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Item Type	Article
Authors	Oguntuyi, S.D.;Nyembwe, K.;Shongwe, M.B.;Johnson, O.T.;Adewumi, J.R.;Malatji, N.;Olubambi, P.A.
DOI	https://doi.org/10.1016/j.ijlmm.2022.10.005
Publisher	AVIC Manufacturing Technology Institute Publishing
Rights	Attribution-NonCommercial-ShareAlike 4.0 International
Download date	2025-05-21 07:59:22
Item License	http://creativecommons.org/licenses/by-nc-sa/4.0/
Link to Item	https://hdl.handle.net/20.500.14519/1540



Improvement on the fabrication of SiC materials: Processing, reinforcing phase, fabricating route—A review

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ARTICLE INFO

Article history:

Received 19 April 2022

Received in revised form

12 September 2022

Accepted 26 October 2022

Available online 31 October 2022

Keywords:

SiC

Ceramic matrix composites

Processing technique

Reinforcing phase

Fabricating route

ABSTRACTS

The ceaseless exploration for the improvement of ceramic materials has created a lot of techniques, all aimed at producing ceramic materials that can withstand environmental conditions and other factors. Most of the common techniques have their advantages and drawbacks. Some of the techniques involve the addition of a reinforcing phase to monolithic ceramic, the application of diverse sintering routes for the fabrication of ceramic products, and the preparatory methods for producing powder materials which cannot be jettisoned. These processes have been evaluated to influence the final ceramic products. Undoped/monolithic/single-phase ceramic has had some limitations in its processing, densification, and mechanical properties limiting its wide application in all circumstances. Hence, the incorporation of reinforcing phase, which can sometimes be called the secondary phase in the ceramic matrix, has significantly evolved into one of the possible means to nullify these challenges posed by undoped ceramics. This review consciously highlights and pinpoints all routes that have been taken to improve the properties of undoped SiC via the introduction of reinforcing phase, processing techniques, sintering techniques, etc. Finally, the possible prospects for future directions, advancement, and opportunities in the production of ceramic materials are concluded.

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1. Introduction

SiC is a ceramic material that is highly regarded for its high structural temperature application because it sublimates at 2730 °C [1]. SiC ceramic materials have some distinguished properties like low thermal expansivity, high stiffness and strength, excellent thermal and chemical stability, good wear and corrosion resistance, moderate hardness, good thermal conductivity, high melting point, fairly good resistance, creep resistance at elevated temperature (beyond 1000 °C) [2–8]. As a result of these distinctive properties, SiC materials have a high proficiency to be applied in aerospace,

nuclear reactors (due to its low activation under neutron irradiation circumstances), cutting tools and grinding tools and also in harsh circumstances where loads and temperature varies, etc. [9,10]. The low self-diffusivity and covalent nature of SiC materials, resulting in the densification challenges, have limited their vast application in certain areas [11]. The bonding energy between the individual element of Si and C of SiC, which comprises 12% ionic and 88% cation, makes the consolidation of SiC very difficult. For this reason, the densification of undoped SiC is mostly carried out at elevated sintering temperatures and pressures.

Advanced research of the prospects of densifying SiC depicted that via liquid phase forming additives, the pressureless sintering of SiC can be attained with Al₂O₃ + Y₂O₃/rare-earth oxides [12,13] and Al₂O₃ [14], which facilitates the reduction of sintering temperature

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(as low as 1700°C), and ensures the achievement of full densification. Also, liquid phase sintering (LPS) provides the advantage of controlling the properties and the microstructure of SiC ceramic. Most of the sintered materials with a fine-grained microstructure are usually equiaxed along with second phases at triple joints of the SiC grains [15,16]. This typical densification procedure is synonymous with the one applied for Si₃N₄. The resultant microstructure usually consists of two key stages, intergranular non-crystalline and crystalline, which are the same as Si₃N₄ formation on liquid-phase sintering. This typical relationship between the procedure techniques and the mechanism happening during the consolidation of both components paved the possibility to be applied in the condition of SiC. Various procedures of properties and structures modification such as sintering aids changes, in-situ toughening, secondary phase crystallization, weight loss control via atmospheric regulator of reaction powder beds or the sintering process, etc., which are effectively established for Si₃N₄-based ceramics, all have strong influence in the processing and final products of the materials [16–18].

Low fracture toughness is one of the factors that have hindered the structural application of the SiC material. To nullify this challenge, nanopowders have been discovered to enhance the sinterability and mechanical properties because they possess greater specific surface activities and surface areas in contrast with micron powders [19–21]. In achieving fine-grain size and high densification for SiC, reinforcing phases (aluminium, boron, or yttrium-based oxide) are mostly used for consolidation. Introducing these reinforcing phases often enhances the composite mechanical properties [22]. However, they present some challenges under irradiation (neutron swelling or absorption) because the oxide phase at the grain interface can hinder the mechanical behavior at elevated temperatures.

The innovation in ceramic matrix composites has drawn a high interest in nullifying the challenges of ceramics because the resulting composites produce a material with enhanced mechanical properties. Hence, the resulting products have gained a high place in space structures, aerospace engines, airframes, and other areas where creep and alternating load is prominent. Various functional structures incorporating ceramic matrix composites and coatings exemplify a practical mechanism for the impending development of high-temperature, aerospace, and other lightweight systems. These have the prospective for use in applications that require the adaptation of a vast range of pressures and temperatures, which may be faced by impending materials used for cutting tools and hypersonic materials.

Diverse sintering techniques of conventional sintering, such as hot-press, hot-isostatic press, etc., and non-conventional sintering, such as microwave sintering, spark plasma sintering, etc., have been used to consolidate ceramics with each sintering process having their advantages and drawbacks. One technique that has received enormous usage owing to its capability to manufacture huge materials with intricate shapes and thus still has high industrial applicability is pressureless sintering [23,24].

This article consciously takes a review of the processing techniques that have been used for the improvement of SiC materials, with more focus on the reinforcing phase, fabricating techniques, and other routes.

1.1. Properties and structures of SiC

Silicon carbide possesses excellent thermal, mechanical and chemical features. It also exhibits an extraordinary chemical inertness, making it a fit for use in a corrosive environment where the operative environments are chemically severe. Silicon carbide has a structural unit of a covalent bond which is a majorly

coordinated tetrahedron, either CSi₄ or SiC₄. The four bonds which are engaged to the surrounding possess a pure covalent nature. And due to the disparity in electronegativity between the carbon atom and the silicon, an electrovalent influence on the interatomic bonds can also be assumed from the change of the Ka doublet, which is situated in the spectrum of the X-ray emission of Si in SiC. The outstanding characteristics of the crystal configuration of silicon carbide are its polytypism, which makes SiC crystal structure show some diverse one-dimensional assembling structures without other differences in stoichiometry. A significant variation of SiC polytypes is identified, and it is generally known that the state of the non-cubic structures (rhombohedral and hexagonal) in a group is α -SiC and to all cubic polytypes is β -SiC.

The crystals of the SiC exist in some variations that possess trigonal or hexagonal symmetry. All these can be designated in the normal hexagonal axis system, particularly the *c*-axis vertical to three equal axes, *a*, *b* and *c*, which have angles of 120° with one another. It was depicted by Ott [25], who stated that all SiC possess a similar structure via the crystallographic adjustments: they all have equal layers perpendicular to the trigonal or hexagonal axes. Although the individual structure maintains its repetitive distance, usually due to the characteristic change of the assembled similar layers in the direction of these axes, The CSi₄ or SiC₄ tetrahedra are typically organized in a manner that the whole atoms lie parallel in planes on the modes of fixed hexagonal networks, as depicted in Fig. 1 (b) [26] in relative to carbon-carbon interplanar distance, the distances from the neighboring silicon planes to the carbon plane have a ratio of 1:3. Consequently, this makes the symmetry axis perpendicular to these planes to be polar.

1.2. Production of SiC

SiC is a family of non-oxide ceramic materials, which may be in the form of powders, thin-film, and molded shapes that have made it possible to be manufactured on a large scale. SiC has fascinated commercial and scientific interests because of its vast, unique properties. These SiC powders can be produced through various routes. One of the conservative techniques of preparing SiC entails heating colloidal silica or silica along with carbon at elevated temperatures. Other routes include sol-gel methods, high-temperature synthesis (SHS), carbothermal reduction, self-propagation, gas-phase reaction method, etc. [27–29]. Lately, the production of nano-sized SiC has been made possible by thermal plasma processing [30]. The thermal plasma technique possesses various benefits in preparing nano-sized powders because it gives a clean reaction environment that produces products of high purity, a high handling temperature to vaporize all reactants, and yields an elevated cooling rate to form the fine powders. This technique is regarded as one of the huge potential methods for industrial structural engagement to manufacture nano-sized powders. Even though the aforementioned techniques can be used to produce nano-sized particles, these particles promote grain growth when used at elevated temperatures. Although, the synthesis of nano-particles at 3000 K via thermal plasma technique enables this particle to be used in an environment where high temperature is of utmost significance. Also, most of the time, milling used in line with the production of ultrafine SiC usually introduces impurities. Therefore, to evade these impurities, the vital technique that has been recognized to allow the production of SiC in a clean environment is thermal plasma techniques [31,32].

1.3. Powder metallurgy

The conventional means of manufacturing ceramic matrix composites with powder metallurgy (PM) commence with the

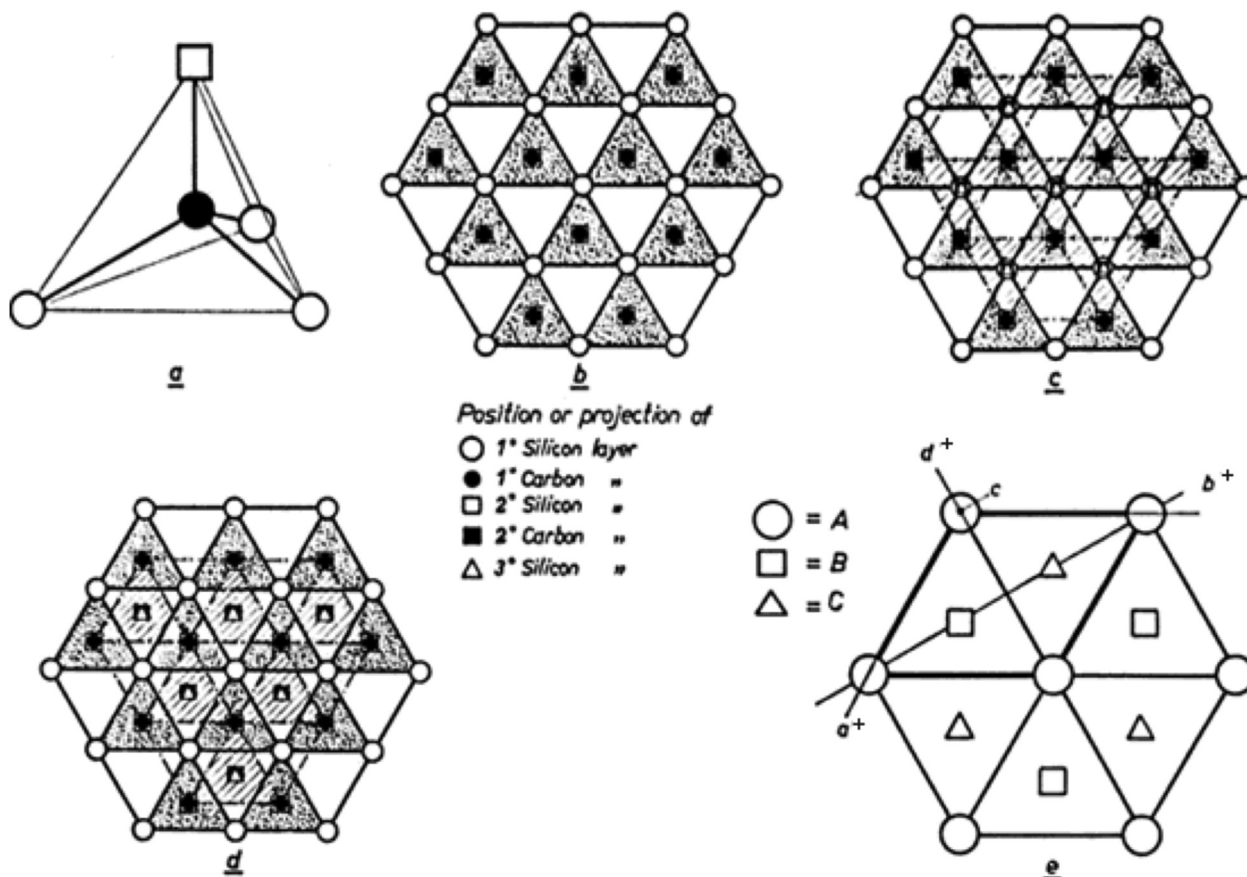


Fig. 1. Projection or position of silicon and carbon atoms in SiC [26]. (a) Tetrahedron of elementary Si-C. (b) Position of a tetrahedral layer. (c) Projection of cubic configuration of two adjacent tetrahedral layers. (d) Hexagonal configuration projection of two neighboring tetrahedral layers. (e) Projection of diverse positions of the atoms, the base and the axes system of the unit cell.

techniques of blending or mixing the as-received powder, which can be achieved via a planetary ball mill (of high energy ball mill). This method is followed by consolidation of the blended or mixed powders (Fig. 2).

PM provides numerous advantages in contrast to other ceramic developing technologies. PM makes the removal of scrap possible because most of the parts produced are net shape; it gives control over the shape, size, and position of porosity in the component; it enables the modification of microstructures to yield a variety of mechanical and physical properties. There is a fabrication of enough-to-high volume quantities, also inherent capacity to manufacture a wide spectrum of ceramic matrix composites with exceptional properties as well as production of huge latitudes of shapes is achievable, which is more cost-effective than ceramic forming/working methods viz forging, casting and machining [33].

In PM, the mechanical alloying procedures begin with blending powder in the exact proportion and after that put the blended powder in the mill with the grinding device. The preferred time for blending is calculated via the size of the powder particle to be attained and also the stability condition of the group of diverse powder particles. However, the ball milling operation entails the mixture of the powder under the subjecting of the effective impact via the milling media, and this brings a breakdown of the initial powders into a reduced size. In attaining improved milled materials, researchers have acknowledged that the wet milling technique is greater than dry milling. The wet milling technique eradicates cold welding, which often leads to a coalescence of powder particles. Also, there is a uniform mixture of the reinforcing

phase and the components matrix. Therefore, the introduction of mechanical alloying to ceramic matrix composites' production is an optimal technique for achieving improved uniformity of properties [34,35].

2. Sintering of SiC

The efficient sintering of SiC materials involves some parameter that must be considered. In the consolidation of undoped SiC, an elevated sintering temperature is usually required, consequently producing a material with developed grain growth because of the elevated temperature. Hence in minimizing this grain growth, the addition of reinforcing phases in the ceramic matrix has been detected to be efficient because they lower the sintering temperature and improve the materials' overall properties. However, some reinforcing phases whose properties are less than the matrix are always observed to impede the overall properties of the consolidated materials. In contrast, others give an increasing shrinkage rate, producing higher densification at a lower sintering temperature with improved mechanical properties. Also, at the grain boundary, there is a separation of the second phase due to the reinforcing phase. This has a negative influence on the features of high temperatures of the consolidated materials. Additionally, pressure can also be engaged to give an additional driving force for the consolidation, which also shortens the sintering time and lowers the temperature. Various methods with diverse reinforcing phases have been applied for the consolidation of SiC, including

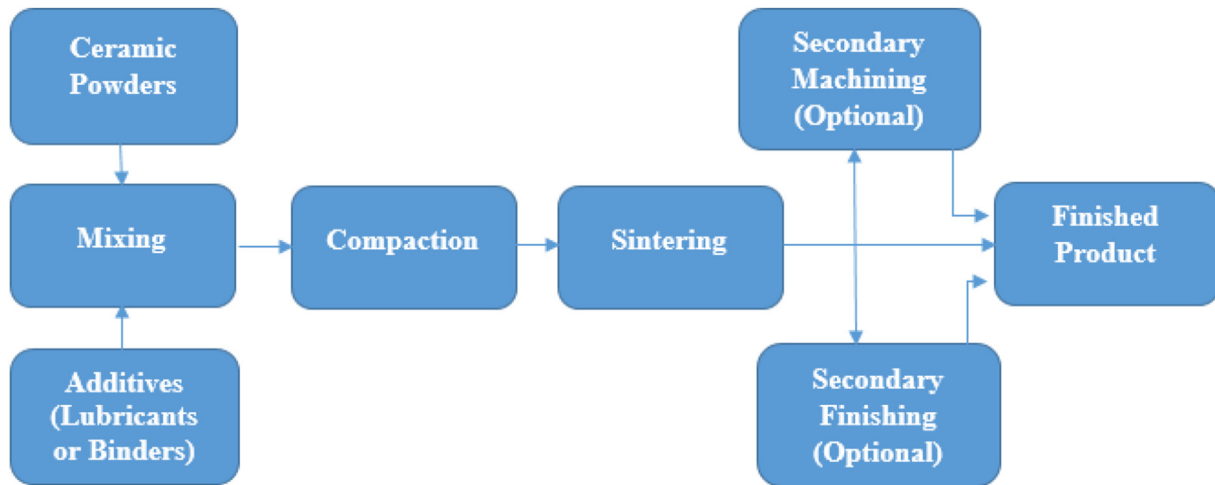


Fig. 2. Metallurgy process.

hot-pressing, pressureless sintering, hot isostatic pressing, microwave sintering, spark plasma sintering, etc.

Effective sintering of diverse contents of SiC–AlN–Y₂O₃ both in nitrogen and argon atmosphere, including or excluding gas overpressure, was stated. But some authors [36,37] noted that the consolidation of the material in nitrogens under standard and high pressure up to 10 MPa resulted in a wholly homogenous microstructure and phase dispersal throughout the composite. However, the consolidation in argon resulted in some secondary phase separation and vast inhomogeneous microstructure in the bulk of the consolidated materials. Although, other researchers [16,38] evaluated the contrary influence of these observations. Such typical differences could be a result of applying diverse compositions via the preparation of different reinforcing phases. This outcome indicates that further research effort is needed to fully comprehend the uniformities of the structure and phase development under certain parameters of liquid phase sintering. The whole SiC materials are mainly synthesized either by the solid-state sintered silicon carbide (SSS–SiC) or via the liquid phase sintered silicon carbide (LPS–SiC) from the initial SiC crystal-like powder [39,40]. In the instance of SSS–SiC, there is absence of developed phases, especially carbon, boron, aluminum, or their compounds, which can be applied for the consolidation of SiC via the decrease of the surface energy grains and the reaction between the carbon and the silica present. Hence, this necessitates the sintering of SiC at a sintering temperature above 2000 °C [41–43]. LPS–SiC is controlled at a particular sintering temperature via the development of a liquid phase of the metal oxide phase. This liquid phase organizes itself as a mass-carrying media during the consolidation of SiC [43,44]. When rare earth oxides, yttria, aluminium, and magnesia are applied as secondary phase, there is a reduction of the sintering temperature below 1850 °C, which is usually subjected to the type of reinforcing phases [44].

Although, the existence of the amorphous silicate compound at the triple points and grain interfaces of LPS–SiC causes a decline in creep resistance, hardness and high-temperature capacity in contrast with the SSS–SiC. Oftentimes, lower mechanical properties at high temperatures are produced when there is a weak secondary phase in the sintered materials [45]. This damaging influence deduces that the least fraction of the reinforcing phase is needed in such a situation. Moreover, the efficiency of the phases hugely hinges on their uniform distribution in the materials. The other method for producing SiC is regarded as a reaction bonded silicon carbide (RB–SiC). In this method, the carbon powder is made to

react with molten silicon, forming SiC [45–48]. However, this method needs a low sintering temperature and, consequently, no hindrance to the final shape and sizes produced; hence lower densification of the material is difficult [49,50]. Although, the reduction of sintering temperature is vital in saving energy. In the modern age, energy-saving has become a pioneer in finding other techniques fitting for the production of SiC ceramics at low temperatures. Lately, nano-sized SiC has been hugely examined to determine their physical, mechanical, and chemical features, which are not the same in contrast to the whole forms [29,50,51]. For instance, nanopowders are used largely due to surface activities and specific surface areas. This can produce the sinterability of nano-sized materials at low temperatures in the synthesis and thus the enhancement of mechanical features and densification can be achieved [52–54].

2.1. Ceramic matrix composites

The simple ideologies of composite materials can be traced back in time, from antiquated constructions with straw being strengthened/reinforced with clay to current-day buildings applying reinforced concrete. This has made it promising for diverse compositions to work collaboratively in overcoming the challenges of individual composition [55]. Ceramic matrix composites (CMCs) have presented a promising potential for the modern generation of materials production, which entails the integration of ceramic materials (whiskers, fibers, etc.) into a ceramic matrix so as to enhance its mechanical properties [56,57]. Single-phase or undoped/monolithic ceramics have some deficient thermal shock resistance and toughness needed for high-temperature structural application. This has propelled the development of materials via CMCs by adding mostly particulate reinforcement or fibers or whiskers (ceramics or metals) into the ceramic matrix [58,59]. The concentration in improving materials via nanostructuring invention has been credited to their optical, magnetic, electrical, and mechanical properties [60]. Particulate or fibers or whiskers (ceramics or metals) have been incorporated to strengthen ceramic matrices with a focus on achieving composite materials with improved mechanical properties that have stood as a challenge for nearly two decades [61,62]. The invention of nanostructured components is because of the reinforcing mechanism attained for components at a nanometer scale stage and the capability to maintain lesser grain size to enhance the mechanical properties [63,64]. The microstructural alteration at a quicker rate during

sintering is attributed to the vital role of grain sizes, which are nanometric [64,65]. Nanoceramic can be classified into two divisions that are largely centered on microstructural development: (a) nanocomposites of nanometric size particles, manufactured via the distribution strengthening route contained by the matrix grains (micron-sized) or distributed at the grain boundary and (b) nanocomposites of nanometer scale, here the matrix grains are in nanosize [66–68].

Developing the mechanical features of a component can be attained with the addition of nano/micro-ceramic phases (secondary phases) to accomplish more strength and hardness [68]. Although, nanoceramic composites exhibit excellent features like strength retention at high temperature, creep resistance, and fatigue than submicron/micron grains [69–71]. The reinforcement's properties of particulate or fibers or whiskers (ceramics or metals) such as toughness and strength in combination with ceramic matrix also having some properties like high modulus produces ceramic matrix composites which have a high propensity to be applied in elevated temperature structural environment. Ceramic composites incorporated with SiC_w often improved properties in contrast to the monolithic matrix [72]. Although several factors influence the characteristics of SiC_w contained in a ceramic composite, which necessitates the vast consideration of diverse perceptions so as to comprehend their behavior, considering their ultimate applications/purposes at first is indispensable.

Therefore, the enhancement in mechanical properties of CMCs has made it essential to be utilized in the automotive, chemical and aerospace industries [73,74]. The following particles are regarded as the utmost proficient reinforcements for ceramic matrix viz SiC, carbon nanotube (CNT), TiB₂, TiN, TiCN, Si₃N₄, TiC, TiB, TiO₂, Al₂O₃, TiAl, Zr₂O₃, etc.

3. The enhancement of SiC properties

The residual stress, grain size, porosity, and pore size strongly influence the strength of anisotropic (non-cubic) structural ceramics, especially SiC. Hence, the grain size variation and changes in the density of SiC along with volume fraction of the reinforcement particles is projected to strengthen the composite. It has been observed that the pores and grains in polycrystalline ceramics from integral flaws stretch into the adjacent matrix [75]. Therefore, the reinforcing phase and appropriate sintering route go a long way toward material improvement. This section will elaborate on the influence of liquid phase sintering and the reinforcing phase for the consolidation of SiC materials.

(1) The application of liquid phase sintering for the processing of SiC materials

The consolidation of SiC via the application of liquid-phase sintering has been given a high consideration in preference to other processing routes. Hence the development of a liquid phase is paramount when the reinforcing phases' selection for SiC liquid phase sintering is established on the eutectic parameter of two or more materials. The liquid phase is usually developed via a eutectic reaction between the SiO₂ on the SiC surface and the secondary phase when a single sintering phase material is applied. Owing to the strong negative Gibbs free energy of SiO₂ (−785 kJ/mol), the development of a SiO₂ film is expected on the SiC surface at normal ambient temperature [76]. Noviyanto and Yoon [77] stated the occurrence of thin SiC film (<2 nm) on fine β-SiC as revealed in Fig. 3.

The desirability of improving the relative density of SiC can be owed to the slight wetting angle of the liquid phase on SiC. Liu et al. [57] investigated the different metal wetting angles on SiC. A thin

film of SiO₂ formed on the SiC surface was discovered to inhibit the adhesion and wetting of molten metals. Thus, the SiO₂ film elimination is proposed to improve wetting, where Au–Si depicted the slight wetting angle between the different binary alloys. The wetting angles between binary alloys often ensure that ceramics avoid degradation; hence, desired properties during service are achievable. It was also stated that the potential additive metals reaction with SiC can be categorized into four which are: development of silicide and C, absence of reaction between the atoms, metal carbide and Si, and both metal carbide and silicide along with Si and C.

Taguchi et al. [78], investigated the wetting performance of binary oxides on SiC using Sm₂O₃–Al₂O₃ and Y₂O₃–Al₂O₃ systems. With increasing temperatures, it was found that the wetting angles declined for both systems, and at the eutectic composition of Sm₂O₃–Al₂O₃ and Y₂O₃–Al₂O₃, the slightest wetting angle was attained. Owing to the development of bubbles in the phases by the sintering atmosphere, it was also discovered that the wetting angle was affected. Thus the Ar atmosphere revealed a slight wetting angle than the N₂ atmosphere.

The liquid volume fraction is another parameter that influences LPS. The liquid phase volume is reserved for lower than 5 vol% for the production of higher ceramics components so as to avoid the deterioration of SiC properties [79]. Contrarily, liquid phase volume higher than 25 vol% is occasionally needed to occupy the interstices between the solid particles for efficient LPS.

The major challenge with using metal oxides, when added to a ceramic matrix, is that they undergo some dynamic interior chemical reaction at the sintering temperatures. Different researchers have proposed a variety of oxidation reactions between metal oxides and SiC producing gaseous substances and developing an austere weight loss and general change of the structure during heat treatment have been proposed in different researches [80–82]. It has been observed that some oxides, viz HfO₂, Al₂O₃, Y₂O₃, BeO, and other rare earth oxides, rarely dissociate SiC during sintering (2300–2400K). Although, the state becomes difficult due to the existence of SiO₂, which is in the form of surface oxide on the particles of any SiC powder. The formation of LPS of SiC progressively prompts the deduction that the procedure is synonymous with the liquid phase consolidation of Si₃N₄. This prompts the efforts of structure fitting by induction via the routes of diverse techniques such as the β to α transformation in SiC. Omori and Takei [82,83] observed that the vast range of rare-earth oxides, often with Al₂O₃ and/or boron compounds, can enhance the consolidation of SiC through the formation of liquid phase during the heating process.

The application of post-sintering at temperatures of 1950–2000 °C (heat treatment) either in nitrogen or in argon is the best examined and direct method to structure modification. This type of heat treatment produces an incomplete or complete β to α conversion resulting in a dissimilar grain structure containing equiaxed plate-like α grains and β grains. This procedure is mostly regarded as in-situ reinforcement or toughening [84]. This technique of structure modification has been fittingly done for Si₃N₄ – based materials [85] and has various benefits over the conventional route, i.e., the inclusion of particles/whiskers/platelets to the typical initial powder mixtures accompanied via hot pressing or sintering. It gives no health dangers related to whiskers, hence providing the capability to produce intricate shapes and large-sized materials. But long heat treatments at elevated temperatures, which are required to activate and attain the transformation from β to α phase in SiC, may lead to extreme weight loss and largely depreciation of the component. The weight loss resultantly impacts the microstructure and the densification of SiC ceramics. The oxide reinforcing phase that is uniformly disseminated in the green ceramics was mostly examined to undergo segregation and develop certain forms that were reliant on the overall weight loss, temperature and

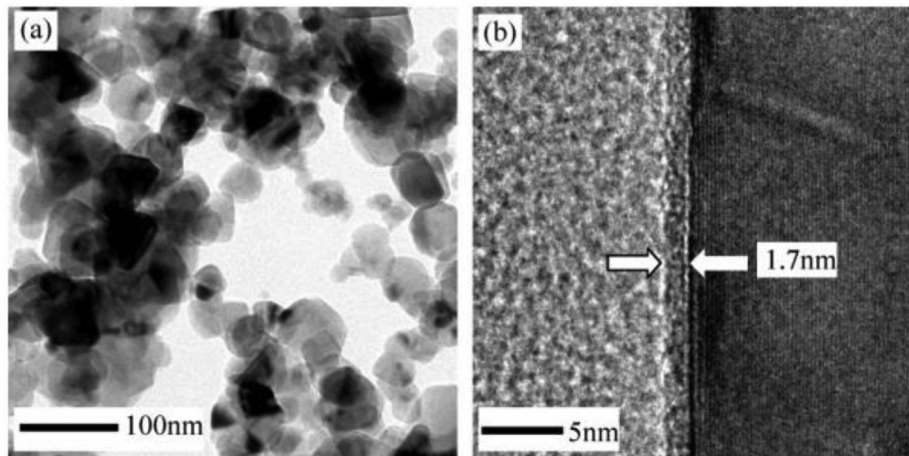
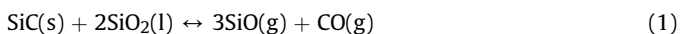
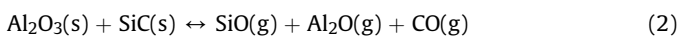


Fig. 3. HR-TEM image of β -SiC depicting (a) the material morphology and (b) the thin SiO₂ adsorbed on the surface [77]. (*HR-TEM — High-resolution transmission electron microscopy).

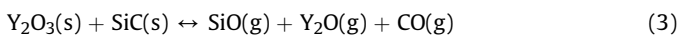
sintering time. Classification of diverse volatile reaction products was analyzed in Ref. [86]. Regarding the examinations of the weight losses arising during sintering of SiC–Y₂O₃–Al₂O₃ compositions in argon, previous weight loss happens as a result of the interface of the existence of SiO₂ (oxide surface layers) on the powder particles of SiC in accordance to the equation (1).



In regards to thermodynamic data, this reaction begins at 1300–1400 °C. At elevated temperatures above 1700 °C, the combination of Al₂O₃ with SiC succeeds in equation (2).



The combination of Y₂O₃ and SiC is also regarded as acceptable concerning the reaction



(2) Sintering of SiC with diverse reinforcing phases

Diverse reinforcing phases have been applied to enhance the features of SiC ceramics, the main pertinent of these phases are TiC, ZrB₂, TiB₂, B₄C, Cr₂O₃, TiC, Al₂O₃, graphene [87–91]. Thus far, Al₂O₃–Y₂O₃ [92,93], Al₂O₃ [93–95], Al₂O₃–Y₂O₃–CaO [13] have been examined to be an efficient secondary phase for SiC. These phases have been detected to improve the microstructure and mechanical features, particularly hardness, flexural strength, fracture toughness, etc.

Cho et al. [96] synthesized SiC ceramic using TiC and TiB₂ as reinforcing phase consolidated via hot press at a sintering temperature of 1850 °C for 1 h with a pressure of 25 MPa. The results depicted the importance of TiB₂ and TiC as the second phase in the matrix because improved toughness was attained, although the strength got reduced (Fig. 4). The composites of SiC containing 50 wt% of TiB₂ and 50 wt% of TiC have their fracture toughness equivalent to 50% and 60%, respectively, which were observed to be greater than the undoped SiC. Microstructural analysis of SiC–TiB₂ (Fig. 5b) composites revealed that the toughening mechanism occurred due to micro-crack development and crack deflection around the reinforcing particles.

Li et al. [97] investigated the behaviour of Magnesium (Mg) as a reinforcement for the properties enhancement of SiC materials. The composites were sintered at 1300 °C for 2 h under 30 MPa. The microstructural analysis via TEM and XRD depicted an absence of polytype transition, and simply Mg₂C₃ was developed. Various stacking faults and dislocations were discovered in both β and α SiC phases. It was further revealed that dislocations entangled close to the boundaries between the silicon carbide and magnesium. Some quantities of phases, such as Mg₂C₃ were detected on the boundaries. The substructures, such as stacking faults and dislocation structures, were detected in the SiC grains, and also dislocation loops were discovered near or on the grain boundaries. It was observed that the substructures possessed a solidification impact on the consolidated composites, which reflected the importance of Mg additives in the matrix [53,98,99].

Shinozaki et al. [100] carried out the pressureless sintering of B–SiC with boron, carbon, and aluminium as reinforcing phases. They detected that the inclusion of aluminium not only prompted the consolidation at significantly lower temperatures than carbon and boron alone but also improved the β to α phase alteration. Cao et al. [101,102] similarly made use of β -SiC as the starting powder with boron, aluminium and carbon as the phases to give in-situ toughened SiC ceramics via hot-pressing. The produced composite depicted optimum strength and fracture toughness.

Li et al. [103] examined the influence of 1 wt% B₄C and various amounts of (0–5 wt%) graphene to consolidate SiC ceramics using pressureless sintering. The obtained results revealed that owing to the optimum thermal conductivity and elevated electron transfer speed in the graphene sheets, the SiC thermal conductivity rised with an increase in the composition of graphene (0–2 wt%). Similarly, Guo et al. [104] manufactured SiC composites via pressureless sintering. The composites were strengthened with graphene obtained from graphite exfoliation. The graphene composition was studied on the sintering performance, microstructure, and electrical, tribological, thermal and mechanical properties. The achieved outcomes indicated that the introduction of graphene to SiC initiated the shrinkage reduction of the final composite. Further increasing the content (amount) of graphene in the matrix, the mechanical features of the resulting composite slowly declined, although thermal conductance and friction were improved.

Bucevac et al. [105] researched the influence of in-situ TiB₂ particles as a reinforcement on the fracture toughness and densification of SiC composites. In this study, the powder of β -SiC with a mean particle size of 0.7 μm was applied as the matrix powder and

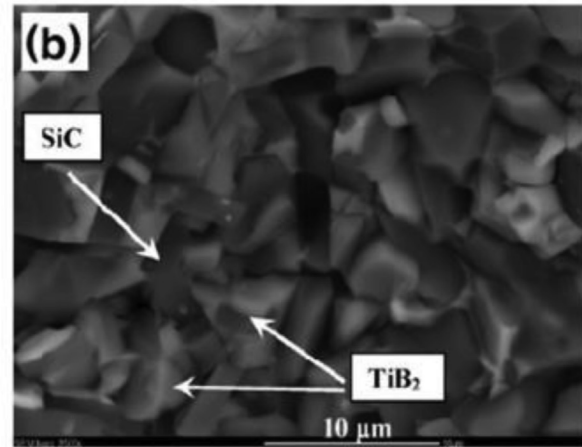
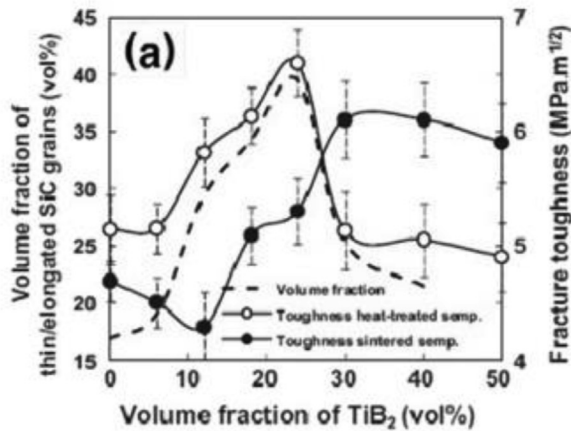


Fig. 4. (a) Fracture toughness, flexural strength of SiC–TiB₂ composites, and (b) microstructure of SiC–TiB₂ composites [96].

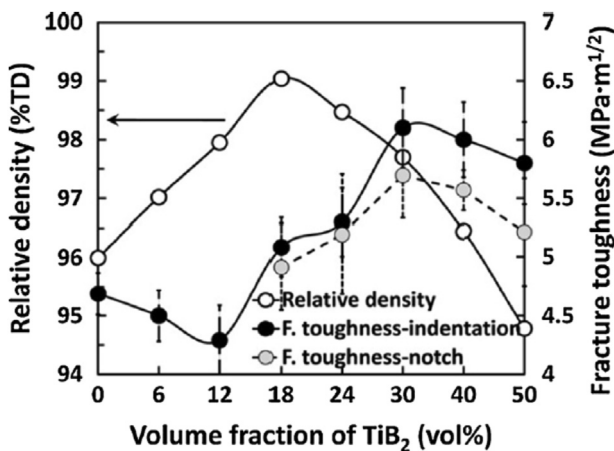


Fig. 5. Relative density and the fracture toughness of the composites as a dependent of TiB₂ composition, consolidated at 1940 °C [105].

Y₂O₃ and Al₂O₃ were used to fabricate the liquid phase and B₄C, TiO₂ and C with a mean size below 1 μm. In attaining 6–50 vol% of TiB₂ in a developed form in-situ in the matrix, the quantity of B₄C, TiO₂ and C and the amounts of Y₂O₃ and Al₂O₃ were chosen in the proportion of 4.3 and 5.7 wt%, respectively. The composites were consolidated via the pressureless sintering technique with a temperature of 1820–1970 °C for 1 h. The results indicated that the fracture toughness was influenced by the percentage volume of TiB₂ and the presence of TiB₂ particles restricted the grain growth of SiC grain. The percentage composition of 30 vol% TiB₂ produced the optimum fracture toughness of 5.7 MPa·m^{1/2} when sintered at 1940 °C. The composites' densification increased with increasing percentage of TiB₂, and the optimum densification was attained with the composite containing 18 vol% TiB₂ (Fig. 5). But the composite densification declined with quantity of TiB₂ beyond 18 vol%, this was attributed to the development of porosities when in-situ TiB₂ was formed.

Lee and Kim [106] studied the principal toughening mechanism in the reinforced composites of SiC–TiC. The reinforcing phase of Y₂O₃ and Al₂O₃ were applied to produce SiC–TiC composites via hot pressing, and afterward, post sintering of annealing was applied. The outcomes revealed that three fundamental interacting grains alongside propagating crack contributed to the toughening mechanism. They were triangular fractured grains, grains detected

at crack bridging sites and grains detected at crack deflection sites. The mean values of thickness, length and aspect ratio of the categorized grains are compared in Fig. 6. Although, elongated SiC grains caused some vital crack deflection which was described to be the principal toughening system in the sample.

Wei et al. [107] synthesized SiC–24.6%TiC composite via hot pressing with C and Al as reinforcing phase at a sintering temperature of 2000 °C. Theoretical densification higher than 99% was attained. The outcome depicted that increased strength and toughness were attained from crack deflection caused via TiC particles. This phenomenon is revealed in Fig. 7. The author established that fracture toughness and flexural strength developed with a rise in the content of TiC. In addition, when hot pressed with carbon and aluminium, the SiC fracture strength got enhanced via the introduction of TiC particles at elevated temperatures.

Khodaei et al. [91] conducted a research on the impact of TiO₂ nanoparticles in collaboration with Y₂O₃ and Al₂O₃ as secondary phases on the physical and mechanical features of SiC composite. The composites were synthesized via pressureless method at 1900 °C. The outcomes depicted that the introduction of TiO₂ to the amount of 4.5 wt% restricted unnecessary grain growth of SiC. Following the microstructural examination, it was observed that raising the amount of the reinforcing phase to 12 wt% produced grain growth and uneven distribution of the reinforcement phase.

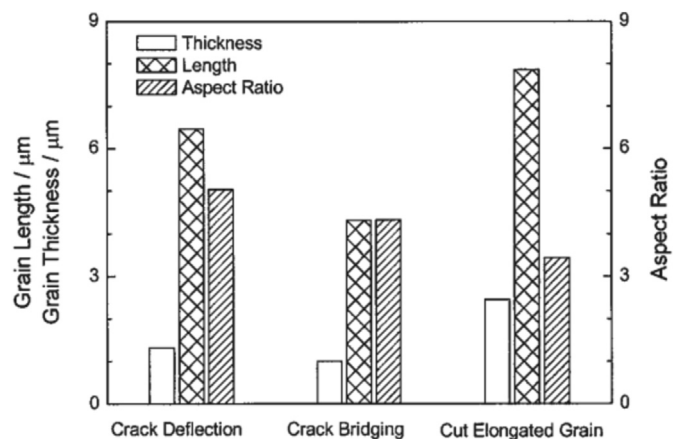


Fig. 6. The relationship between a toughening system and microstructural parameters in reinforced SiC–TiC composite [106].

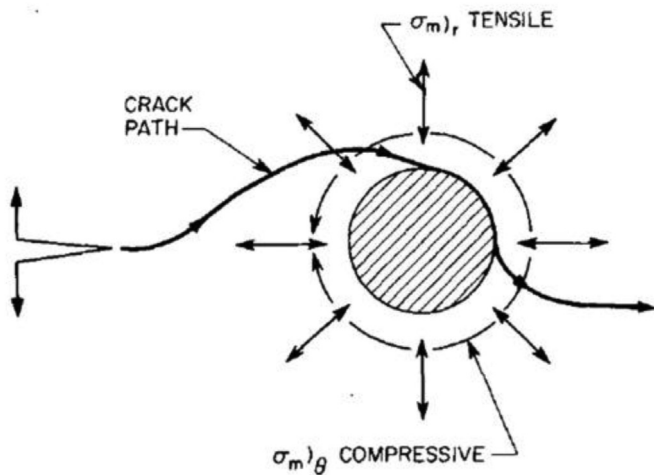


Fig. 7. The system of crack deflection. Crack propagation in the particle plane was deflected (compressive stress axis is perpendicular to the crack plane). As the crack propagates about the particle, there is an attraction to the particle interface [107].

This was due to the localization of particles reinforcement on grain boundaries which restricted the movement of grain boundaries, which were often detected when reinforcement particles were introduced at the critical level. Although, if the nanocomposite structure of the reinforcement content goes beyond a certain boundary, the sample properties decline. The undesirable trend was ascribed to the agglomeration of the particle reinforcement [108]. As observed from Fig. 8 (b) [91], most TiC phases, which were contained in a composite with 12 wt% TiO₂ nanoparticles, were seen to be agglomerated. Hence, an uneven reinforcement distribution could have produced lower densification and some of the samples' properties. In addition, the decrease in grain size was credited to the quantity of TiO₂ nanoparticles present in the composites. This is in concordance with the Zener pinning impact, according to which a rise in the amount of reinforcement declines grain size [109]. The composite with 4.5 wt% TiO₂ produces the optimum densification, indentation fracture resistance, young's modulus, flexural strength, and hardness of 98.7%, 6.1 MPa·m^{1/2}, 401.2 GPa, 522.7 MPa, and 27.1 GPa, respectively. The improvement in the indentation fracture resistance was ascribed to the stresses produced via the disparity in thermal expansion coefficients of TiC and SiC and the development of micro-cracks, grain pull-out, as

well as existing crack branching and crack deflection systems (Fig. 9 [91]).

Ki-Woong Chae et al. [110] scrutinized the densification performance and mechanical features of SiC composites reinforced with 30 vol% TiC fabricated alongside Cr₃C₂. It was reported that Cr₃C₂ in the composite had huge benefits as a reinforcement phase in the aspect of microstructural control and densification. The densification and fracture strength of 98.5% and 750 MPa were achieved after being hot-pressed at 1950 °C. The elongated α-SiC grains and the β-α phase conversion in SiC contributed to the fracture toughness improvement. The liquid phase, which was developed via the introduction of Cr₃C₂, consequently enhanced the samples' fracture strength. The development of the liquid phase by Cr₃C₂ in the composite was due to the reason that the reinforcing phase (Cr₃C₂) melts at 1895 °C, which was below the sintering condition (1950 °C) for the entire composite.

Dong Shaoming et al. [111] examined the mechanical features of SiC–TiC composites processed via Hot isostatic press (HIP). Two forms of TiC powders were used. As regards the mixture preparation, a die was developed and glass was also encapsulated. The solidification was achieved at 1850 °C under 200 MPa. Higher densification was attained for the increase in TiC particle contents. The bending test outcomes revealed that TiC size had little significance on the composites' strength as no tangible variation was observed in the obtained values. The composites with a higher composition of TiC particles have improved fracture toughness, whereas the composite with a small amount of TiC depicted greater hardness.

Khodaei et al. [89] carried out the influence of diverse nanoparticle compositions of Cr₂O₃ on the sinterability and features of SiC–Al₂O₃–Y₂O₃ composite. The microstructural examination revealed some phases of Yttrium aluminum garnet and Yttrium aluminum monoclinic besides the Cr₂O₃ and SiC. It was reported that the composite containing 5 wt% Cr₂O₃ produced the optimum densification, hardness, elastic modulus and fracture resistance of 97.45%, 28.19 GPa, 403 GPa, and 6.2 MPa·m^{1/2}, respectively. Furthermore, it was stated that the quantity of reinforcement phase in the composite is the vital factor influencing the grain size and density of the samples. It was discovered that the higher composition of Cr₂O₃ enhances the SiC grains growth, with crack branching, crack deflection and crack bridging being the main parameters for the composites' toughness improvement. Although, the increment in the aspect ratio of the grains can enhance then decline the fracture toughness to some degree [91].

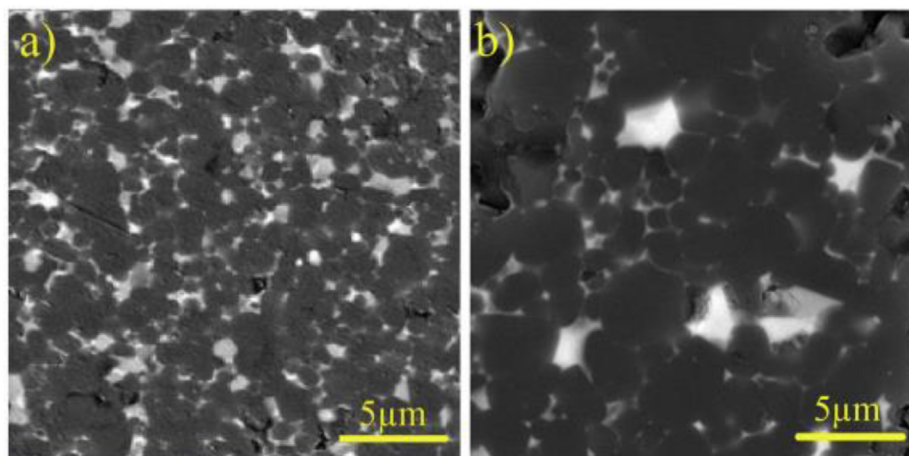


Fig. 8. SEM images of the composites having TiO₂ nanoparticles of (a) 4.5 wt% and 12 wt% [91].

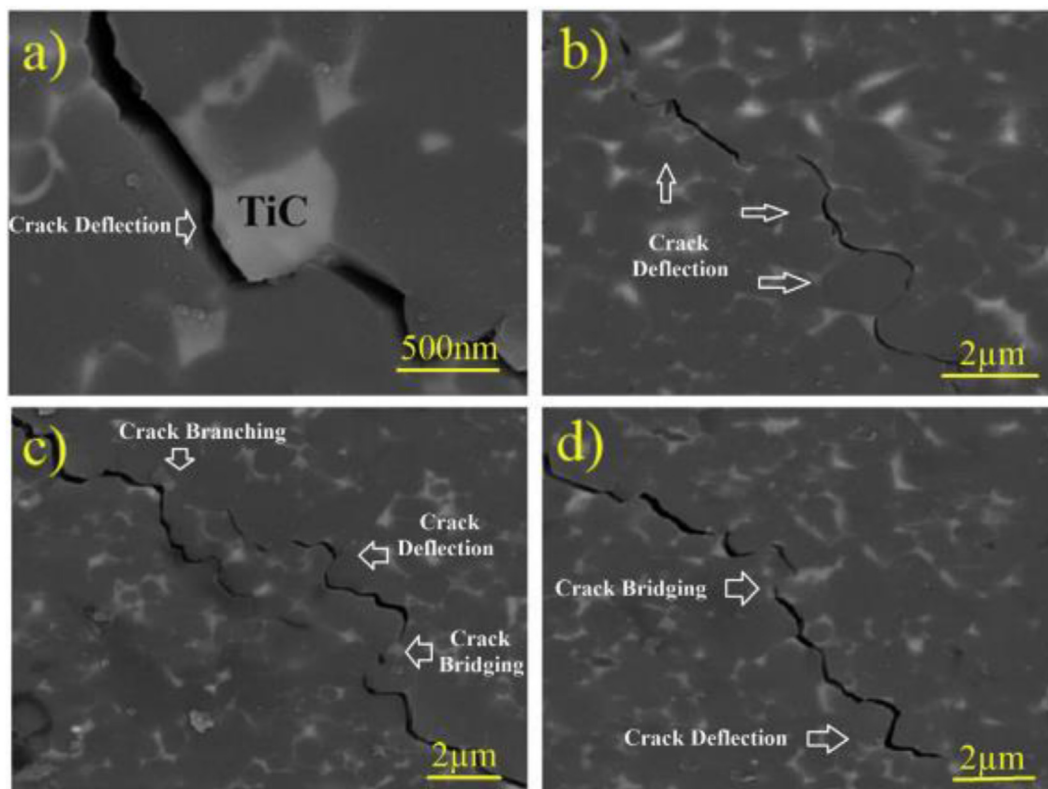


Fig. 9. SEM images of the composite with 4.5 wt% nano-TiO₂ showing the crack path [91].

Strecker et al. [112] observed the influence of microstructural variations emanating from sintering time as well as the ratio change of the raw materials on the fracture toughness of the sintered SiC composites. The composites were fabricated via pressureless route in the liquid phase of SiC using the powder mixtures of Y₂O₃ and AlN as secondary phase. The samples were consolidated at the temperature of 2080 °C for 1 h while other samples were given post sintering of annealing at 2000 °C for 4 h. The obtained results indicated that the samples with a higher composition of AlN produced the optimum densification. When the post-sintering process of annealing was carried out on the samples, the densification of the samples with a lower percentage of AlN got reduced. In contrast, the sample's densification with a higher percentage of AlN remained unaltered. This outcome indicated that weight loss is often susceptible to compounds rich in AlN via the phase evaporation or the combination between the SiC and reinforcing phases because the dissociation of AlN is strictly affected via the N₂ atmosphere, and AlN rarely combines with SiC [113,114]. The microstructural analysis of the sample with less percentage of AlN and also the sample with a higher percentage of AlN is depicted in Fig. 10. The later underwent post-sintering of annealing. It was observed that the aspect ratio remained unchanged, but the grain size got increased. The fracture mechanism is a collection of transgranular and intergranular modes. Fig. 11 shows the fracture surface and microstructure of the sample with a higher percentage of AlN, though without annealing; it was detected that the quantity of SiC grains (elongated) rised compared to the sample with less percentage of AlN. Likewise, by carrying out the annealing technique, non-vital grain growth was developed, and hence the transgranular fracture mode was produced. It can be established from the outcomes that the increment in the quantity of AlN as a reinforcement prominently minimizes the influences of reactions and evaporation between the SiC matrix and the secondary phases,

thus leading to higher densification. Despite engaging heat treatment at 2000 °C for 4 h, there was no decline in the densification.

Moreover, the increase in AlN composition as a reinforcing phase in the composite resulted in elongated SiC grains in the microstructure with an elevated aspect ratio which consequently improved the fracture toughness. Similarly, there was an observation that the growth of grains could improve fracture toughness, but during heat treatment, the aspect ratio remained unchanged. Therefore, fracture toughness of 6.7 MPa·m^{1/2} was attained, which depicted a nearly 100% rise in contrast to solid-state sintered SiC.

4. Futuristic approach to the production and consolidation of SiC materials

A futuristic approach to the consolidation of SiC nanoceramics should be made via properly handling the powders in a regulated atmosphere and diffusing the powder in an organic medium with the perspective of eliminating surface oxidation.

Researchers have established that post-sintering heat treatment has a significant role in enhancing composites' densification and mechanical properties. There is an initiation of α -SiC elongation and grain growth via this heat treatment. The development of elongated SiC in the structure produces 60% improvement in fracture toughness. Essentially, plate-like grains in composites produce some systems especially crack bridging, crack deflection, and grain pull-out. It should be well-known that the long-time usage of post-sintering heat treatment can produce some decline in a material's fracture toughness and some other mechanical features. Intergranular fracture and over-annealing, which causes cavities in fabricated materials, are the reasons behind the decline in mechanical features. Hence, a projected heat treatment accompanied by appropriate temperature should be well selected for the

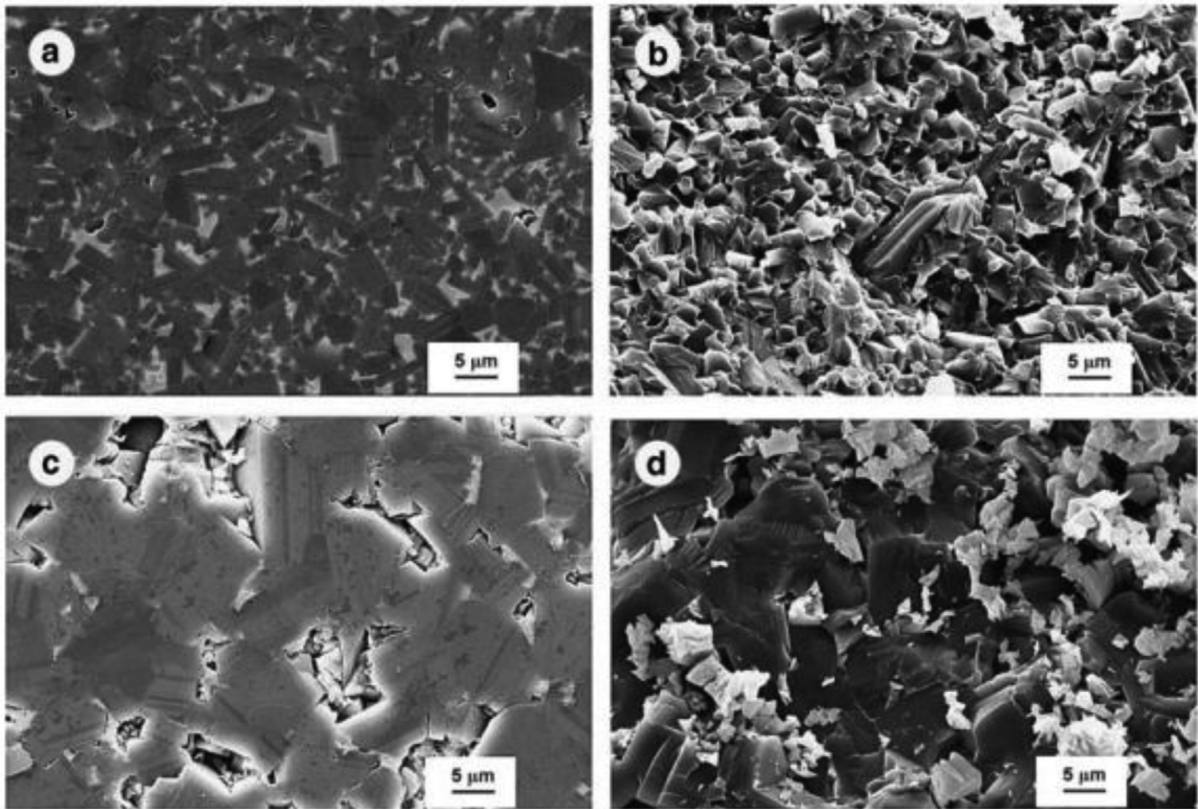


Fig. 10. The microstructure and fracture surface of the samples with a small percentage of AlN sintered at 2080 °C for 1 h under N₂ atmosphere – (a) and (b); (c) and (d) – the same sample sintered at 2080 °C for 1 h and annealed for 4 h at the temperature of 2000 °C [112].

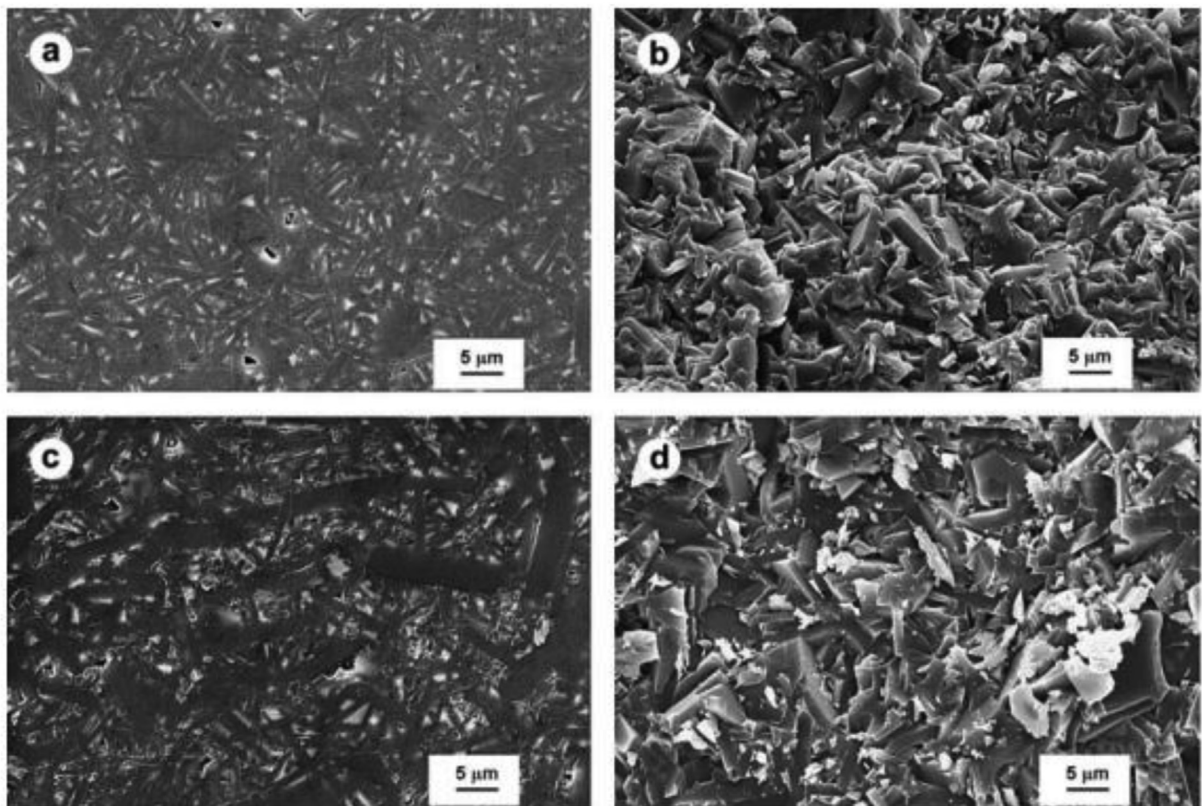


Fig. 11. The microstructure and fracture surface of the samples with a higher percentage of AlN sintered at 2080 °C for 1 h under N₂ atmosphere – (a) and (b); (c) and (d) – the same sample sintered at 2080 °C for 1 h and annealed for 4 h at the temperature of 2000 °C [112].

fabrication of ceramics, this will produce materials with enhanced properties.

In the characterization of SiC materials, the elevated temperature features of SiC must be examined under a vast range of thermal shock situations and also under environmental conditions and thermo-mechanical cycling that simulate the real applications set-up. These should be joined with real engine testing to determine the real feasibility of the system for pragmatic applications. There has been a huge advancement in synthesizing ceramic matrix composites over the last decades. Although, future examination of ceramic matrix composites is required under the combined loading of thermal and mechanical properties so as to comprehend their failure/damage mechanisms and mechanical behavior before they can be confidently applied in service. However, the projected method must incorporate combined modeling efforts and experiments to fully comprehend local and global failure behavior. Also, structural/engine testing needs to be discovered to know the reliability and safety of the proposed systems/structures under the circumstances that simulate the real application set-up.

5. Conclusions

Diverse routes and reinforcing phases have been conspicuously reviewed for the performance enhancement of SiC materials. Studies have pinpointed the important impact of the presence of the supporting phases and also liquid phase-assisted sintering, which initiates enhancement in the samples' densification and fracture toughness.

The main significant parameters influencing the sinterability and features of final composite, comprise of the form of as-received material, the application and non-application of sintering aids, sintering technique, and sintering temperature, reinforcing particle size, the quantity and techniques of process in the structure. In addition, uniform distribution of the reinforcing phase in SiC matrix is among the vital factors influencing samples' properties. Although, the achievement of a homogenous structure can sometimes be difficult. Therefore, studies have newly introduced in-situ sintering to proffer a solution to this challenge. A contrast between the samples' properties of which individual reinforcing phases are directly included in the composition or they may be established using an in-situ technique, the analysis depicted that the latter samples achieved improved densification, toughness, and hardness because of uniform dissemination of the reinforcing phase.

Also, the introduction of post-sintering treatment, especially annealing, has received high recognition because this technique, when regulated at an appropriate temperature with other parameters, enhances the materials' properties.

Conflicts of 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.

Acknowledgments

The authors acknowledge the funding from NRF, CPAM project, as well as the assistance of the Metallurgy department of the University of Johannesburg and Tshwane University of Technology.

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