- Firstly, pressureless sintering, reaction-bonded sintering, hot pressing, and recrystallization sintering are still essential processes for producing SiC products, especially for large-sized and complex-structured components that operate in harsh environments. These methods are widely used because of their relatively low cost, scalability, and suitability for manufacturing lightweight yet durable components in industries such as aerospace and energy;
- Secondly, the role of additives in enhancing sintering processes remains crucial. Additives have a dual function: they reduce sintering temperatures and improve densification while also affecting the high-temperature mechanical and thermal properties of SiC ceramics. Therefore, determining the optimal composition and content of sintering aids is essential to achieving a balance between performance and processing efficiency;
- Thirdly, advanced sintering techniques such as spark plasma sintering, oscillatory pressure sintering, and flash sintering show great potential for producing high-purity and high-performance SiC ceramics. However, they are limited by high equipment costs and difficulties in scaling up for industrial applications. Striking a balance between cost and performance is a major challenge for their widespread adoption.

By advancing sintering processes, optimizing material properties, and integrating innovative techniques, the next generation of SiC materials is well-positioned to meet the challenges of modern engineering and contribute to the sustainable development of critical technologies.

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Author Contributions

Conceptualization, Y.C., C.Y., R.W. and J.H.; Investigation, Y.C., X.C. and C.D.; Data Curation, Y.C., J.D., B.M. and C.T.; Writing—Original Draft Preparation, Y.C., C.Y. and Z.L.; Writing—Review & Editing, Y.C. and C.Y.; Visualization, Y.C. and H.Z.; Project Administration, X.C. and C.Y.; Funding Acquisition, C.D. and C.Y.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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