

## REVIEW

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[rsc.li/materials-advances](https://rsc.li/materials-advances)Recent progress in B<sub>4</sub>C–SiC composite ceramics:  
processing, microstructure, and mechanical  
properties

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B<sub>4</sub>C–SiC composite ceramics are a very promising alternative to pure B<sub>4</sub>C ceramics and pure SiC ceramics. B<sub>4</sub>C–SiC composite ceramics exhibit a combination of the desirable performance of B<sub>4</sub>C and SiC. B<sub>4</sub>C–SiC composite ceramics are a better candidate material for engineering applications as structural ceramic materials. The sintering performance, microstructure, and mechanical properties of B<sub>4</sub>C–SiC composite ceramics are systematically elaborated in this review. Many factors can affect the sintering performance and microstructure of B<sub>4</sub>C–SiC composite ceramics; also, the microstructure plays an important role in the mechanical properties of B<sub>4</sub>C–SiC composite ceramics. The mechanical properties of B<sub>4</sub>C–SiC composite ceramics are crucial for their applications. Finally, the future development trend of B<sub>4</sub>C–SiC composite ceramics as structural ceramic materials is proposed.

## 1. Introduction

Both boron carbide (B<sub>4</sub>C) and silicon carbide (SiC) have been recognized as important structural ceramic materials due to their outstanding properties, including high melting point,

ultra-high hardness, high elastic modulus, good wear resistance, low density, excellent chemical stability, high thermal tolerance, *etc.*<sup>1–5</sup> Especially, B<sub>4</sub>C has a high neutron capacity cross-sectional area and good thermoelectric properties, and SiC has high thermal conductivity, excellent thermal shock resistance, and good oxidation resistance; these properties allow B<sub>4</sub>C and SiC to have unique applications, respectively. B<sub>4</sub>C and SiC with excellent properties are widely used in the modern high-technology industry, such as mechanical and automotive engineering, high-temperature thermoelectric conversion, tribology, aviation, aerospace, military, chemical industry, nuclear energy, *etc.*<sup>6,7</sup> In particular, the materials with a combination of low density and high hardness are more desirable than the materials without these characteristics; thus, both B<sub>4</sub>C and SiC are very suitable for use as lightweight structural materials and rotating tribo-components.<sup>8,9</sup> Therefore, compared with other ceramics (Al<sub>2</sub>O<sub>3</sub> ceramics, ZrO<sub>2</sub> ceramics, Si<sub>3</sub>N<sub>4</sub> ceramics, *etc.*), B<sub>4</sub>C and SiC ceramics serve much better as vehicle armors and rotating rings in mechanical seals. It is noteworthy that B<sub>4</sub>C is an acronym for boron carbide, rather than its actual chemical formula, because boron carbide exists over a range of chemical compositions B<sub>12+x</sub>C<sub>3-x</sub> (0.06 < x < 1.7).<sup>10–13</sup>

Despite the numerous advantages of B<sub>4</sub>C and SiC ceramics, both pure B<sub>4</sub>C ceramics (monolithic B<sub>4</sub>C ceramics) and pure SiC ceramics (monolithic SiC ceramics) are difficult to sinter to achieve high densification because of their high covalent bond ratios and oxide film contamination on the raw materials.<sup>14,15</sup> In the case of no external pressure, extremely high sintering temperatures are necessary to fabricate pure B<sub>4</sub>C ceramics and pure SiC ceramics. The high sintering temperature, however,



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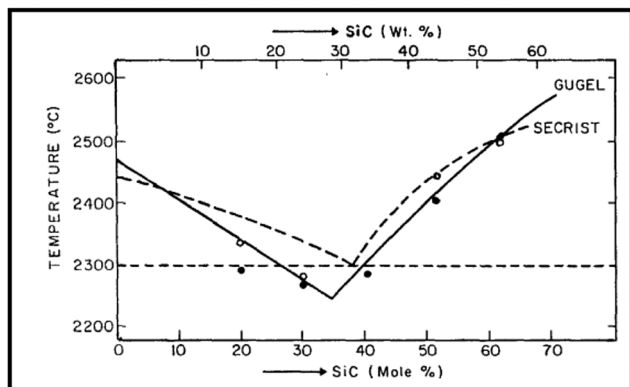


Fig. 1 Binary phase diagram of B<sub>4</sub>C-SiC<sup>19</sup> (reprinted with permission, Copyright 1979, Elsevier).

will induce abnormal grain growth, deteriorating the mechanical properties of ceramics.<sup>16</sup> Currently, the production of pure B<sub>4</sub>C ceramics and pure SiC ceramics with high relative density through a pressureless sintering method can be achieved only by adding sintering aids. A variety of additives are used as sintering aids to facilitate the densification of pure B<sub>4</sub>C ceramics and pure SiC ceramics. In theory, according to the binary phase diagram of B<sub>4</sub>C-SiC (Fig. 1),<sup>17–19</sup> B<sub>4</sub>C and SiC can be used as the sintering aid for each other to improve each other's sinterability; thus, the sintering of B<sub>4</sub>C-SiC composite ceramics is possible at lower temperatures than pure B<sub>4</sub>C ceramics and pure SiC ceramics.

For B<sub>4</sub>C ceramics, Thévenot<sup>20,21</sup> reported that the addition of SiC coupled with C can promote the densification of pressureless sintered B<sub>4</sub>C ceramics. The addition of SiC can lead to segregation at grain boundaries of B<sub>4</sub>C ceramics, thus limiting B<sub>4</sub>C grain coarsening or facilitating diffusion in grain boundaries. Zorzi *et al.*<sup>22</sup> found that the addition of 4 wt% SiC alone can also promote the sintering of B<sub>4</sub>C ceramics, which in turn increases the hardness of B<sub>4</sub>C ceramics. For SiC ceramics, the simultaneous introduction of B, which can be introduced as elemental B, LiBH<sub>4</sub> or B<sub>4</sub>C,<sup>23,24</sup> and C can promote the sintering of  $\alpha$ -SiC ceramics and  $\beta$ -SiC ceramics.<sup>23–28</sup> On the one hand, both B and C upset an unfavorable equilibrium at grain boundary-pore surface intersections by reducing the grain boundary-surface energy ratio (B can reduce the grain boundary energy, and C can increase the interfacial energy), thereby inducing the driving force for diffusional mass transport necessary for solid-state sintering.<sup>23,25</sup> Furthermore, B segregated at the grain boundaries of SiC ceramics can impede surface and vapor-phase transport and grain growth at low temperatures, leading to increased densification due to improved grain boundary diffusivity at high temperatures.<sup>29</sup> On the other hand, carbon forms a uniform layer on the surface of SiC grains in the first stage of sintering, which occurs because of the high grain boundary and surface diffusion coefficient of C; as the temperature increases, C can react with SiO<sub>2</sub> existing on the surface of SiC grains, forming a secondary SiC phase and removing the oxide film contamination, which can increase the surface energy of SiC and limit the formation of the SiO<sub>2</sub> glass phase.<sup>27,30,31</sup> Meanwhile, C can prevent the evolution

of gaseous products in chemical reactions or the thermal decomposition of SiC.<sup>32,33</sup> In order to enhance the densification of SiC ceramics by the addition of sole B<sub>4</sub>C, Bind *et al.*<sup>34</sup> stated that B atoms can partly replace C atoms in the SiC lattice, forming a solid solution, which can improve the SiC volume diffusion. In contrast, Li *et al.*<sup>35</sup> noted that B atoms replace Si atoms, forming a solid solution in SiC ceramics, and the densification of SiC ceramics is promoted by the generation of Si and C vacancies in the SiC lattice.

Moreover, the fracture toughness of both pure B<sub>4</sub>C ceramics and pure SiC ceramics is relatively low, especially B<sub>4</sub>C ceramics, which is mainly attributed to their transgranular fracture mode.<sup>36,37</sup> Although the utilization of nano/submicron-sized B<sub>4</sub>C and SiC powders as starting materials can improve the fracture toughness and sinterability of pure B<sub>4</sub>C ceramics and pure SiC ceramics,<sup>38,39</sup> these nano/submicron-sized powders are limited to laboratory use because of low yield and high cost; thus, nano/submicron-sized B<sub>4</sub>C and SiC powders are not suitable for the industrial preparation of B<sub>4</sub>C ceramics and SiC ceramics. Both B<sub>4</sub>C powders and SiC powders obtained through industrial manufacturing are micron-sized. Adding a second phase into B<sub>4</sub>C ceramics and SiC ceramics can improve their fracture toughness to a certain extent; however, the addition of some second phases, such as Al, Al<sub>2</sub>O<sub>3</sub>, and ZrO<sub>2</sub>, reduces the hardness of B<sub>4</sub>C ceramics and SiC ceramics.<sup>40,41</sup> Both B<sub>4</sub>C and SiC have high microhardness; theoretically, B<sub>4</sub>C and SiC can be added to each other to improve each other's mechanical properties. B<sub>4</sub>C shows higher hardness and lower density than SiC, and SiC exhibits higher fracture toughness than B<sub>4</sub>C. Given that each component can act as a second phase to affect matrix performance, the production of B<sub>4</sub>C-SiC composite ceramics is an effective approach to combine the advantages of B<sub>4</sub>C and SiC.

In brief, a uniform distribution of B<sub>4</sub>C and SiC in B<sub>4</sub>C-SiC composite ceramics can prevent direct contact between B<sub>4</sub>C-B<sub>4</sub>C and SiC-SiC; thus, B<sub>4</sub>C and SiC seem to act as grain growth inhibitors for each other in B<sub>4</sub>C-SiC composite ceramics, which is conducive to densification. Also, B<sub>4</sub>C and SiC have good physical and chemical compatibility with each other; the B<sub>4</sub>C-SiC system can offer a combination of good sinterability and relatively high fracture toughness with high hardness and low density. B<sub>4</sub>C-SiC composite ceramics can exhibit better mechanical properties and tribological performance as compared to pure B<sub>4</sub>C and SiC ceramics;<sup>42,43</sup> thus, B<sub>4</sub>C-SiC composite ceramics are a better candidate material for engineering applications as structural ceramic materials.

In recent years, B<sub>4</sub>C-SiC composite ceramics have attracted more and more attention from scientific and commercial disciplines because B<sub>4</sub>C-SiC composite ceramics provide some outstanding properties, such as mechanical properties, tribological properties, and thermoelectric properties,<sup>44,45</sup> for applications in harsh environments. So far, there have been some review articles on pure B<sub>4</sub>C ceramics<sup>46–49</sup> and pure SiC ceramics;<sup>50,51</sup> however, the review articles on B<sub>4</sub>C-SiC materials are very limited. The synthesis of B<sub>4</sub>C-SiC composite powders and tribological properties of B<sub>4</sub>C-SiC composite ceramics have been summarized in the previous



review papers;<sup>52,53</sup> therefore, the sintering performance, microstructure, and mechanical properties of B<sub>4</sub>C–SiC composite ceramics are systematically elaborated in this review. It is of great importance to colligate this information for current ceramic research. Furthermore, the future development trend of B<sub>4</sub>C–SiC composite ceramics as structural ceramic materials is also proposed.

## 2. Sintering method of B<sub>4</sub>C–SiC composite ceramics

The general methods used to sinter B<sub>4</sub>C–SiC composite ceramics include pressureless sintering, hot-press (HP) sintering, spark plasma sintering (SPS), and reaction-bonded sintering. B<sub>4</sub>C–SiC ceramics are difficult to sinter due to the high covalent bond ratios of both B<sub>4</sub>C and SiC. When B<sub>4</sub>C–SiC ceramics are prepared by pressureless sintering, sintering aids are often added to promote sintering. Prior to pressureless sintering, the green body needs to be prepared from composite powders using different molding technologies, such as dry pressing, cold isostatic press (CIP), and slip casting. Hot-press sintering is used to produce B<sub>4</sub>C–SiC composite ceramics under external pressure from composite powders without pre-molding. Spark plasma sintering is a technology that utilizes an extremely high heating rate and is assisted by a uniaxial pressure. B<sub>4</sub>C–SiC ceramics can be prepared by spark plasma sintering in a very short processing time at relatively low sintering temperatures; thus, a fine microstructure will be obtained for B<sub>4</sub>C–SiC ceramics due to the high heating rate and short dwell time. The preparation of B<sub>4</sub>C–SiC composite ceramics by reaction-bonded sintering was first developed by Taylor in the 1970s,<sup>54</sup> and the preparation method is similar to that of SiC ceramics produced by reaction-bonded sintering, in which molten Si with appropriate fluidity infiltrates into a porous green/partially sintered body composed of SiC and free C at high temperatures.<sup>55,56</sup> The mechanism of reaction-bonded sintering for B<sub>4</sub>C–SiC composite ceramics is the same as that for SiC ceramics. The porous green preforms have interconnected pores, which can provide a good channel for the penetration of molten Si; molten Si infiltrates into a green preform, which is composed of only B<sub>4</sub>C, the mixture of B<sub>4</sub>C and free C, or B<sub>4</sub>C–SiC–C or B<sub>4</sub>C–SiC powders,<sup>57</sup> driven by capillary force in a vacuum because the wetting angle of Si with both B<sub>4</sub>C and C is 0° at 1430 °C.<sup>58</sup> Then, the molten Si infiltrated reacts with C either from free C or B<sub>4</sub>C to form SiC,<sup>59,60</sup> the reaction of which leads to volume expansion occupying partial pores in the preform;<sup>61</sup> the remaining excess pores in the preform are filled with molten Si after the reaction, making the reaction-bonded B<sub>4</sub>C–SiC ceramics dense.<sup>62</sup> The preparation of reaction-bonded B<sub>4</sub>C–SiC ceramics is actually an *in situ* chemical reaction. In addition to the conventional process, the microwave-assisted processing method, which can shorten the processing time, is another strategy employed to prepare reaction-bonded B<sub>4</sub>C–SiC ceramics.<sup>63</sup> Recently, a so-called ultra-high pressure (4 GPa) sintering method has been developed to successfully prepare additive-free B<sub>4</sub>C–SiC ceramics at a low temperature

(1500 °C).<sup>64</sup> It is noteworthy that the pressure applied during ultra-high pressure sintering is significantly higher than the pressures applied during HP and SPS, leading to the rapid densification of B<sub>4</sub>C–SiC ceramics. This phenomenon results from the fact that the ultra-high pressure sintering allows the reduction of distance between the grains and endures the improvement of contact between individual grains resulting in plastic deformation.<sup>65</sup> Also, the ultra-high pressure has an influence on particle redistribution, agglomerate omission, and pore elimination.<sup>66</sup> The sintering performance, microstructure, and mechanical properties of the B<sub>4</sub>C–SiC ceramics prepared through different sintering methods mentioned above will be described in detail later.

Each sintering method used to prepare B<sub>4</sub>C–SiC ceramics has its own advantages and disadvantages. Pressureless sintering is suitable for large-scale production and products with complicated shapes or large sizes. Pressureless sintering has a much wider range of applications and is suitable for extensive industrialization. But the disadvantages of pressureless sintering to fabricate B<sub>4</sub>C–SiC ceramics are that the sintering temperature is high and the sintering time is long; it is difficult to obtain high relative density and small grain size for B<sub>4</sub>C–SiC ceramics. Hence, various sintering aids are often added to reduce the sintering temperature and ultra-fine powders are usually chosen as raw materials. For hot-press sintering and spark plasma sintering, highly dense B<sub>4</sub>C–SiC ceramics without sintering aids can be prepared at relatively low temperatures *via* these routes, applying heat and pressure simultaneously. The sintering time of these routes is relatively short, especially SPS. The grain size of B<sub>4</sub>C–SiC ceramics prepared *via* these routes, especially by SPS, is relatively small. Also, less costly coarser-grained initial powders can be densified into compacts of acceptable density *via* these routes. However, compared with pressureless sintering, these routes are more limiting in terms of the shape and size of products and more costly; thus, these technologies are not suitable for industrial applications. Moreover, the physical properties of B<sub>4</sub>C–SiC ceramics produced *via* hot-press sintering and spark plasma sintering perpendicular and parallel to the uniaxial pressure direction show direction dependence. Reaction-bonded sintering is an energy-saving process due to much lower sintering temperatures and is favorable of producing large, complex-shaped products. In the case of B<sub>4</sub>C–SiC ceramics prepared by reaction-bonded sintering, B<sub>4</sub>C, SiC, and residual Si particles can interconnect into a uniform and strong three-dimensional network at low sintering temperatures without the need for applied pressure; near-net shaped products with zero shrinkage can be produced.<sup>67</sup> Also, fine reactive starting powders capable of being densified are not required, reducing the cost of raw materials. Therefore, the preparation of B<sub>4</sub>C–SiC ceramics *via* reaction-bonded sintering is a low-cost method; this route is suitable for large-sized and complex-shaped products. Reaction-bonded B<sub>4</sub>C–SiC ceramics have reached the industrial production stage; however, their characteristics of inhomogeneous microstructures and residual Si with low hardness and stiffness may limit the application of B<sub>4</sub>C–SiC ceramics in terms of reliability and high-temperature



mechanical properties. Therefore, the B<sub>4</sub>C–SiC products produced by reaction-bonded sintering lose the partial superior performance of B<sub>4</sub>C–SiC ceramics.

### 3. Sintering performance and microstructure of B<sub>4</sub>C–SiC composite ceramics

Although the sintering temperature of B<sub>4</sub>C–SiC composite ceramics is lower than that of pure B<sub>4</sub>C ceramics and pure SiC ceramics theoretically, B<sub>4</sub>C–SiC ceramics are still difficult to sinter because both B<sub>4</sub>C and SiC have strong bonding, high resistance to grain boundary sliding, low plasticity, and low superficial tension in the solid state. Many factors can affect the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics, such as the ratio of B<sub>4</sub>C to SiC, raw materials, preparation process, sintering aids, *etc.*, which will be summarized in detail in this part. High relative density can achieve some properties and applications of B<sub>4</sub>C–SiC ceramics, such as good wear resistance in the tribo-component application and acceptable ballistic resistance in the armor application. Also, the microstructure plays an important role in the mechanical properties of B<sub>4</sub>C–SiC ceramics.

#### 3.1. Ratio of B<sub>4</sub>C to SiC

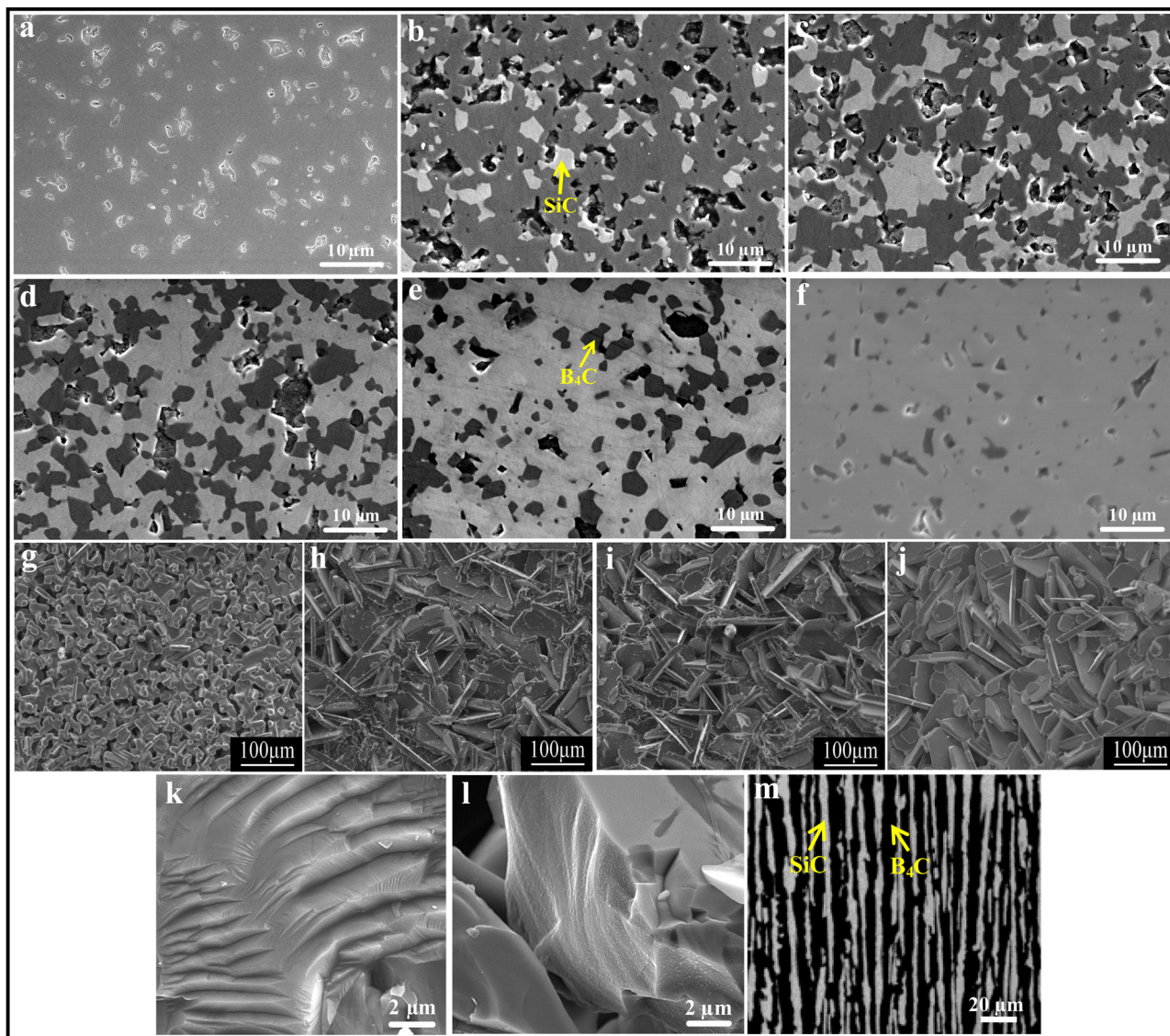
Different ratios of B<sub>4</sub>C to SiC will cause different impacts on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics. When the volume fraction of B<sub>4</sub>C is more than that of SiC, SiC grains distribute in the B<sub>4</sub>C matrix; otherwise, B<sub>4</sub>C grains distribute in the SiC matrix. Meanwhile, the density of SiC (3.21 g cm<sup>−3</sup>) is higher than that of B<sub>4</sub>C (2.51 g cm<sup>−3</sup>); thus, the density of B<sub>4</sub>C–SiC ceramics increases with an increase in the ratio of SiC.

The high covalent bond ratio, which is responsible for intrinsically low diffusion mobility, is one of the factors inhibiting the sintering performance of ceramic materials. Theoretically, the densification of B<sub>4</sub>C is more difficult than that of SiC because the covalent bond ratio in B<sub>4</sub>C (94%) is higher than that in SiC (88%);<sup>15</sup> thus, the B<sub>4</sub>C–SiC ceramics with more SiC content than B<sub>4</sub>C content can achieve better sintering performance. This means that a higher sintering temperature may be required to achieve a higher relative density for the composite ceramic containing more B<sub>4</sub>C.

For the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics with different ratios of B<sub>4</sub>C to SiC prepared by different sintering methods, some regular results have been found by the researchers. Magnani *et al.*<sup>68</sup> found that the pressureless sintered SiC-5 vol% B<sub>4</sub>C ceramics show a higher relative density than pure SiC ceramics in the sintering temperature range of 1950–2200 °C. The presence of B<sub>4</sub>C as a secondary phase can improve the sinterability of SiC powders. Furthermore, the addition of B<sub>4</sub>C reduces the abnormal growth of SiC grains; thus, the SiC-5 vol% B<sub>4</sub>C ceramics exhibit a finer microstructure than pure SiC ceramics. Cho *et al.*<sup>69</sup> mentioned that the relative density of the pressureless sintered SiC ceramics decreases with the addition of B<sub>4</sub>C particles from 1 to 5 wt%. This phenomenon can be

explained by the fact that the B<sub>4</sub>C grains existing between SiC grains impede mass transport through surface diffusion; thus, the grain growth of SiC is slowed down with the increase in B<sub>4</sub>C addition, resulting in the formation of large amounts of pores. Thévenot<sup>20</sup> reported that the relative density of the pressureless sintered B<sub>4</sub>C–SiC ceramics (10/90 < B<sub>4</sub>C wt%/SiC wt% < 96/4) increases from 93 to 99% with an increase in  $\alpha$ -SiC content from 10 to 90 wt%. The B<sub>4</sub>C–SiC ceramic with the highest SiC content exhibits the best sintering capability. When the SiC content is less than 10 wt%, the densification of B<sub>4</sub>C–SiC ceramics is low despite higher sintering temperature, and the grains are coarser (<80  $\mu$ m). Zhang *et al.*<sup>70</sup> also observed similar results for the relative density of pressureless sintered B<sub>4</sub>C–SiC ceramics (3/97 < B<sub>4</sub>C wt%/SiC wt% < 100/0). The relative density is higher and fewer pores are observed on the ceramic surfaces when the SiC content is more than the B<sub>4</sub>C content in the B<sub>4</sub>C–SiC ceramics (Fig. 2a–f). Yaşar and Haber<sup>71</sup> noted that the relative density of the spark plasma sintered B<sub>4</sub>C–SiC ceramics decreases from 99.6 to 98.9% with the increase in B<sub>4</sub>C content from 10 to 50 wt%. So *et al.*<sup>72</sup> studied the sintering performance and microstructure of the hot-press sintered B<sub>4</sub>C–SiC ceramics with the volume ratios of B<sub>4</sub>C to SiC of 35 : 65, 56 : 44, and 75 : 25. It was found that the densification mechanisms are different for B<sub>4</sub>C–SiC ceramics with different ratios of B<sub>4</sub>C to SiC. When the B<sub>4</sub>C grains distribute in the SiC matrix (the volume fraction of SiC is more than that of B<sub>4</sub>C), the partial phase transition of SiC from 6H to 4H accompanying the grain growth promotes densification. In contrast, when the SiC grains distribute in the B<sub>4</sub>C matrix (the volume fraction of B<sub>4</sub>C is more than that of SiC), the ceramics are densified through grain boundaries and volume diffusion, and there is no phase transition of SiC in the ceramics. The solubility of B<sub>4</sub>C in  $\alpha$ -SiC is approximately 0.5 wt% at a temperature between 2000 and 2100 °C,<sup>73</sup> which can decrease the surface energy at the phase boundary between B<sub>4</sub>C and SiC and can increase the mass transfer, promoting the densification of SiC. However, the diffusion coefficient and densification rate will decrease when the B<sub>4</sub>C content is above the solubility. The grain growth of SiC is inhibited, but the grain size of B<sub>4</sub>C is increased with an increase in B<sub>4</sub>C content, leading to the larger grain size of B<sub>4</sub>C than that of SiC, which is attributed to the growth of B<sub>4</sub>C grains by the diffusion of B and C, and the difference in grain size between B<sub>4</sub>C and SiC is increased with an increase in B<sub>4</sub>C content in the composite ceramics. Zhang *et al.*<sup>74</sup> found that the relative density of the gas-pressure sintered B<sub>4</sub>C–SiC ceramics decreases from 94.2 to 88.9% with the increase in B<sub>4</sub>C content from 5 to 20 wt% in the composite ceramics, and the surface morphology changes from an island-like distribution and better continuity to a plate-type structure (Fig. 2g–j). Matović *et al.*<sup>64</sup> mentioned that B<sub>4</sub>C–SiC ceramics can achieve a high relative density (>96%) *via* ultra-high pressure sintering at a relatively low temperature combined with a short holding time; the composite ceramics with the equal-weighted contributions of B<sub>4</sub>C and SiC achieve the maximal relative density, which is attributed to the best mixing of the initial raw materials and thus their best distribution in the composite powders.





**Fig. 2** Polished surfaces of the pressureless sintered  $B_4C$ -SiC ceramics with different ratios of  $B_4C$  to SiC: (a)  $B_4C$ , (b)  $B_4C$ -20 wt% SiC, (c)  $B_4C$ -40 wt% SiC, (d)  $B_4C$ -60 wt% SiC, (e)  $B_4C$ -80 wt% SiC, and (f)  $B_4C$ -97 wt% SiC<sup>70</sup> (reprinted with permission, Copyright 2020, Elsevier); microstructure of the gas-pressure sintered  $B_4C$ -SiC ceramics with different ratios of  $B_4C$  to SiC: (g) SiC-5 wt%  $B_4C$ , (h) SiC-10 wt%  $B_4C$ , (i) SiC-15 wt%  $B_4C$ , (j) SiC-20 wt%  $B_4C$ <sup>74</sup> (reprinted with permission, Copyright 2014, Trans Tech Publications); SEM images of  $B_4C$ -SiC ceramics revealing the cleavage surfaces: (k)  $B_4C$ -5 vol% SiC and (l)  $B_4C$ -7.5 vol% SiC<sup>80</sup> (reproduced with permission, Copyright 2017, Elsevier); (m) microstructure of eutectic  $B_4C$ -SiC ceramics showing lamellar texture<sup>82</sup> (reproduced with permission, Copyright 2002, The Japan Institute of Metals. This is an open access article distributed under the terms of the Creative Commons Attribution License).

For the reaction-bonded  $B_4C$ -SiC ceramics, different ratios of  $B_4C$  to SiC and microstructures can be obtained by adjusting the chemical composition and microstructure of their preforms. The preforms containing high C content can form  $B_4C$ -SiC ceramics rich in SiC after Si infiltration. Zhang *et al.*<sup>75</sup> reported that the content of generated SiC increases with an increase in the initial amount of nano-carbon black in the reaction-bonded  $B_4C$ -SiC ceramics. The density of reaction-bonded  $B_4C$ -SiC ceramics increases with the increase in the initial amount of carbon black (0–12 wt%), which is attributed to the gradually increased amount of SiC generated. Although the relative density of the  $B_4C$ -SiC ceramics slightly decreases with the increase

in carbon black,  $B_4C$ -SiC ceramics with different amounts of carbon black are rather dense. Li *et al.*<sup>76</sup> also found that the amount of fine SiC grains formed increases with the increasing amount of the C source. In contrast, Hayun *et al.*<sup>77</sup> mentioned that the amount of SiC generated essentially depends on the porosity of the preform, and only depends on the C source to a slight extent.

Different from these regular results mentioned above, Tomohiro *et al.*<sup>78</sup> found that the relative density of the hot-press sintered  $B_4C$ -SiC ceramics is independent of the SiC content from 0 to 50 vol% when the sintering temperature is 2200 °C, and the relative density of composite ceramics is nearly fully dense.



However, when the sintering temperatures are 2000 and 2100 °C, the relative density of B<sub>4</sub>C–SiC ceramics with an SiC addition of 10–20 vol% is at a maximum, the reason for which is not explained.

The microstructure of B<sub>4</sub>C–SiC ceramics is also related to the ratio of B<sub>4</sub>C to SiC. Compared with pure B<sub>4</sub>C ceramics, the B<sub>4</sub>C–20 wt% SiC ceramics achieve a more refined and denser microstructure due to the incorporation of SiC.<sup>79</sup> Moradkhani and Baharvandi<sup>80</sup> pointed out that the addition of SiC particles in the B<sub>4</sub>C matrix leads to the formation of cleavage surfaces within grains (Fig. 2k and l); the greater the volume fraction of the SiC additive, the greater the density of cleavage surfaces. As for the microstructure of eutectic composites, it is mainly dependent on the volume fractions of phases.<sup>81</sup> The lamellar texture will appear when each phase is more than 30 vol%. Gunjishima *et al.*<sup>82</sup> observed lamellar texture in B<sub>4</sub>C–40 vol% SiC ceramics prepared by the floating zone method (Fig. 2m), which is the eutectic composition of the B<sub>4</sub>C–SiC binary system. Also, the spacing between lamellae is related to the solidification rate.

Some previous studies on the effect of the ratio of B<sub>4</sub>C to SiC on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics are tabulated in Table 1.

### 3.2. Raw material

Raw materials are the basis for the preparation of B<sub>4</sub>C–SiC ceramics. The characteristics of raw materials, such as particle size, oxide impurity, and species, can affect the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics.

**3.2.1. Particle size.** Generally, raw materials with large sizes are not easy to sinter into dense blocks; inversely, raw materials with particle sizes in the submicron or even nanometer range are easier to sinter due to higher surface energy. Shi *et al.*<sup>83</sup> studied the sintering performance of hot-press sintered B<sub>4</sub>C–20 vol% SiC ceramics using B<sub>4</sub>C powders with a size of 10.22 μm and β-SiC powders with a size of 1.07 μm as raw materials. The porosity of the B<sub>4</sub>C–SiC ceramics gradually decreases with an increase in sintering temperature from 1900 to 2100 °C; however, obvious pores can still be observed after sintering at 2100 °C. This indicates that it is difficult to obtain dense B<sub>4</sub>C–SiC ceramics using B<sub>4</sub>C powders with micron size as the raw material, although the increase of sintering temperature can reduce the porosity to a certain extent. Therefore, the utilization of raw materials with fine particle size is more conducive to promoting the sintering of B<sub>4</sub>C–SiC ceramics. For the grain size of B<sub>4</sub>C–SiC ceramics, Moradkhani and Baharvandi<sup>80</sup> found that the effect of the addition of SiC with nanoscale and microscale sizes on the grain size of the pressureless sintered B<sub>4</sub>C–SiC ceramics is not very significant.

Using graded particles as raw materials is an effective strategy to improve the packing density of the green body. For the reaction-bonded B<sub>4</sub>C–SiC ceramics, theoretically, high green density is conducive to reducing the fraction of residual Si in the final product. The lower the porosity, the lower the amount of residual Si present after the infiltration with Si. Therefore, it is reasonable to decrease the porosity of the green body as much as possible before the infiltration process.

A multimodal particle size distribution results in maximal volume filling by the initial ceramic powers prior to infiltration, and thus reduces the fraction of residual Si after infiltration. Hayun *et al.*<sup>84</sup> used B<sub>4</sub>C powders with different particle sizes (130, 70, 50, 13, and 1 μm) as raw materials to prepare the preform. Compared with the relative density (65%) of the preform composed of monosized fine B<sub>4</sub>C particles (1 μm), the relative densities (70–75%) of the preforms composed of graded B<sub>4</sub>C particles are higher. After Si infiltration, the space between coarse B<sub>4</sub>C particles is uniformly filled with fine B<sub>4</sub>C, newly formed SiC, and residual Si particles. Both the preforms composed of graded B<sub>4</sub>C particles and the preform composed of monosized fine B<sub>4</sub>C particles are fully infiltrated; however, the amount of residual Si in the final B<sub>4</sub>C–SiC ceramics produced from the graded B<sub>4</sub>C particles (8–10 vol%) is lower than that produced from the monosized fine B<sub>4</sub>C particles (20 vol%). Li *et al.*<sup>76</sup> also proved that the relative density of the green body composed of graded B<sub>4</sub>C powders with 8.671 μm and 323.7 nm can reach 75%, which is higher than that of the preform composed of monosized B<sub>4</sub>C particles (59.9%). Meanwhile, compared with the green body with a similar relative density prepared by Hayun *et al.*,<sup>84</sup> the particle size of B<sub>4</sub>C used by Li *et al.*<sup>76</sup> is much smaller, which contributes to decreasing open pore size of the preform and the consequent size of free Si. On the other hand, Song *et al.*<sup>85</sup> found that because there are coarse B<sub>4</sub>C particles in the reaction-bonded B<sub>4</sub>C–SiC preform composed of graded B<sub>4</sub>C particles (14, 7, and 1.5 μm), the uniform distribution of the residual Si is prevented, leading to the formation of scattered fragments; thus, the use of fine B<sub>4</sub>C particles makes it easier to form a uniform microstructure in the reaction-bonded B<sub>4</sub>C–SiC ceramics. Therefore, using a multimodal powder mixture including coarse B<sub>4</sub>C particles to prepare the green body is helpful for improving the relative density of the green body, which in turn contributes to reducing the amount of residual Si in the reaction-bonded B<sub>4</sub>C–SiC ceramics; however, the use of coarse B<sub>4</sub>C particles is not conducive to the formation of uniform microstructure in the reaction-bonded B<sub>4</sub>C–SiC ceramics. Hereto, the size of coarse particles in the graded B<sub>4</sub>C particles should be as small as possible under the premise of improving the relative density of the green body.

**3.2.2. Oxide impurity.** B<sub>4</sub>C and SiC powders, as the main raw materials for preparing B<sub>4</sub>C–SiC ceramics, have oxide layers on their surfaces.<sup>14,86</sup> These oxide film impurities (B<sub>2</sub>O<sub>3</sub>/H<sub>3</sub>BO<sub>3</sub>, SiO<sub>2</sub>) on the raw materials can cause abnormal grain growth, increase porosity, and deteriorate sintering performance in the sintering process. In particular, the presence of these oxide impurities reduces the application potential of B<sub>4</sub>C–SiC ceramics at high temperatures. Therefore, it is necessary to control surface oxide impurities on the raw materials. To remove these oxide impurities, there are two main approaches. One is adding C to remove these oxide layers according to the reactions between C and B<sub>2</sub>O<sub>3</sub> and between C and SiO<sub>2</sub> in the sintering process.<sup>70</sup> The other is using acid etching to remove these oxide layers. HCl and HF are commonly used to wash B<sub>4</sub>C and SiC to remove B<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>, respectively.<sup>71</sup> It is worth noting that the





Table 1 Effect of the ratio of B<sub>4</sub>C to SiC on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics

| Ceramics                                   | Raw material                                                  | Sintering method            | Sintering temperature (°C) | Sintering aid                  | Relative density (%) | Phase composition                                                  | Average grain size (μm)         |
|--------------------------------------------|---------------------------------------------------------------|-----------------------------|----------------------------|--------------------------------|----------------------|--------------------------------------------------------------------|---------------------------------|
| SiC <sup>68</sup>                          | α-SiC (0.6 μm)                                                | Pressureless                | 2150                       | 0.6 wt% B + 2 wt% carbon black | 93.5                 | —                                                                  | > 8.0                           |
| SiC-5 vol% B <sub>4</sub> C <sup>68</sup>  | α-SiC (0.6 μm), B <sub>4</sub> C (0.7–0.9 μm)                 | Pressureless                | 2150                       | 1 wt% carbon black             | 96.0                 | —                                                                  | SiC: 8.0, B <sub>4</sub> C: 2.0 |
| B <sub>4</sub> C-10 wt% SiC <sup>20</sup>  | B <sub>4</sub> C (<5.0 μm), α-SiC                             | Pressureless                | 2200                       | 2.5 wt% phenolic resin         | 93.0                 | —                                                                  | 0.5–3.0                         |
| B <sub>4</sub> C-30 wt% SiC <sup>20</sup>  | B <sub>4</sub> C (<5.0 μm), α-SiC                             | Pressureless                | 2200                       | 2.5 wt% phenolic resin         | 97.3                 | —                                                                  | 0.5–3.0                         |
| B <sub>4</sub> C-70 wt% SiC <sup>20</sup>  | B <sub>4</sub> C (<5.0 μm), α-SiC                             | Pressureless                | 2200                       | 2.5 wt% phenolic resin         | 97.6                 | —                                                                  | 0.5–3.0                         |
| B <sub>4</sub> C-90 wt% SiC <sup>20</sup>  | B <sub>4</sub> C (<5.0 μm), α-SiC                             | Pressureless                | 2200                       | 2.5 wt% phenolic resin         | 99.4                 | —                                                                  | 0.5–3.0                         |
| B <sub>4</sub> C <sup>70</sup>             | B <sub>4</sub> C (0.8 μm)                                     | Pressureless                | 2300                       | 3 wt% carbon black             | 94.4                 | B <sub>4</sub> C, C                                                | 3.0–4.0                         |
| B <sub>4</sub> C-20 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 μm), α-SiC (0.4 μm)                     | Pressureless                | 2300                       | 3 wt% carbon black             | 93.8                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| B <sub>4</sub> C-40 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 μm), α-SiC (0.4 μm)                     | Pressureless                | 2300                       | 3 wt% carbon black             | 93.5                 | B <sub>4</sub> C, SiC, C                                           | B <sub>4</sub> C: 2.0, SiC: 3.0 |
| B <sub>4</sub> C-60 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 μm), α-SiC (0.4 μm)                     | Pressureless                | 2300                       | 3 wt% carbon black             | 95.6                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| B <sub>4</sub> C-80 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 μm), α-SiC (0.4 μm)                     | Pressureless                | 2300                       | 3 wt% carbon black             | 96.5                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| B <sub>4</sub> C-97 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 μm), α-SiC (0.4 μm)                     | Pressureless                | 2300                       | 3 wt% carbon black             | 99.0                 | SiC, C                                                             | —                               |
| SiC-10 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, α-SiC                                       | Spark plasma (50 MPa)       | 1950 (×5 min)              | 1.5 wt% C                      | 99.6                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| SiC-20 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, α-SiC                                       | Spark plasma (50 MPa)       | 1950 (×5 min)              | 1.5 wt% C                      | 99.2                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| SiC-30 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, α-SiC                                       | Spark plasma (50 MPa)       | 1950 (×5 min)              | 1.5 wt% C                      | 98.8                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| SiC-40 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, α-SiC                                       | Spark plasma (50 MPa)       | 1950 (×5 min)              | 1.5 wt% C                      | 98.8                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| SiC-50 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, α-SiC                                       | Spark plasma (50 MPa)       | 1950 (×5 min)              | 1.5 wt% C                      | 98.9                 | B <sub>4</sub> C, SiC, C                                           | —                               |
| B <sub>4</sub> C-65 vol% SiC <sup>72</sup> | B <sub>4</sub> C (0.8 μm), α-SiC (0.5 μm)                     | Hot-press (40 MPa)          | 2000                       | No                             | 100.0                | B <sub>4</sub> C, SiC                                              | B <sub>4</sub> C: 1.5, SiC: 1.3 |
| B <sub>4</sub> C-44 vol% SiC <sup>72</sup> | B <sub>4</sub> C (0.8 μm), α-SiC (0.5 μm)                     | Hot-press (40 MPa)          | 2000                       | No                             | 99.9                 | B <sub>4</sub> C, SiC, C                                           | B <sub>4</sub> C: 1.6, SiC: 1.0 |
| B <sub>4</sub> C-25 vol% SiC <sup>72</sup> | B <sub>4</sub> C (0.8 μm), α-SiC (0.5 μm)                     | Hot-press (40 MPa)          | 2000                       | No                             | 99.8                 | B <sub>4</sub> C, SiC, C                                           | B <sub>4</sub> C: 2.1, SiC: 1.1 |
| B <sub>4</sub> C-75 wt% SiC <sup>64</sup>  | B <sub>4</sub> C (2.5 μm), β-SiC (0.6 μm)                     | Ultra-high pressure (4 GPa) | 1500 (×1 min)              | No                             | 96.4                 | B <sub>4</sub> C, β-SiC                                            | —                               |
| B <sub>4</sub> C-50 wt% SiC <sup>64</sup>  | B <sub>4</sub> C (2.5 μm), β-SiC (0.6 μm)                     | Ultra-high pressure (4 GPa) | 1500 (×1 min)              | No                             | 98.0                 | B <sub>4</sub> C, β-SiC                                            | —                               |
| B <sub>4</sub> C-25 wt% SiC <sup>64</sup>  | B <sub>4</sub> C (2.5 μm), β-SiC (0.6 μm)                     | Ultra-high pressure (4 GPa) | 1500 (×1 min)              | No                             | 96.9                 | B <sub>4</sub> C, β-SiC                                            | —                               |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 μm), 0 wt% carbon black, Si (5–10 mm)  | Reaction                    | 1550                       | No                             | 99.9                 | B <sub>4</sub> C, SiC, Si, B <sub>12</sub> (B, C, Si) <sub>3</sub> | —                               |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 μm), 6 wt% carbon black, Si (5–10 mm)  | Reaction                    | 1550                       | No                             | 99.9                 | B <sub>4</sub> C, SiC, Si, B <sub>12</sub> (B, C, Si) <sub>3</sub> | —                               |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 μm), 8 wt% carbon black, Si (5–10 mm)  | Reaction                    | 1550                       | No                             | 99.4                 | B <sub>4</sub> C, SiC, Si, B <sub>12</sub> (B, C, Si) <sub>3</sub> | —                               |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 μm), 10 wt% carbon black, Si (5–10 mm) | Reaction                    | 1550                       | No                             | 99.1                 | B <sub>4</sub> C, SiC, Si, B <sub>12</sub> (B, C, Si) <sub>3</sub> | —                               |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 μm), 12 wt% carbon black, Si (5–10 mm) | Reaction                    | 1550                       | No                             | 98.7                 | B <sub>4</sub> C, SiC, Si, B <sub>12</sub> (B, C, Si) <sub>3</sub> | —                               |

acid etching treatment cannot completely remove oxide film impurities; the content of oxide film contamination is reduced through this approach. After the pre-washing of raw materials, the relative density of the obtained B<sub>4</sub>C–SiC ceramics can be slightly increased.<sup>87</sup>

**3.2.3. Species.** B<sub>4</sub>C–SiC ceramics can be produced from different species of raw materials, which have different effects on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics.  $\alpha$ -SiC and  $\beta$ -SiC are the two main species for SiC raw materials. Thévenot<sup>20</sup> found that B<sub>4</sub>C–60 wt% SiC ceramics, when using  $\beta$ -SiC as the raw material, exhibit a poorer sintering behavior compared to those using  $\alpha$ -SiC as the raw material. This phenomenon may be attributed to the partial transformation of  $\beta \rightarrow \alpha$ -SiC during the sintering process, resulting in the formation of plate-like (or acicular) grains with a length of 15  $\mu$ m. Rocha and Melo<sup>88,89</sup> also proved that the relative density of the pressureless sintered B<sub>4</sub>C–SiC ceramics with  $\beta$ -SiC as the raw material decreases from 81.3 to 67.5% with an increase in SiC content from 10 to 50 wt%. This conclusion is different from that with  $\alpha$ -SiC as the raw material mentioned in Section 3.1. During the SiC phase transformation, equiaxed shaped  $\beta$ -SiC grains change to plate-like shaped  $\alpha$ -SiC grains with a high aspect ratio, and the amount of these platelet-shaped SiC grains increases with an increase in SiC content in the ceramics. The platelet-shaped SiC grains can lead to early impingement of large grains, forming a skeleton that can arrest the densification of the ceramics. The higher the amount of platelet-shaped SiC grains, the lower the relative density the B<sub>4</sub>C–SiC ceramics achieve.

Different from the mechanical method to physically mix B<sub>4</sub>C and SiC powders, using organic precursors is another method to prepare B<sub>4</sub>C–SiC ceramics. SiC can be generated from the pyrolysis of organic precursors. For example, polycarbosilane (PCS) can be converted to nanocrystalline SiC after pyrolysis at high temperatures (1000–1300 °C) with a conversion yield of 60–70 wt%.<sup>90</sup> Therefore, many researchers investigate the sintering performance and microstructure of the B<sub>4</sub>C–SiC ceramics fabricated *via* the preceramic polymer (PCP) route. Thévenot<sup>20</sup> used PCS and Alnovol PN 320 as the precursors of SiC and C, respectively, mixing B<sub>4</sub>C powders to prepare B<sub>4</sub>C–SiC ceramics. The relative density of the green body is 60% after cold pressing, and the relative density of the resulting pressureless sintered B<sub>4</sub>C–SiC ceramics is 95%. Du *et al.*<sup>91</sup> mentioned that the introduction of SiC in the form of PCS can promote the sinterability of B<sub>4</sub>C–SiC ceramics. The SiC obtained from PCS after pyrolyzing at 850 °C is amorphous, but  $\beta$ -SiC crystals are formed after hot-press sintering at 1950 °C. On the one hand, the size distribution of SiC formed ranges from 80 nm to 1  $\mu$ m. The fine SiC nanocrystals with high activity can bond B<sub>4</sub>C grains together and fill spaces to generate a dense structure. On the other hand, a small amount of active carbon derived from the pyrolysis residue of PCS can remove oxide layers existing on B<sub>4</sub>C raw materials, thus improving the sinterability of the B<sub>4</sub>C–SiC ceramics. Hwang *et al.*<sup>87</sup> found that increasing the pyrolysis temperature of PCS cannot change the phase composition and content of the spark plasma sintered B<sub>4</sub>C–SiC ceramics; however, it can change the ceramic

microstructure, which in turn improves the relative density of the ceramics. This is because the increase in the pyrolysis temperature of PCS can reduce the gas evolution during the sintering process. Moreover, organic precursors not only provide a source of raw materials but are also used as polymer additives in a warm pressing process to increase the relative density of the B<sub>4</sub>C–SiC green body. Lin and He<sup>92</sup> first used PCS as a precursor of SiC to prepare PCS-coated B<sub>4</sub>C powders, and then the B<sub>4</sub>C–SiC green bodies were produced from these powders by warm pressing at 300 °C. Because PCS can undergo plastic rheology at 300 °C, which can reduce the friction between B<sub>4</sub>C particles as well as between B<sub>4</sub>C particles and the die wall, thus, the powders can be rearranged smoothly under pressure. As a result, the relative density of the B<sub>4</sub>C–15 wt% SiC green body (65%) produced through warm pressing (50 MPa) is higher than that of the B<sub>4</sub>C–15 wt% SiC green body (54%) produced through cold isostatic pressing (800 MPa). The improvement in the relative density of the green body is helpful in increasing the densification of the final B<sub>4</sub>C–SiC ceramics; therefore, the relative density of the B<sub>4</sub>C–15 wt% SiC ceramics (97%) produced through warm pressing is higher than that of the B<sub>4</sub>C–15 wt% SiC ceramics (91%) produced through cold isostatic pressing after pressureless sintering at 2000 °C. Meanwhile,  $\beta$ -SiC grains formed from PCS are uniformly distributed in the B<sub>4</sub>C matrix.

The PCP route provides an approach for the improved microstructure control of B<sub>4</sub>C–SiC ceramics, and it is an effective method to obtain fine-grained B<sub>4</sub>C–SiC ceramic. For the microstructure of the B<sub>4</sub>C–SiC ceramics prepared from the SiC generated by the pyrolysis of organic precursors, compared with the microstructure of the B<sub>4</sub>C–SiC ceramics prepared by the conventional powder mixing, Lörcher *et al.*<sup>93</sup> found that B<sub>4</sub>C–SiC ceramics show a preferable presence of SiC at the B<sub>4</sub>C grain boundaries when the SiC phase is generated from the precursor of copolymerized polysilane containing dimethylsilylene and methylphenylsilylene groups; thus, SiC grains are more homogeneously distributed in the B<sub>4</sub>C matrix. The SiC phase existing at the grain boundaries plays a role in inhibiting the growth of B<sub>4</sub>C grains. Du *et al.*<sup>91</sup> noted that some SiC grains with nano or submicron size formed from PCS locate within B<sub>4</sub>C grains (Fig. 3a) or at B<sub>4</sub>C grain boundaries (Fig. 3b), forming intragranular and intergranular SiC structures. These nano-sized or submicron-sized SiC grains are favorable for forming a sub-boundary structure in B<sub>4</sub>C–SiC ceramics under internal stress, which can refine B<sub>4</sub>C grains and improve the mechanical properties of B<sub>4</sub>C–SiC ceramics. Meanwhile, the formation of these fine SiC grains means that more barriers are placed in the way of grain boundaries, thereby pinning the migration of grain boundaries and inhibiting the growth of B<sub>4</sub>C grains. In addition, the SiC grains formed from PCS show a layered structure (Fig. 3c), and dislocation defects appear in the SiC grains (Fig. 3b). The formation of the layered structure is caused by the pyrolysis of PCS and crystallization process. When SiC nuclei grow from an amorphous medium, the content of free C also increases, resulting in the formation of a heterogeneous material with an extremely divided microtexture: SiC nuclei are considered to be divided by a thin film of C arranged as a stack of few layers. Thus, the formation of the layered



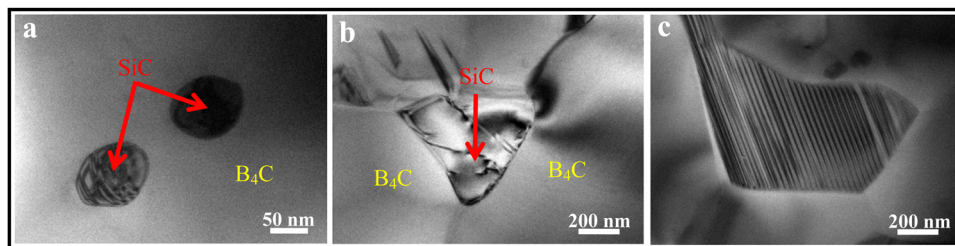
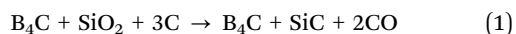


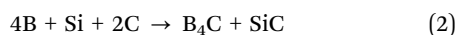
Fig. 3 TEM images of hot-press sintered  $B_4C$ –15 wt% SiC ceramics produced *via* the introduction of SiC in the form of PCS: (a) intragranular SiC structure, (b) intergranular SiC structure, and (c) SiC grains with a layered structure<sup>91</sup> (reproduced with permission, Copyright 2013, Elsevier).

structure within the SiC grains generated from PCS pyrolysis is due to the presence of disordered residual C between SiC layers. The microstructure characteristics of the layered structure and dislocation can affect the mechanical properties of  $B_4C$ –SiC ceramics produced by the introduction of SiC in the form of PCS, especially the fracture toughness, which will be discussed in Section 4.3.2. The use of PCS is a suitable approach to achieve a homogeneous structure in  $B_4C$ –SiC ceramics, which helps avoid the polluting milling process; however, the main drawback is that the  $\beta$ -SiC obtained from PCS pyrolysis will be transformed into  $\alpha$ -SiC coarse grains during sintering.

Besides directly mixing commercial  $B_4C$  and SiC powders,  $B_4C$ –SiC ceramics can also be produced *in situ* through chemical reactions of two or more raw materials. Zhang *et al.*<sup>94,95</sup> first used  $B_4C$ , Si, and amorphous carbon powders to prepare  $B_4C$ –20 wt% SiC nanocomposite powders (50–150 nm) *in situ via* high-energy ball milling; then,  $B_4C$ –SiC ceramics were produced from these  $B_4C$ –SiC nanocomposite powders *via* hot-press sintering at 1950 °C or spark plasma sintering at 1800 °C. The relative densities of the resulting  $B_4C$ –SiC ceramics were in the range of 98.5% to 99.5%, and fine grains were obtained in the ceramics *via* this route. Sahin *et al.*<sup>96</sup> used  $B_4C$ ,  $SiO_2$ , and carbon black as raw materials to produce  $B_4C$ –SiC ceramics *via* spark plasma sintering at 1750 °C, the formation of which is shown as follows:



The relative density of the resulting  $B_4C$ –SiC ceramics decreased linearly from 97.7% to 88.3% with the increase in *in situ* formed SiC content from 5 to 20 vol%. This phenomenon is caused by the fact that the *in situ* formed SiC is oxidized by the intermediate product of  $B_2O_3$  to  $SiO$  gas during the sintering process, resulting in the formation of residual pores in the  $B_4C$ –SiC ceramics; the formation of more SiC content *in situ* is accompanied by an increase in residual pores. This suggests that  $B_4C$ –SiC ceramics with a high SiC content are not easily densified through this route. In addition, Pánek<sup>97</sup> used B powders, Si platelets, and carbon black as raw materials to produce  $B_4C$ –SiC ceramics *in situ* (reaction (2)) by combustion hot-press sintering, which is based on the combination of the self-propagating high-temperature synthesis technique and hot-press sintering. The resulting  $B_4C$ –SiC ceramics can achieve an extremely low porosity (0.3%), and their purity is rather high.



Some previous studies on the effect of raw material on the sintering performance and microstructure of  $B_4C$ –SiC ceramics are tabulated in Table 2.

### 3.3. Preparation process

The sintering performance and microstructure of  $B_4C$ –SiC ceramics vary depending on the processing conditions and parameters. Various factors including powder mixing methods, preparation of the green body, and parameters during sintering affect the sintering performance and microstructure of  $B_4C$ –SiC ceramics.

**3.3.1. Powder mixing method.** In general,  $B_4C$ –SiC composite powders are prepared from multiple single-component powders by dry mixing or wet mixing. The difference between dry mixing and wet mixing is the presence of a liquid medium. Ethanol and water are commonly used as media for wet mixing to prepare  $B_4C$ –SiC composite powders. Yaşar and Haber<sup>71</sup> compared the effects of dry mixing and wet mixing methods of  $B_4C$ –SiC composite powders on the sintering performance and microstructure of spark plasma sintered  $B_4C$ –SiC ceramics. The  $B_4C$ –SiC ceramics produced from  $B_4C$ –SiC composite powders prepared by dry mixing cannot achieve a uniform microstructure; there are some large pockets of individual components (Fig. 4a), while the microstructure of the  $B_4C$ –SiC ceramics produced from  $B_4C$ –SiC composite powders prepared by wet mixing is uniform (Fig. 4b). Compared with the relative density of the  $B_4C$ –SiC ceramics produced from the  $B_4C$ –SiC composite powders prepared by dry mixing, the relative density of the  $B_4C$ –SiC ceramics produced from the  $B_4C$ –SiC composite powders prepared by wet mixing is higher. The agglomeration problem caused by dry mixing has a negative impact on the mechanical properties of  $B_4C$ –SiC ceramics.

Ball milling and high-energy ball milling are two common methods for mixing multiple single-component powders. Zhang *et al.*<sup>98</sup> first prepared  $B_4C$ –SiC composite powders by ball milling and high-energy ball milling, and then compared the sintering performance of  $B_4C$ –SiC ceramics produced from these  $B_4C$ –SiC composite powders synthesized by the two milling methods. Although the particle sizes of raw materials of  $B_4C$  and SiC used in the high-energy ball milling method are larger than those used in the ball milling method (Table 3), the resulting mean particle size (0.7  $\mu$ m) after high-energy ball milling remains the same as that achieved through ball milling. In the  $B_4C$ –SiC ceramics produced from the  $B_4C$ –SiC composite powders



Table 2 Effect of raw material on the sintering performance and microstructure of  $B_4C$ -SiC ceramics

| Ceramics                           | Raw material                                                       | Sintering method              | Sintering temperature (°C) | Sintering aid          | Relative density (%) | Phase composition                 | Average grain size (μm)     |
|------------------------------------|--------------------------------------------------------------------|-------------------------------|----------------------------|------------------------|----------------------|-----------------------------------|-----------------------------|
| $B_4C$ -20 vol% SiC <sup>83</sup>  | $B_4C$ (10.22 μm), β-SiC (1.07 μm)                                 | Hot-press (20 MPa)            | 1900                       | No                     | 73.7                 | $B_4C$ , SiC                      | —                           |
| $B_4C$ -20 vol% SiC <sup>83</sup>  | $B_4C$ (10.22 μm), β-SiC (1.07 μm)                                 | Hot-press (20 MPa)            | 2000                       | No                     | 77.8                 | $B_4C$ , SiC                      | —                           |
| $B_4C$ -20 vol% SiC <sup>83</sup>  | $B_4C$ (10.22 μm), β-SiC (1.07 μm)                                 | Hot-press (20 MPa)            | 2100                       | No                     | 87.0                 | $B_4C$ , SiC                      | —                           |
| $B_4C$ -5 vol% SiC <sup>80</sup>   | $B_4C$ (307 nm), SiC (80 nm)                                       | Pressureless                  | 2200                       | No                     | —                    | $B_4C$ , SiC                      | 16.1                        |
| $B_4C$ -5 vol% SiC <sup>80</sup>   | $B_4C$ (307 nm), SiC (1.0 μm)                                      | Pressureless                  | 2200                       | No                     | —                    | $B_4C$ , SiC                      | 16.3                        |
| $B_4C$ -7.5 vol% SiC <sup>80</sup> | $B_4C$ (307 nm), SiC (80 nm)                                       | Pressureless                  | 2200                       | No                     | —                    | $B_4C$ , SiC                      | 15.8                        |
| $B_4C$ -7.5 vol% SiC <sup>80</sup> | $B_4C$ (307 nm), SiC (1.0 μm)                                      | Pressureless                  | 2200                       | No                     | —                    | $B_4C$ , SiC                      | 15.8                        |
| $B_4C$ -10 vol% SiC <sup>80</sup>  | $B_4C$ (307 nm), SiC (80 nm)                                       | Pressureless                  | 2200                       | No                     | —                    | $B_4C$ , SiC                      | 15.6                        |
| $B_4C$ -10 vol% SiC <sup>80</sup>  | $B_4C$ (307 nm), SiC (1.0 μm)                                      | Pressureless                  | 2200                       | No                     | —                    | $B_4C$ , SiC                      | 14.8                        |
| $B_4C$ -60 wt% SiC <sup>20</sup>   | $B_4C$ (<5.0 μm), α-SiC                                            | Pressureless                  | 2200                       | 2.5 wt% phenolic resin | 97.5                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -60 wt% SiC <sup>20</sup>   | $B_4C$ (<5.0 μm), β-SiC                                            | Pressureless                  | 2200                       | 2.5 wt% phenolic resin | 95.7                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -10 wt% SiC <sup>88</sup>   | $B_4C$ , β-SiC                                                     | Pressureless                  | 2000                       | No                     | 81.3                 | $B_4C$ , α-SiC, (β-SiC)           | —                           |
| $B_4C$ -30 wt% SiC <sup>88</sup>   | $B_4C$ , β-SiC                                                     | Pressureless                  | 2000                       | No                     | 74.0                 | $B_4C$ , α-SiC, (β-SiC)           | —                           |
| $B_4C$ -50 wt% SiC <sup>88</sup>   | $B_4C$ , β-SiC                                                     | Pressureless                  | 2000                       | No                     | 67.5                 | $B_4C$ , α-SiC, (β-SiC)           | —                           |
| $B_4C$ -5 wt% SiC <sup>20</sup>    | $B_4C$ , PCS                                                       | Pressureless                  | 2175                       | Phenolic resin         | 95.0                 | $B_4C$ , SiC                      | 32.0                        |
| $B_4C$ <sup>91</sup>               | $B_4C$ (3.5 μm)                                                    | Hot-press (30 MPa)            | 1950                       | No                     | 91.7                 | $B_4C$                            | —                           |
| $B_4C$ -15 wt% SiC <sup>91</sup>   | $B_4C$ (3.5 μm), PCS                                               | Hot-press (30 MPa)            | 1950                       | No                     | 96.1                 | $B_4C$ , β-SiC                    | SiC < 1.0                   |
| $B_4C$ -10 wt% SiC <sup>87</sup>   | $B_4C$ (0.3–0.6 μm, as-received), PCS (pyrolyzed at 800 °C)        | Spark plasma (50 MPa)         | 1900 (×5 min)              | No                     | 96.2                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -10 wt% SiC <sup>87</sup>   | $B_4C$ (0.3–0.6 μm, washed off by HCl), PCS (pyrolyzed at 800 °C)  | Spark plasma (50 MPa)         | 1900 (×5 min)              | No                     | 97.2                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -10 wt% SiC <sup>87</sup>   | $B_4C$ (0.3–0.6 μm, washed off by HCl), PCS (pyrolyzed at 1385 °C) | Spark plasma (50 MPa)         | 1900 (×5 min)              | No                     | 99.7                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -20 wt% SiC <sup>87</sup>   | $B_4C$ (0.3–0.6 μm, washed off by HCl), PCS (pyrolyzed at 1385 °C) | Spark plasma (50 MPa)         | 1900 (×5 min)              | No                     | 99.5                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -20 wt% SiC <sup>94</sup>   | $B_4C$ , SiC, mean particle size of 50–150 nm                      | Hot-press (30 MPa)            | 1950                       | No                     | 98.6                 | $B_4C$ , SiC                      | $B_4C$ = 1.0–3.0, SiC < 2.0 |
| $B_4C$ -20 wt% SiC <sup>95</sup>   | $B_4C$ , SiC, mean particle size of 50–150 nm                      | Spark plasma (30 MPa)         | 1800 (×5 min)              | No                     | 99.2                 | $B_4C$ , SiC                      | $B_4C$ = 1.0, SiC < 1.0     |
| $B_4C$ -5 vol% SiC <sup>96</sup>   | $B_4C$ , SiO <sub>2</sub> , carbon black                           | Spark plasma (40 MPa)         | 1750 (×5 min)              | No                     | 97.7                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -10 vol% SiC <sup>96</sup>  | $B_4C$ , SiO <sub>2</sub> , carbon black                           | Spark plasma (40 MPa)         | 1750 (×5 min)              | No                     | 93.8                 | $B_4C$ , SiC, C                   | —                           |
| $B_4C$ -15 vol% SiC <sup>96</sup>  | $B_4C$ , SiO <sub>2</sub> , carbon black                           | Spark plasma (40 MPa)         | 1750 (×5 min)              | No                     | 91.2                 | $B_4C$ , SiC, C, SiO <sub>2</sub> | —                           |
| $B_4C$ -20 vol% SiC <sup>96</sup>  | $B_4C$ , SiO <sub>2</sub> , carbon black                           | Spark plasma (40 MPa)         | 1750 (×5 min)              | No                     | 88.3                 | $B_4C$ , SiC, C, SiO <sub>2</sub> | —                           |
| $B_4C$ -50 vol% SiC <sup>97</sup>  | B powders (1.5 μm), Si platelets, carbon black                     | Combustion hot-press (30 MPa) | 1900 (×20 min)             | No                     | 99.7                 | $B_4C$ , SiC                      | —                           |



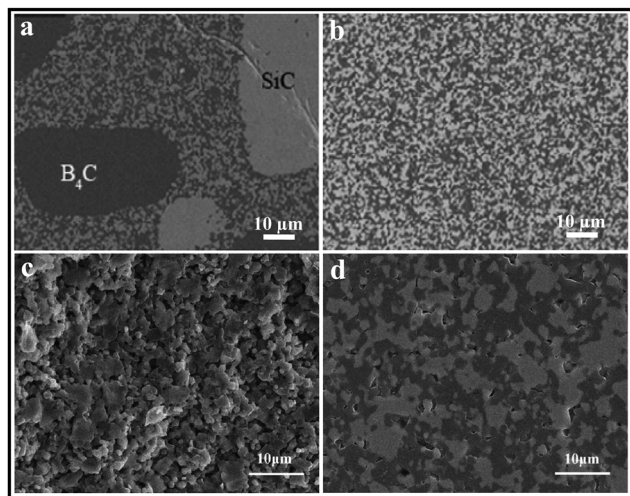


Fig. 4 Microstructure of spark plasma sintered SiC–40 wt% B<sub>4</sub>C ceramics produced from the B<sub>4</sub>C–SiC composite powders prepared by: (a) dry mixing and (b) wet mixing<sup>71</sup> (reproduced with permission, Copyright 2020, Elsevier). Fracture surfaces of hot-press sintered B<sub>4</sub>C–50 wt% SiC ceramics using B<sub>4</sub>C–SiC composite powders prepared by: (c) ball milling and (d) high-energy ball milling<sup>98</sup> (reprinted with permission, Copyright 2013, Elsevier).

synthesized *via* usual wet ball milling, there are a lot of pores and separate fine powders (Fig. 4c); the relative density of the ceramics is 85%. However, under the same sintering conditions, few pores and no separate fine powders exist in the B<sub>4</sub>C–SiC ceramics produced from the B<sub>4</sub>C–SiC composite powders synthesized *via* high-energy ball milling (Fig. 4d), whose relative density is up to 96%. With the same particle size and sintering conditions, using high-energy ball milling to prepare B<sub>4</sub>C–SiC composite powders can decrease the sintering temperature and promote the sintering for the preparation of B<sub>4</sub>C–SiC ceramics. High-energy ball milling can induce transformation of B<sub>4</sub>C and SiC composite powders from an ordered to disordered structure during the milling process; then these composite powders with a disordered structure are transformed into B<sub>4</sub>C–SiC ceramics with an ordered structure in the subsequent sintering process. The energy released during the transformation of disorder-order can serve as a sintering driving force. Therefore, using the composite powders prepared by high-energy ball milling can improve the sintering performance of B<sub>4</sub>C–SiC ceramics.

Some previous studies on the effect of the powder mixing method on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics are tabulated in Table 3.

**3.3.2. Preparation of the green body.** For some preparation methods of B<sub>4</sub>C–SiC ceramics, such as pressureless sintering and reaction-bonded sintering, multiple single-component powders need to be pre-compacted into the green body. At first, the mixed composite powders are loosely stacked in the mold; even after the compaction, there are still a large number of pores present in the green body. The improvement of the relative density of the green body can increase the relative density and mechanical properties of the resulting ceramics.

As mentioned in Section 3.2.1, the particle size and packing structure affect the relative density of the green body.

Table 3 Effect of the powder mixing method on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics

| Ceramics                                  | Raw material                                                                                           | Powder mixing method               | Sintering method      | Sintering temperature (°C) | Sintering aid | Relative density (%) | Phase composition        | Average grain size (μm) |
|-------------------------------------------|--------------------------------------------------------------------------------------------------------|------------------------------------|-----------------------|----------------------------|---------------|----------------------|--------------------------|-------------------------|
| SiC-10 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Dry mixing                         | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 98.6                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-10 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Wet mixing (ethanol)               | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 99.6                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-20 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Dry mixing                         | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 98.7                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-20 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Wet mixing (ethanol)               | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 99.2                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-30 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Dry mixing                         | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 98.5                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-30 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Wet mixing (ethanol)               | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 98.8                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-40 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Dry mixing                         | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 97.8                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-40 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Wet mixing (ethanol)               | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 98.8                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-50 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Dry mixing                         | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 97.5                 | B <sub>4</sub> C, SiC, C | —                       |
| SiC-50 wt% B <sub>4</sub> C <sup>71</sup> | B <sub>4</sub> C, SiC                                                                                  | Wet mixing (ethanol)               | Spark plasma (50 MPa) | 1950 (×5 min)              | 1.5 wt% C     | 98.9                 | B <sub>4</sub> C, SiC, C | —                       |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup> | B <sub>4</sub> C (0.7 μm), SiC (0.8 μm)                                                                | Ball milling (ethanol)             | Hot-press (30 MPa)    | 1950                       | No            | 85.0                 | B <sub>4</sub> C, SiC    | 1.0                     |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup> | B <sub>4</sub> C (2.57 μm), SiC (3.11 μm), mean particle size of 0.7 μm after high-energy ball milling | High-energy ball milling (ethanol) | Hot-press (30 MPa)    | 1950                       | No            | 96.0                 | B <sub>4</sub> C, SiC    | <1.0                    |

Furthermore, to achieve the maximal relative density of the green body without generating internal cracks, the compaction pressure during compaction should be taken into account.<sup>99</sup> A suitable compaction pressure is rather important to achieve the maximal relative density of the ceramic preform. Hayun *et al.*<sup>84</sup> found that the relative density of the green body composed of either graded B<sub>4</sub>C particles or monosized fine B<sub>4</sub>C particles increases with an increase in compaction pressure from 40 to 160 MPa. The relative density remains constant under a higher compaction pressure (180 MPa); however, excessive compaction pressure may result in the generation of internal cracks in the green body.

Warm pressing is one of the methods to increase the relative density of the green body. Adding a polymer into ceramic powders and pressing the green body above the softening temperature of the polymer can lead to the production of a green body with higher relative density by using the viscous flow of the polymer, thus improving the relative density and mechanical properties of the obtained ceramic. As mentioned in Section 3.2.3, the addition of PCS, which can be used as a precursor of SiC, can increase the relative density of the green body by warm pressing at 300 °C.

For the green body produced for the preparation of reaction-bonded B<sub>4</sub>C–SiC ceramics, interconnected pores that can provide a penetration path for molten Si are necessary; thus, a necessary minimum porosity should be provided for capillary impregnation. Meanwhile, the high volume expansion caused by the siliconisation reaction easily blocks the capillary channels, inhibiting Si infiltration; thus, the pore size also needs to be considered. Both pore volume fraction and pore size control the impregnation efficiency and phase composition. On the one hand, increasing pore parameters can improve the impregnation efficiency of molten Si and increase the amount of SiC generated;<sup>77</sup> on the other hand, decreasing pore parameters contributes to limiting the fraction of residual non-reacted Si after infiltration.<sup>84</sup> Therefore, it is necessary to balance the two aspects to achieve an optimum relative density of the green body. In addition, the addition of C affects the porosity of the green body. Li *et al.*<sup>76</sup> found that carbon black can decrease the open pore size of the green body prepared by slip casting, but can increase the porosity of the green body, which is attributed to the particle agglomeration and consequently increased slip-casting slurry viscosity.

For the reaction-bonded B<sub>4</sub>C–SiC ceramics, the properties of the green body decide the final properties of the ceramics. The forming technique for the green body affects the microstructures of the green body and the resulting B<sub>4</sub>C–SiC ceramics. Conventionally, the green body composed of B<sub>4</sub>C and carbon black is prepared by uniaxial compaction. However, the distribution of density and pores in the green body is not uniform *via* this route due to the inhomogeneous mold pressure, leading to the formation of some inhomogeneous carbon black agglomerates,<sup>100</sup> which in turn is not conducive to the homogenization of the microstructure of the obtained B<sub>4</sub>C–SiC ceramics; many large-sized SiC zones and relatively large, uneven residual Si phases are formed in the obtained ceramics.<sup>101</sup> Xu *et al.*<sup>102</sup> found an

alternative solution to prepare the green body with a uniform microstructure, *viz.*, gel-casting technique. A hierarchical porous B<sub>4</sub>C–C green body with both mesopores and macropores is produced by the gel-casting method. The polymerization-induced phase separation and pyrolysis result in the formation of mesopores on the carbon matrix; the space occupied by solvent becomes macropores after evaporation. The hierarchical porous green body is suitable for the molten Si infiltration process and favors the reduction in the size of residual Si islands. Upon molten Si infiltration, such hierarchically porous structure in the C-bonded B<sub>4</sub>C green body prepared by the gel-casting method can not only improve the uniformity of the microstructure but also generate a SiC-bonded B<sub>4</sub>C scaffold structure in the resulting B<sub>4</sub>C–SiC ceramics. In addition, the pore structure and porosity of the green body will control the content and size of the residual Si, which in turn affects the mechanical properties of the reaction-bonded B<sub>4</sub>C–SiC ceramics. Therefore, the performance of reaction-bonded B<sub>4</sub>C–SiC ceramics can be adjusted by controlling the pore characteristics of the green body. Ren *et al.*<sup>103</sup> found that adjusting the content of the catalyst Na<sub>2</sub>CO<sub>3</sub> can help control the pore characteristics of the B<sub>4</sub>C–C green body prepared by gel-casting, whose mechanism is that the degree of cross-linking within the gel is modified to control the phase separation process by adjusting the content of the catalyst. With an increase in catalyst content, the porosity and pore size of the green body decrease, and the pore structure of the green body changes from a single macroporous or mesoporous structure to a hierarchical macroporous–mesoporous structure, reducing the residual Si content in the B<sub>4</sub>C–SiC ceramics.

### 3.3.3. Parameters during sintering

**3.3.3.1. Sintering temperature.** Sintering temperature is a crucial parameter for the preparation of B<sub>4</sub>C–SiC ceramics in the sintering process. Generally, increasing the sintering temperature can accelerate the diffusion rate of atoms, which is beneficial for improving the densification of B<sub>4</sub>C–SiC ceramics. Also, the grain size of B<sub>4</sub>C–SiC ceramics increases with an increase in sintering temperature; however, excessive sintering temperature can cause grain coarsening and abnormal grain growth. For reaction-bonded sintering, increasing infiltration temperature can enhance the liquid–solid wettability and liquid Si fluidity,<sup>104</sup> thus improving its permeability in the preform; meanwhile, high temperature will accelerate the diffusion of C atoms in molten Si, accelerating the grain growth of SiC.<sup>105,106</sup>

For B<sub>4</sub>C–SiC ceramics produced *via* pressureless sintering, Zhu *et al.*<sup>107</sup> studied the effect of sintering temperature in the range of 2100 to 2200 °C on the sintering performance and microstructure of B<sub>4</sub>C–15 wt% SiC ceramics under the mechanism of solid-state sintering. The phase composition of the composite ceramics is B<sub>4</sub>C, SiC, and graphite after sintering at different temperatures. The formation of graphite suggests that amorphous carbon black that is used as a sintering aid undergoes crystallization, whose degree increases with the increase in sintering temperature. The relative density of B<sub>4</sub>C–SiC ceramics increases first and then decreases with increasing temperature from 2100 to 2200 °C; the grain size of the ceramics increases with an increase in sintering temperature. At 2100 °C, most of the



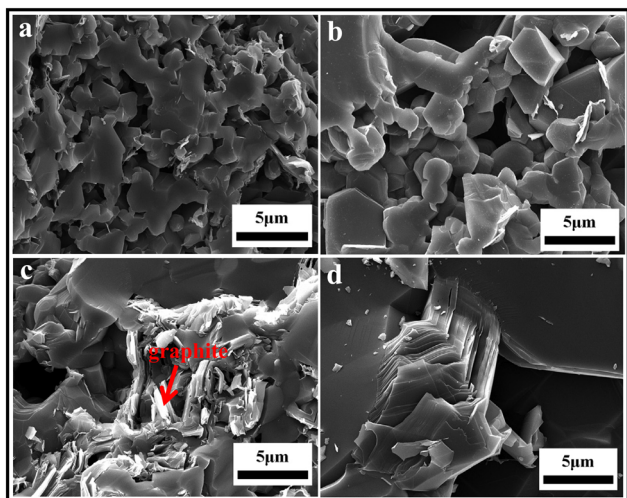


Fig. 5 Fracture surfaces of pressureless sintered  $B_4C$ -15 wt% SiC ceramics sintered at: (a) 2100 °C, (b) 2125 °C, (c) 2150 °C, and (d) 2175 °C<sup>107</sup> (reprinted with permission, Copyright 2019, Elsevier).

sintered necks do not grow, and there are a lot of pores in the matrix (Fig. 5a). With an increase in sintering temperature to 2150 °C, sintered necks grow gradually, and the number of pores is reduced (Fig. 5b and c). Meanwhile, some fine SiC grains uniformly distribute at the grain boundary, pinning the migrating grain boundaries and inhibiting the growth of  $B_4C$  grains. The lamellar graphite is located on the surface of  $B_4C$  grains. However, when the sintering temperature is further increased to more than 2150 °C, the movement of the grain boundary is so rapid that pores cannot be eliminated, resulting in the decreased relative density of  $B_4C$ -SiC ceramics. Also, the sizes of lamellar graphite and pore increase (Fig. 5d). Vandeperre and Teo<sup>108</sup> investigated the effect of sintering temperature in the range of 1950 to 2200 °C on the sintering performance of  $B_4C$ -SiC ceramics with different ratios of  $B_4C$  to SiC. The relative density of SiC-rich ceramics can reach up to 95% after sintering at 2050 °C. However, higher sintering temperatures are needed for  $B_4C$ -rich ceramics to achieve better sintering performance, and the relative density of  $B_4C$ -rich ceramics is 95% only after sintering at 2200 °C. This phenomenon may be caused by the greater proportion of covalent bonds in  $B_4C$ . Moradkhani and Baharvandi<sup>80</sup> found that the grain size of  $B_4C$ -10 wt% SiC ceramics slightly increases with the increase in sintering temperature from 2100 to 2200 °C. In addition, the excessive sintering temperature is also not beneficial for improving the densification of  $B_4C$ -SiC ceramics under the mechanism of liquid-phase sintering. Zhang *et al.*<sup>109</sup> observed that the relative density of SiC-10 wt%  $B_4C$  ceramics with the sintering aids of  $Al_2O_3$  and  $La_2O_3$  increases first and then decreases with the increase in sintering temperature from 1800 to 1935 °C. Higher sintering temperatures result in the volatilization of the liquid phase with a low melting point and the anisotropic growth of the SiC grains, decreasing the relative density.

For  $B_4C$ -SiC ceramics prepared by hot-press sintering, Zhang *et al.*<sup>98</sup> reported that the relative density of  $B_4C$ -50 wt% SiC ceramics increases linearly with an increase in sintering temperature in the

range of 1800–1950 °C. At 1800 °C, the densification of  $B_4C$ -SiC ceramics begins, but most of the particles are not sintered. When the sintering temperature rises to 1950 °C, there are few pores in the ceramics and the relative density of  $B_4C$ -SiC ceramics is up to 96%. Chen *et al.*<sup>110</sup> found that the grains of  $B_4C$ -20 wt% SiC ceramics become smaller and the microstructure becomes denser with the increase in sintering temperature from 1800 to 1900 °C, which is attributed to the elimination of pores between grains due to the movement of grain boundaries with the increase in sintering temperature.

For spark plasma sintered  $B_4C$ -SiC ceramics, Wu *et al.*<sup>111</sup> observed that the relative density of the  $B_4C$ -20 vol% SiC ceramics increases with the increase in sintering temperature from 1900 to 2100 °C. When the sintering temperature is lower than 2000 °C, a large number of pores exist in the ceramics, but many sintered necks have been formed. When the sintering temperature is 2000 °C, the grown grains are tightly connected, and the pores almost completely disappear. When the sintering temperature is higher than 2000 °C, the microstructure of the ceramics no longer changes significantly. Moshtaghionoun *et al.*<sup>112</sup> reported that the grain sizes of both  $B_4C$  and SiC in the  $B_4C$ -15 wt% SiC ceramics are independent of the sintering temperature in the range of 1650 to 1700 °C. Although the particle sizes of  $B_4C$  and SiC raw materials are the same, the  $B_4C$  grains are larger than the SiC grains in the resulting  $B_4C$ -SiC ceramics. This is because  $B_4C$  is the connected phase in the microstructure; as a result, the diffusion of B and C resulting in  $B_4C$  grain growth is easier.

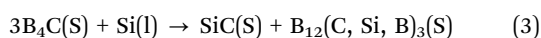
The sintering temperature not only affects the porosity and grain size but also affects the crystallization of  $B_4C$ -SiC ceramics. Zhang *et al.*<sup>94,95</sup> noted that the structure of  $B_4C$ -SiC ceramics undergoes a disorder–order transformation from 1700 to 1900 °C *via* hot-press sintering or from 1600 to 1700 °C *via* spark plasma sintering when  $B_4C$ -SiC composite powders composed of  $B_4C$  with increased volume of lattice defects and amorphous SiC, which are prepared by high-energy ball milling, are used as raw materials. This indicates that increasing the sintering temperature within a certain range can increase the stacking order of the structure.

For  $B_4C$ -SiC ceramics fabricated by reaction-bonded sintering, because the melting temperature of Si is 1410 °C, there is little difference in phase composition between the sintered ceramics and the original powder mixture when the sintering temperature is lower than 1410 °C, indicating that no reaction occurs among  $B_4C$ , C, and Si.<sup>113</sup> When the sintering temperature is higher than 1410 °C, Si can melt and infiltrate into the top part of the green body to rapidly react with C to form  $\beta$ -SiC.<sup>113</sup> Although Si can infiltrate into the green body composed of  $B_4C$  and graphite, the resulting  $B_4C$ -SiC ceramics are still quite porous because the viscosity of molten Si at 1410 °C is relatively high, preventing the infiltration to the porous green body. This suggests that infiltration temperature affects the viscosity of molten Si, and a sufficient temperature is needed to ensure a good fluidity of molten Si. With the increase in sintering temperature to 1450 °C, the reaction between  $B_4C$  and Si is further promoted; thus, the obtained  $B_4C$ -SiC ceramics are very dense and nearly nonporous. Ordan'yan *et al.*<sup>114</sup>



also pointed out that the temperature of the impregnation process (1450–1800 °C) generally exceeds the melting temperature of Si, resulting from the need to decrease the viscosity of Si melt and enhance the wetting of B<sub>4</sub>C and C to facilitate capillary impregnation. Therefore, 1410 °C is a critical temperature for Si infiltration and reaction bonding. Nesmelov and Perevislov<sup>115</sup> mentioned that the temperature interval of 1600–1800 °C is sufficient for Si viscosity to wet the total porous preform. Sun *et al.*<sup>116</sup> noted that the relative density of B<sub>4</sub>C–SiC ceramics increases with the increase in sintering temperature from 1660 to 1780 °C. During the molten Si infiltration, C atoms on carbon particles are dissolved at the Si/C interface where a submicron SiC layer is formed; then this SiC layer rapidly cracks into crystalline particles because of the lattice mismatch between the carbon particles and SiC layer. After being dissolved in molten Si, the crystalline SiC particles precipitate on the initial SiC particles. Therefore, the dissolution rate of C atoms and the precipitation rate of crystalline SiC are the main factors affecting the reaction rate. A high sintering temperature is beneficial for increasing the solubility of C atoms and crystalline SiC, improving the reaction rate.

When the infiltration temperature is higher than 1410 °C, the sintering temperature will affect the phase amount of reaction-bonded B<sub>4</sub>C–SiC ceramics. Zhang *et al.*<sup>117</sup> found that the amount of B<sub>4</sub>C decreases, but the amounts of generated SiC phase and residual Si phase increase with the increase in infiltration temperature from 1450 to 1650 °C. On the one hand, the solubility of B and C in molten Si increases with an increase in infiltration temperature, leading to the increased amount of dissolved B<sub>4</sub>C particles; on the other hand, the interface reaction between B<sub>4</sub>C and molten Si (reaction (3)), which is negligible at 1450 °C but significant at 1650 °C, is gradually intensified with increasing infiltration temperature, causing further dissolution of B<sub>4</sub>C particles in molten Si and increasing the amounts of generated SiC and precipitated B<sub>12</sub>(C, Si, B)<sub>3</sub> on the original B<sub>4</sub>C particles.



Moreover, the grain shape and grain size of reaction-bonded B<sub>4</sub>C–SiC ceramics are also affected by the infiltration temperature.<sup>118</sup> When the sintering temperature is 1450 °C, the grain shape of B<sub>4</sub>C basically maintains the original irregular shape of initial B<sub>4</sub>C particles with flexuous edges due to the mild dissolution of B<sub>4</sub>C grains in molten Si at temperatures below 1550 °C. When the sintering temperature is increased to 1650 °C, the shape of partial large B<sub>4</sub>C grains evolves from an irregular shape to a faceted shape with sharp corners and straight edges; the small B<sub>4</sub>C grains evolve into a spherical shape because the dissolution of B<sub>4</sub>C grains in molten Si is intensified. The grain shape evolution of B<sub>4</sub>C can be described by Ostwald ripening: the dissolution of the smaller grains and the precipitation of dissolved components on the grains that are larger than the critical ones.<sup>119</sup> The dissolved materials transfer and precipitate as B<sub>12</sub>(B, C, Si)<sub>3</sub> on the defective concave surface of the large B<sub>4</sub>C grains. Thus, the large B<sub>4</sub>C grains exhibit the growth shape and the small grains show the dissolution shape. When the sintering

temperature is further increased to 1750 °C, the grain shape of B<sub>4</sub>C is mostly faceted. Zhang *et al.*<sup>117</sup> also observed that the B<sub>4</sub>C particles with the precipitation of B<sub>12</sub>(C, Si, B)<sub>3</sub> gradually develop a multifaced surface morphology with angular shapes and triangular prisms when the sintering temperature is between 1600 and 1650 °C. Meanwhile, the shape of the formed SiC is also affected by the sintering temperature.<sup>117</sup> The SiC morphology evolves from discontinuous, cloud-like SiC to continuous, integrated SiC zones with the increase in sintering temperature from 1450 to 1650 °C. With the increase in the amount of generated SiC, the original discontinuous SiC grains coalesce and connect to each other, forming continuous, integrated SiC zones. Also, the amount and size of these integrated SiC zones increase with an increase in sintering temperature. On the other side, the grain sizes of both B<sub>4</sub>C with the precipitation of B<sub>12</sub>(C, Si, B)<sub>3</sub> and generated SiC particles increase with an increase in infiltration temperature.<sup>117</sup> The increased grain size of B<sub>4</sub>C with the precipitation of B<sub>12</sub>(C, Si, B)<sub>3</sub> is attributed to the coalescence of neighboring B<sub>4</sub>C particles. With the increase in infiltration temperature, there is a greater precipitation of the B<sub>12</sub>(C, Si, B)<sub>3</sub> phase on the surfaces of original B<sub>4</sub>C particles, increasing the chance for neighboring B<sub>4</sub>C particles to coalesce. Most SiC grains are generated *via* the reaction between molten Si and carbon black, which is controlled by the dissolution–precipitation mechanism at the beginning,<sup>105</sup> and then by the diffusion of Si and C atoms in solid SiC when molten Si is not in contact with C.<sup>106</sup> With the increase in infiltration temperature, the dissolution of C in molten Si is promoted because of the higher solubility of C in molten Si, and the diffusion of Si and C atoms in solid SiC is accelerated; thus, the generated SiC grains grow and ripen at higher temperatures. Zhang *et al.*<sup>118</sup> pointed out that the growth behavior of B<sub>4</sub>C grains depends on the sintering temperature and the grain shape. The grain size of B<sub>4</sub>C increases with an increase in the sintering temperature. When the sintering temperature is below 1750 °C, the B<sub>4</sub>C grains show a unimodal size distribution, suggesting normal grain growth; the grain growth of B<sub>4</sub>C is primarily controlled by diffusion. However, when the sintering temperature is above 1750 °C, the B<sub>4</sub>C grains exhibit a bimodal size distribution, indicating an abnormal grain growth; the grain growth of B<sub>4</sub>C is controlled by coalescence-enhanced two-dimensional nucleation. Abnormal grain growth only occurs when the grain shape of B<sub>4</sub>C is faceted.

Some previous studies on the effect of sintering temperature on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics are tabulated in Table 4.

**3.3.3.2. Holding time.** Holding time is another factor affecting the microstructure and phase composition of B<sub>4</sub>C–SiC ceramics. Tomohiro *et al.*<sup>78</sup> reported that the grain size of the hot-press sintered B<sub>4</sub>C–15 vol% SiC ceramics increases from 2–3 to 10 μm with the increase in holding time from 30 to 120 min when the sintering temperature is 2200 °C; however, the relative density of the ceramics is independent on the holding time. For reaction-bonded B<sub>4</sub>C–SiC ceramics, when the sintering temperature is fixed at 1550 °C, increasing the holding time can enhance the transformation of B<sub>4</sub>C grains from irregular shape to faceted





**Table 4** Effect of sintering temperature on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics

| Ceramics                                    | Raw material                                                                       | Sintering method      | Sintering temperature (°C) | Sintering aid                                                                              | Relative density (%) | Phase composition                                                                              | Average grain size (μm)                 |
|---------------------------------------------|------------------------------------------------------------------------------------|-----------------------|----------------------------|--------------------------------------------------------------------------------------------|----------------------|------------------------------------------------------------------------------------------------|-----------------------------------------|
| B <sub>4</sub> C-15 wt% SiC <sup>107</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)                                            | Pressureless          | 2100                       | 2 wt% carbon black                                                                         | 91.6                 | B <sub>4</sub> C, SiC, graphite                                                                | 2.3                                     |
| B <sub>4</sub> C-15 wt% SiC <sup>107</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)                                            | Pressureless          | 2125                       | 2 wt% carbon black                                                                         | 93.6                 | —                                                                                              | 11.2                                    |
| B <sub>4</sub> C-15 wt% SiC <sup>107</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)                                            | Pressureless          | 2150                       | 2 wt% carbon black                                                                         | 95.3                 | B <sub>4</sub> C, SiC, graphite                                                                | 13.6                                    |
| B <sub>4</sub> C-15 wt% SiC <sup>107</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)                                            | Pressureless          | 2175                       | 2 wt% carbon black                                                                         | 93.1                 | —                                                                                              | 17.2                                    |
| B <sub>4</sub> C-15 wt% SiC <sup>107</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)                                            | Pressureless          | 2200                       | 2 wt% carbon black                                                                         | —                    | —                                                                                              | 27.9                                    |
| B <sub>4</sub> C-10 vol% SiC <sup>80</sup>  | B <sub>4</sub> C (307 nm), SiC (1.0 μm)                                            | Pressureless          | 2100                       | No                                                                                         | —                    | B <sub>4</sub> C, SiC                                                                          | 14.1                                    |
| B <sub>4</sub> C-10 vol% SiC <sup>80</sup>  | B <sub>4</sub> C (307 nm), SiC (1.0 μm)                                            | Pressureless          | 2150                       | No                                                                                         | —                    | B <sub>4</sub> C, SiC                                                                          | 14.3                                    |
| B <sub>4</sub> C-10 vol% SiC <sup>80</sup>  | B <sub>4</sub> C (307 nm), SiC (1.0 μm)                                            | Pressureless          | 2200                       | No                                                                                         | —                    | B <sub>4</sub> C, SiC                                                                          | 14.8                                    |
| SiC-10 wt% B <sub>4</sub> C <sup>109</sup>  | α-SiC (1.0 μm), B <sub>4</sub> C (0.5 μm)                                          | Pressureless          | 1800                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> :La <sub>2</sub> O <sub>3</sub> = 1:1, molar ratio) | 90.2                 | SiC, B <sub>4</sub> C, LaAlO <sub>3</sub>                                                      | —                                       |
| SiC-10 wt% B <sub>4</sub> C <sup>109</sup>  | α-SiC (1.0 μm), B <sub>4</sub> C (0.5 μm)                                          | Pressureless          | 1835                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> :La <sub>2</sub> O <sub>3</sub> = 1:1, molar ratio) | 91.8                 | SiC, B <sub>4</sub> C, LaAlO <sub>3</sub>                                                      | —                                       |
| SiC-10 wt% B <sub>4</sub> C <sup>109</sup>  | α-SiC (1.0 μm), B <sub>4</sub> C (0.5 μm)                                          | Pressureless          | 1875                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> :La <sub>2</sub> O <sub>3</sub> = 1:1, molar ratio) | 94.0                 | SiC, B <sub>4</sub> C, LaAlO <sub>3</sub>                                                      | —                                       |
| SiC-10 wt% B <sub>4</sub> C <sup>109</sup>  | α-SiC (1.0 μm), B <sub>4</sub> C (0.5 μm)                                          | Pressureless          | 1900                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> :La <sub>2</sub> O <sub>3</sub> = 1:1, molar ratio) | 96.8                 | SiC, B <sub>4</sub> C, LaAlO <sub>3</sub>                                                      | —                                       |
| SiC-10 wt% B <sub>4</sub> C <sup>109</sup>  | α-SiC (1.0 μm), B <sub>4</sub> C (0.5 μm)                                          | Pressureless          | 1935                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> :La <sub>2</sub> O <sub>3</sub> = 1:1, molar ratio) | 95.3                 | SiC, B <sub>4</sub> C, LaAlO <sub>3</sub>                                                      | —                                       |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup>   | B <sub>4</sub> C, SiC, mean particle size of 0.7 μm                                | Hot-press (30 MPa)    | 1800                       | No                                                                                         | 74.0                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup>   | B <sub>4</sub> C, SiC, mean particle size of 0.7 μm                                | Hot-press (30 MPa)    | 1850                       | No                                                                                         | 79.2                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup>   | B <sub>4</sub> C, SiC, mean particle size of 0.7 μm                                | Hot-press (30 MPa)    | 1900                       | No                                                                                         | 89.2                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup>   | B <sub>4</sub> C, SiC, mean particle size of 0.7 μm                                | Hot-press (30 MPa)    | 1950                       | No                                                                                         | 96.4                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C <sup>110</sup>             | B <sub>4</sub> C (0.8 μm)                                                          | Hot-press (30 MPa)    | 1800                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> )                   | 97.2                 | B <sub>4</sub> C                                                                               | —                                       |
| B <sub>4</sub> C-20 wt% SiC <sup>110</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.45 μm)                                           | Hot-press (30 MPa)    | 1800                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> )                   | 94.0                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C <sup>110</sup>             | B <sub>4</sub> C (0.8 μm)                                                          | Hot-press (30 MPa)    | 1900                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> )                   | 98.6                 | B <sub>4</sub> C                                                                               | —                                       |
| B <sub>4</sub> C-20 wt% SiC <sup>110</sup>  | B <sub>4</sub> C (0.8 μm), SiC (0.45 μm)                                           | Hot-press (30 MPa)    | 1900                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> )                   | 98.5                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 vol% SiC <sup>111</sup> | B <sub>4</sub> C (3.5 μm), SiC (0.5 μm)                                            | Spark plasma (40 MPa) | 1900 (×10 min)             | No                                                                                         | 90.1                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 vol% SiC <sup>111</sup> | B <sub>4</sub> C (3.5 μm), SiC (0.5 μm)                                            | Spark plasma (40 MPa) | 1950 (×10 min)             | No                                                                                         | 91.0                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 vol% SiC <sup>111</sup> | B <sub>4</sub> C (3.5 μm), SiC (0.5 μm)                                            | Spark plasma (40 MPa) | 2000 (×10 min)             | No                                                                                         | 96.3                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 vol% SiC <sup>111</sup> | B <sub>4</sub> C (3.5 μm), SiC (0.5 μm)                                            | Spark plasma (40 MPa) | 2050 (×10 min)             | No                                                                                         | 96.6                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 vol% SiC <sup>111</sup> | B <sub>4</sub> C (3.5 μm), SiC (0.5 μm)                                            | Spark plasma (40 MPa) | 2100 (×10 min)             | No                                                                                         | 96.8                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-15 wt% SiC <sup>112</sup>  | B <sub>4</sub> C (0.5 μm), β-SiC (0.5 μm)                                          | Spark plasma (75 MPa) | 1650 (×5 min)              | No                                                                                         | 96.6                 | B <sub>4</sub> C, SiC                                                                          | B <sub>4</sub> C: 0.537, SiC: 0.05–0.25 |
| B <sub>4</sub> C-15 wt% SiC <sup>112</sup>  | B <sub>4</sub> C (0.5 μm), β-SiC (0.5 μm)                                          | Spark plasma (75 MPa) | 1700 (×3 min)              | No                                                                                         | 99.4                 | B <sub>4</sub> C, SiC                                                                          | B <sub>4</sub> C: 0.537, SiC: 0.05–0.25 |
| B <sub>4</sub> C-20 wt% SiC <sup>94</sup>   | B <sub>4</sub> C, SiC, mean particle size of 50–150 nm                             | Hot-press (30 MPa)    | 1900                       | No                                                                                         | 97.2                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 wt% SiC <sup>94</sup>   | B <sub>4</sub> C, SiC, mean particle size of 50–150 nm                             | Hot-press (30 MPa)    | 1950                       | No                                                                                         | 98.6                 | B <sub>4</sub> C, SiC                                                                          | B <sub>4</sub> C = 1.0–3.0, SiC < 2.0   |
| B <sub>4</sub> C-20 wt% SiC <sup>95</sup>   | B <sub>4</sub> C, SiC, mean particle size of 50–150 nm                             | Spark plasma (30 MPa) | 1700 (×5 min)              | No                                                                                         | 96.7                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 wt% SiC <sup>95</sup>   | B <sub>4</sub> C, SiC, mean particle size of 50–150 nm                             | Spark plasma (30 MPa) | 1750 (×5 min)              | No                                                                                         | 98.3                 | B <sub>4</sub> C, SiC                                                                          | —                                       |
| B <sub>4</sub> C-20 wt% SiC <sup>95</sup>   | B <sub>4</sub> C, SiC, mean particle size of 50–150 nm                             | Spark plasma (30 MPa) | 1800 (×5 min)              | No                                                                                         | 99.2                 | B <sub>4</sub> C, SiC                                                                          | B <sub>4</sub> C = 1.0, SiC < 1.0       |
| B <sub>4</sub> C-SiC <sup>113</sup>         | B <sub>4</sub> C (45 μm), graphite (10 μm), Si lump                                | Reaction              | 1380                       | No                                                                                         | —                    | B <sub>4</sub> C, graphite                                                                     | —                                       |
| B <sub>4</sub> C-SiC <sup>113</sup>         | B <sub>4</sub> C (45 μm), graphite (10 μm), Si lump                                | Reaction              | 1410                       | No                                                                                         | —                    | B <sub>4</sub> C, SiC, graphite, B <sub>12</sub> (C,Si,B) <sub>3</sub> , B <sub>10</sub> C, Si | —                                       |
| B <sub>4</sub> C-SiC <sup>113</sup>         | B <sub>4</sub> C (45 μm), graphite (10 μm), Si lump                                | Reaction              | 1450                       | No                                                                                         | —                    | B <sub>4</sub> C, SiC, graphite, B <sub>12</sub> (C,Si,B) <sub>3</sub> , B <sub>10</sub> C, Si | —                                       |
| SiC-50 wt% B <sub>4</sub> C <sup>116</sup>  | B <sub>4</sub> C (1.5 μm), α-SiC (7.0 μm), phenolic resin, carbon black, Si powder | Reaction              | 1660                       | No                                                                                         | 92.7                 | —                                                                                              | —                                       |
| SiC-50 wt% B <sub>4</sub> C <sup>116</sup>  | B <sub>4</sub> C (1.5 μm), α-SiC (7.0 μm), phenolic resin, carbon black, Si powder | Reaction              | 1690                       | No                                                                                         | 94.6                 | —                                                                                              | —                                       |

Table 4 (continued)

| Ceramics                                   | Raw material                                                                       | Sintering method | Sintering temperature (°C) | Sintering aid | Relative density (%) | Phase composition                                                 | Average grain size (μm)         |
|--------------------------------------------|------------------------------------------------------------------------------------|------------------|----------------------------|---------------|----------------------|-------------------------------------------------------------------|---------------------------------|
| SiC-50 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 μm), α-SiC (7.0 μm), phenolic resin, carbon black, Si powder | Reaction         | 1720                       | No            | 97.2                 | —                                                                 | —                               |
| SiC-50 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 μm), α-SiC (7.0 μm), phenolic resin, carbon black, Si powder | Reaction         | 1750                       | No            | 98.0                 | —                                                                 | —                               |
| SiC-50 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 μm), α-SiC (7.0 μm), phenolic resin, carbon black, Si powder | Reaction         | 1780                       | No            | 98.2                 | —                                                                 | —                               |
| B <sub>4</sub> C-SiC <sup>117</sup>        | B <sub>4</sub> C (4.08 μm), carbon black, Si lump                                  | Reaction         | 1450                       | No            | 99.8                 | B <sub>4</sub> C, SiC, B <sub>12</sub> (C,Si,B) <sub>3</sub> , Si | B <sub>4</sub> C: 2.9, SiC: 5.8 |
| B <sub>4</sub> C-SiC <sup>117</sup>        | B <sub>4</sub> C (4.08 μm), carbon black, Si lump                                  | Reaction         | 1500                       | No            | 99.8                 | B <sub>4</sub> C, SiC, B <sub>12</sub> (C,Si,B) <sub>3</sub> , Si | B <sub>4</sub> C: 3.2, SiC: 5.8 |
| B <sub>4</sub> C-SiC <sup>117</sup>        | B <sub>4</sub> C (4.08 μm), carbon black, Si lump                                  | Reaction         | 1550                       | No            | 99.9                 | B <sub>4</sub> C, SiC, B <sub>12</sub> (C,Si,B) <sub>3</sub> , Si | B <sub>4</sub> C: 3.3, SiC: 6.0 |
| B <sub>4</sub> C-SiC <sup>117</sup>        | B <sub>4</sub> C (4.08 μm), carbon black, Si lump                                  | Reaction         | 1600                       | No            | 99.9                 | B <sub>4</sub> C, SiC, B <sub>12</sub> (C,Si,B) <sub>3</sub> , Si | B <sub>4</sub> C: 3.8, SiC: 6.5 |
| B <sub>4</sub> C-SiC <sup>117</sup>        | B <sub>4</sub> C (4.08 μm), carbon black, Si lump                                  | Reaction         | 1650                       | No            | 99.8                 | B <sub>4</sub> C, SiC, B <sub>12</sub> (C,Si,B) <sub>3</sub> , Si | B <sub>4</sub> C: 4.6, SiC: 6.7 |

shape, and most of the B<sub>4</sub>C grains evolve to the faceted shape after infiltration for 40 h.<sup>118</sup> Karandikar *et al.*<sup>120</sup> found that infiltration time has an effect on the phase composition of the reaction-bonded B<sub>4</sub>C-SiC ceramics. When the infiltration temperature is 1530 °C, only the β-SiC phase is present at low infiltration time (60–120 min); however, some α-SiC is generated at a longer infiltration time (240–360 min), and the α-SiC content increases with the increase in infiltration time. Meanwhile, part of the B<sub>4</sub>C phase is converted to the B<sub>4-x</sub>Si<sub>x</sub>C phase when the infiltration time is within 60–120 min, while all the B<sub>4</sub>C phase is converted to the B<sub>4-x</sub>Si<sub>x</sub>C phase when the infiltration time is within 240–360 min. This indicates that the conversion of the B<sub>4</sub>C phase to the B<sub>4-x</sub>Si<sub>x</sub>C phase is a time-dependent phenomenon, whose mechanism is the diffusion of Si into the B<sub>4</sub>C grain (lattice) or solution of the B<sub>4</sub>C grain in molten Si and reprecipitation.

**3.3.3.3. Sintering pressure.** For some preparation methods, B<sub>4</sub>C-SiC ceramics have to be sintered under a pressure, such as hot-press sintering and spark plasma sintering; pressure causes particle rearrangement, plastic flow, and grain boundary movement, promoting the sintering of B<sub>4</sub>C-SiC ceramics. The sintering pressure will affect the sintering performance and microstructure of B<sub>4</sub>C-SiC ceramics. According to Rahaman,<sup>121</sup> in the presence of sintering pressure, the densification rate of the ceramic can be described as follows:

$$\rho = \frac{1}{l} \frac{d\rho}{dt} = \frac{HD(\Phi P_a)^n}{G^m k T} \quad (4)$$

where  $\rho$  is the densification rate,  $H$  is a numerical constant,  $D$  is the diffusion coefficient of the rate-controlling species,  $\Phi$  is the intensification factor,  $P_a$  is the applied pressure,  $G$  is the grain size,  $k$  is the Boltzmann constant, and  $T$  is the absolute temperature. When other factors are constant, the densification rate is exponentially influenced by the sintering pressure. Chen *et al.*<sup>122</sup> found that the hot-press sintered B<sub>4</sub>C-20 wt% SiC ceramics becomes denser and the grain size becomes smaller as the sintering pressure increases from 30 to 40 MPa (Fig. 6). During the sintering process, the growth of B<sub>4</sub>C and SiC grains is inhibited due to the higher sintering pressure, leading to the formation of more refined grains.

Some previous studies on the effect of sintering pressure on the sintering performance and microstructure of B<sub>4</sub>C-SiC ceramics are tabulated in Table 5.

### 3.4. Sintering aid

B<sub>4</sub>C-SiC ceramics are difficult to sinter to obtain a sufficiently dense product, especially in the absence of externally applied pressure during sintering. Generally, a sintering temperature higher than 2000 °C is required to obtain a dense B<sub>4</sub>C-SiC ceramics produced *via* hot-press sintering without sintering aids. Thus, to reduce the sintering temperature, one approach is to add sintering aids to promote the densification of B<sub>4</sub>C-SiC ceramics; also, the use of some sintering aids can hinder grain growth. Various elements and compounds have been sought as suitable sintering aids for B<sub>4</sub>C-SiC ceramics. The application of



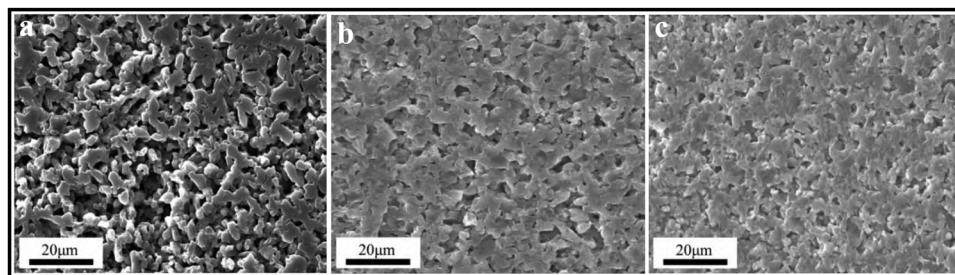


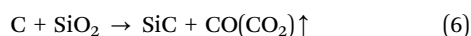
Fig. 6 Microstructure of hot-press sintered B<sub>4</sub>C–20 wt% SiC ceramics sintered under different sintering pressures: (a) 30 MPa, (b) 35 MPa, and (c) 40 MPa.<sup>122</sup>

Table 5 Effect of sintering pressure on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics

| Ceramics                                   | Raw material                             | Sintering method | Sintering temperature (°C) | Sintering pressure (MPa) | Sintering aid                                                            | Relative density (%) | Phase composition     | Average grain size (μm) |
|--------------------------------------------|------------------------------------------|------------------|----------------------------|--------------------------|--------------------------------------------------------------------------|----------------------|-----------------------|-------------------------|
| B <sub>4</sub> C–20 wt% SiC <sup>122</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.45 μm) | Hot-press        | 1900                       | 30                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> ) | 98.5                 | B <sub>4</sub> C, SiC | —                       |
| B <sub>4</sub> C–20 wt% SiC <sup>122</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.45 μm) | Hot-press        | 1900                       | 35                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> ) | 98.6                 | B <sub>4</sub> C, SiC | —                       |
| B <sub>4</sub> C–20 wt% SiC <sup>122</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.45 μm) | Hot-press        | 1900                       | 40                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> + Y <sub>2</sub> O <sub>3</sub> ) | 99.0                 | B <sub>4</sub> C, SiC | —                       |

sintering aids can affect the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics. The sintering mechanisms of B<sub>4</sub>C–SiC ceramics with the addition of sintering aids include solid-state sintering and liquid-phase sintering. Under the solid-state sintering mechanism, no liquid phase is generated; thus, B<sub>4</sub>C–SiC ceramics have sufficient strength, especially at high temperatures. However, the sintering temperature for B<sub>4</sub>C–SiC ceramics is relatively high. For liquid-phase sintering, liquid phases are formed at high temperatures. B<sub>4</sub>C–SiC ceramics can be densified at relatively low temperatures; however, some amorphous secondary phases are generated at grain boundaries, causing grain coarsening, changing the crack propagation mode, and reducing the strength of B<sub>4</sub>C–SiC ceramics.

**3.4.1. C.** Generally, oxide films (B<sub>2</sub>O<sub>3</sub>/H<sub>3</sub>BO<sub>3</sub>, SiO<sub>2</sub>) are easily formed on the surfaces of B<sub>4</sub>C and SiC raw powders during processing and storage. These oxide film impurities contribute to the evaporation-condensation process in the sintering process, resulting in the coarsening of grain rather than densification.<sup>123</sup> To prepare dense B<sub>4</sub>C–SiC ceramics, it is necessary to eliminate these oxide film impurities. The addition of C into the B<sub>4</sub>C–SiC system is an excellent method because C can remove surface oxides of B<sub>4</sub>C and SiC raw powders by reacting with B<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>, respectively, forming carbides and gas according to the following reactions,<sup>124</sup>



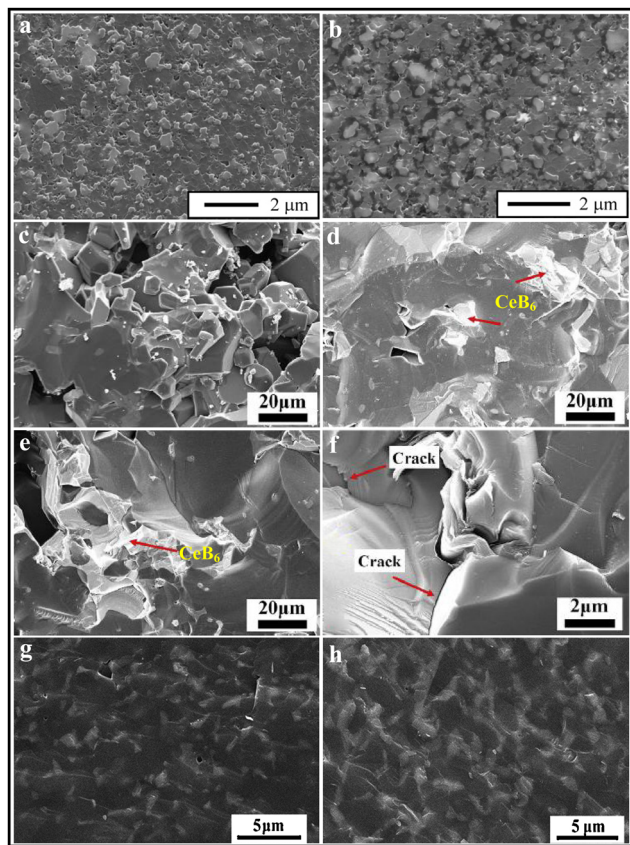
As a result, the surfaces of B<sub>4</sub>C and SiC particles are purified, increasing the contact area of sintered particles; thus, the driving force for the densification of B<sub>4</sub>C–SiC ceramics is improved. Furthermore, C does not generate a liquid phase in the system; thus, it is used as a sintering aid for solid-state sintering.<sup>23</sup> C can be added in the form of carbon black, phenolic resin, graphite,

*etc.* In the case of preparing B<sub>4</sub>C–SiC ceramics by pressureless sintering, if the B<sub>4</sub>C–SiC composite powders contain a C precursor, the advantages of using such a precursor include: (1) it can serve as a binder and plasticizer for the subsequent cold-pressing process; and (2) it can distribute on the surface of composite powders uniformly and activate the sintering process.

Related studies have shown that C sintering aids can improve the densification of B<sub>4</sub>C–SiC ceramics. Thévenot<sup>20</sup> found that the addition of C can promote the sintering of pressureless sintered B<sub>4</sub>C–3.8 wt% SiC ceramics. When the amount of C precursor is 2.5 wt%, the relative density of B<sub>4</sub>C–SiC ceramics can reach 95%. Most importantly, the obtained composite ceramics do not contain free carbon which is considered to impair the mechanical performance of B<sub>4</sub>C–SiC ceramics. Furthermore, for B<sub>4</sub>C–SiC ceramics with different ratios of B<sub>4</sub>C to SiC, an increase in C precursor amount (2–9 wt%) does not change the final relative density (97–98%) of the composite ceramics, but increases the final free C content. Vandeperre and Teo<sup>108</sup> also demonstrated that 3 wt% C addition can allow pressureless sintered B<sub>4</sub>C–SiC ceramics with different ratios of B<sub>4</sub>C to SiC to achieve a high relative density. Moshtaghioun *et al.*<sup>112</sup> stated that the addition of graphite is beneficial for more intimate contact favoring the diffusion between the powders in B<sub>4</sub>C–SiC ceramics during the first moment of spark plasma sintering. First, graphite is an effective process-control agent that can minimize the formation of agglomerates during the milling of brittle ceramics.<sup>125</sup> Second, graphite can lubricate the contacts during the compaction stage, improving the particle packing. As a result, graphite can further promote the densification of spark plasma sintered B<sub>4</sub>C–SiC ceramics (Fig. 7a and b). The grain sizes of B<sub>4</sub>C and SiC in the spark plasma sintered B<sub>4</sub>C–SiC ceramics with graphite are slightly larger than those in the B<sub>4</sub>C–SiC ceramics without graphite, the reason for which is not explained.<sup>126</sup>

**3.4.2. Oxide.** To promote the sintering of B<sub>4</sub>C–SiC ceramics, some oxide sintering aids, such as Al<sub>2</sub>O<sub>3</sub> and Y<sub>2</sub>O<sub>3</sub>, have been





**Fig. 7** Microstructure of B<sub>4</sub>C-SiC ceramics with different sintering aids: (a) spark plasma sintered B<sub>4</sub>C-15 wt% SiC ceramics without graphite and (b) spark plasma sintered B<sub>4</sub>C-15 wt% SiC ceramics with 2 wt% graphite<sup>112</sup> (reprinted with permission, Copyright 2013, Elsevier); (c) pressureless sintered B<sub>4</sub>C-15 wt% SiC ceramics without CeO<sub>2</sub>, (d) pressureless sintered B<sub>4</sub>C-15 wt% SiC ceramics with 5 wt% CeO<sub>2</sub>, and (e) and (f) pressureless sintered B<sub>4</sub>C-15 wt% SiC ceramics with 9 wt% CeO<sub>2</sub><sup>129</sup> (reprinted with permission, Copyright 2019, Elsevier); (g) hot-press sintered B<sub>4</sub>C-15 wt% SiC ceramics without Si, and (h) hot-press sintered B<sub>4</sub>C-15 wt% SiC ceramics with 8 wt% Si<sup>91</sup> (reprinted with permission, Copyright 2013, Elsevier).

extensively investigated. Oxide sintering aids are mainly used to achieve liquid-phase sintering.

Jamale and Kumar<sup>127</sup> found that the addition of Al<sub>2</sub>O<sub>3</sub> can improve the densification of spark plasma sintered B<sub>4</sub>C-10 wt% SiC ceramics due to the formation of liquid-phase Al<sub>2</sub>SiO<sub>5</sub>, and the relative density of the obtained ceramics is more than 99%. Sahin *et al.*<sup>96</sup> noted that three new phases (YBO<sub>3</sub>, YB<sub>4</sub>, and YB<sub>2</sub>C<sub>2</sub>) are formed after 5 wt% Y<sub>2</sub>O<sub>3</sub> is added into the spark plasma sintered B<sub>4</sub>C-SiC ceramics, and the formation of these liquid phases improves the densification of B<sub>4</sub>C-SiC ceramics. Therefore, the relative densities of B<sub>4</sub>C-SiC ceramics with the addition of 5 wt% Y<sub>2</sub>O<sub>3</sub> are higher than those of B<sub>4</sub>C-SiC ceramics without Y<sub>2</sub>O<sub>3</sub>. Rocha and Melo<sup>88,89</sup> reported that the addition of sintering aids of Al<sub>2</sub>O<sub>3</sub>-Y<sub>2</sub>O<sub>3</sub> or AlN-Y<sub>2</sub>O<sub>3</sub> can promote the sintering of the pressureless sintered B<sub>4</sub>C-SiC ceramics. Compared with the sintering aids of Al<sub>2</sub>O<sub>3</sub>-Y<sub>2</sub>O<sub>3</sub>, the sintering aids of AlN-Y<sub>2</sub>O<sub>3</sub> can better promote the densification of B<sub>4</sub>C-SiC ceramics. B<sub>4</sub>C-10 wt% SiC ceramics with AlN-Y<sub>2</sub>O<sub>3</sub> exhibit the highest relative density. According to the observation

of fracture surfaces of B<sub>4</sub>C-SiC ceramics with sintering aids of AlN-Y<sub>2</sub>O<sub>3</sub>, platelet-shaped SiC grains are formed, which is attributed to the phase transformation from β-SiC to α-SiC at high temperatures. Regarding different sintering aids, on the one hand, it is possible that Al<sub>2</sub>O<sub>3</sub> promotes the formation of a more elongated and interlocking structure;<sup>128</sup> thus, the use of sintering aids of Al<sub>2</sub>O<sub>3</sub>-Y<sub>2</sub>O<sub>3</sub> leads to the formation of more platelet-shaped SiC grains in the B<sub>4</sub>C-SiC ceramics, resulting in lower relative densities of B<sub>4</sub>C-SiC ceramics with Al<sub>2</sub>O<sub>3</sub>-Y<sub>2</sub>O<sub>3</sub> than those of B<sub>4</sub>C-SiC ceramics with AlN-Y<sub>2</sub>O<sub>3</sub>. On the other hand, AlN can reduce the problem of volatilization of sintering aids at high temperatures. Zhang *et al.*<sup>109</sup> mentioned that the addition of Al<sub>2</sub>O<sub>3</sub>-La<sub>2</sub>O<sub>3</sub> can promote the sintering of pressureless sintered SiC-10 wt% B<sub>4</sub>C ceramics, which is attributed to the formation of the LaAlO<sub>3</sub> liquid phase through the reaction between Al<sub>2</sub>O<sub>3</sub> and La<sub>2</sub>O<sub>3</sub>. Zhang *et al.*<sup>74</sup> noted that the densification of gas-pressure sintered B<sub>4</sub>C-SiC ceramics can be improved using the Al<sub>2</sub>O<sub>3</sub>-Er<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> sintering aid system. Al<sub>2</sub>O<sub>3</sub> can react with Er<sub>2</sub>O<sub>3</sub> and SiO, generating a eutectic point phase, which can reduce the sintering temperature and promote sintering.

Besides the sintering aid systems based on Al<sub>2</sub>O<sub>3</sub> or Y<sub>2</sub>O<sub>3</sub> systems, rare-earth oxide CeO<sub>2</sub> can also be used as a sintering aid for B<sub>4</sub>C-SiC ceramics. Zhu *et al.*<sup>129</sup> studied the effect of CeO<sub>2</sub> addition on the sintering performance of pressureless sintered B<sub>4</sub>C-15 wt% SiC ceramics. The phase compositions of the resulting B<sub>4</sub>C-SiC ceramics with different CeO<sub>2</sub> contents are B<sub>4</sub>C, SiC, and CeB<sub>6</sub>. The formation of CeB<sub>6</sub> is according to the following reaction:



The relative density of the ceramics first increases and then decreases with an increase in CeO<sub>2</sub> content from 0 to 9 wt% (Fig. 7c-f). B<sub>4</sub>C-SiC ceramics achieve the highest relative density of 96.4% when the CeO<sub>2</sub> content is 5 wt%. The improvement in the sintering performance of B<sub>4</sub>C-SiC ceramics by the addition of CeO<sub>2</sub> can be attributed to the following facts. First, the thermal conductivity of CeB<sub>6</sub> formed during sintering is 34.02 W m<sup>-1</sup> K<sup>-1</sup>, which is higher than that of B<sub>4</sub>C (13.2 W m<sup>-1</sup> K<sup>-1</sup>); the formation of CeB<sub>6</sub> with a higher thermal conductivity can benefit the delivery of heat quantity, promoting the sintering of B<sub>4</sub>C-SiC ceramics.<sup>130</sup> Second, according to reaction (7), B-rich transition zones, such as B<sub>51.02</sub>C<sub>1.82</sub> and B<sub>38.22</sub>C<sub>6</sub>, are formed between CeB<sub>6</sub> and B<sub>4</sub>C grains, causing local lattice distortion of the B<sub>4</sub>C matrix. The lattice distortion can increase the chemical potential energy and consequently the sintering driving force. Furthermore, some vacancies are formed in some local areas, where C atoms combine with O atoms, forming CO gas that escapes from the ceramics, facilitating substance transport. However, when the CeO<sub>2</sub> content is more than 5 wt%, more CO gas is generated, and the gas cannot be timely discharged from inside the ceramics, resulting in a large number of residual pores (Fig. 7e). CeB<sub>2</sub> grains grow to form large grains, which introduce large residual stress between B<sub>4</sub>C and CeB<sub>6</sub> as well as cracks because the irregular CeB<sub>6</sub> grains are subjected to uneven forces from the adjacent grains (Fig. 7f). The formation of a large number of pores and cracks results in a decrease in the relative density.



**3.4.3. Si.** In addition to C and oxide sintering aids, Si can also be used as a sintering aid for  $B_4C$ -SiC ceramics. On the one hand, the addition of an appropriate amount of Si can promote the sintering of the ceramics by forming a liquid phase; on the other hand, free C released from  $B_4C$  can react with molten Si to form SiC at high temperatures, increasing the SiC content.<sup>131</sup> Du *et al.*<sup>91,132</sup> reported that the addition of Si can not only improve the densification of the hot-press sintered  $B_4C$ -SiC ceramics produced with PCS as the precursor of SiC because of the formation of the liquid phase (Fig. 7g and h) but also react with C derived from pyrolysis residue of PCS and  $B_4C$  powders, increasing the SiC content. The dissolution of Si in  $B_4C$  can facilitate mass transfer in solid-state sintering of  $B_4C$ -SiC ceramics. The content of SiC increases with the increase in the content of added Si, leading to the refinement of  $B_4C$  grains. Compared with  $B_4C$ -SiC ceramics without Si additives, the grain size of  $B_4C$  is smaller in the  $B_4C$ -SiC ceramics with Si additives, which is attributed to the more efficient grain boundary pinning by the larger amount of SiC grains. Most SiC grains are located at  $B_4C$  grain boundaries; thus these SiC grains are dragged along as grain boundaries move. The more the SiC content, the more obvious the pinning effect is. This suggests that a larger SiC content is more helpful in inhibiting the growth of  $B_4C$  grains. Furthermore, the total area of the  $B_4C$ -SiC phase boundary increases with the increase in the Si additive; thus, the energy requirements for phase boundary diffusion and phase boundary mobility are increased. Therefore, the introduction of Si can refine  $B_4C$  grains. Although the addition of Si slightly increases the grain size of SiC, the average grain size of SiC is still less than 2  $\mu m$ . Sahani and Chaira<sup>131</sup> mentioned that the improvement in the sintering performance of SiC- $B_4C$  ceramics depends on the amount of Si added and the sintering method. When the SiC- $B_4C$  ceramics are sintered by pressureless sintering, adding 2 or 5 wt% Si cannot improve the sintering performance of SiC- $B_4C$  ceramics. Vandeperre and Teo<sup>108</sup> also demonstrated that the addition of 4 wt% Si cannot promote the sinterability for pressureless sintered  $B_4C$ -SiC ceramics. The mechanism that the low addition of Si cannot promote the sintering for  $B_4C$ -SiC ceramics needs to be further studied. However, the sintering performance of pressureless sintered SiC- $B_4C$  ceramics is improved when the addition of Si is 10 or 20 wt%.<sup>131</sup> When the SiC- $B_4C$  ceramics are sintered by spark plasma sintering, adding 2, 5, 10, or 20 wt% Si can improve the sintering performance of SiC- $B_4C$  ceramics. The addition of Si is helpful for homogeneous microstructural distribution. When the amount of Si added is 10 wt%, the relative density of SiC- $B_4C$  ceramics prepared by either pressureless sintering or spark plasma sintering is the highest.

Some previous studies on the effect of sintering aids on the sintering performance and microstructure of  $B_4C$ -SiC ceramics are tabulated in Table 6.

### 3.5. Microstructure characteristics of $B_4C$ -SiC composite ceramics

$B_4C$ -SiC composite ceramics have some unique microstructure characteristics different from those of pure  $B_4C$  or SiC ceramics. The microstructure of  $B_4C$ -SiC ceramics is controlled by

many factors, which have been discussed in Sections 3.1 to 3.4. In this section, the microstructure characteristics of  $B_4C$ -SiC ceramics affected by the sintering mechanism and sintering method are described.

**3.5.1. Phase boundary characteristics of  $B_4C$ -SiC ceramics prepared by solid-state sintering.** Generally, the grain boundary is clean when the ceramics are produced by a solid-state sintering mechanism,<sup>133</sup> whereas the intergranular phase exists at the grain boundary when the sintering mechanism is liquid-phase sintering.<sup>134,135</sup>

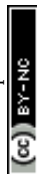
For the phase boundary of  $B_4C$ -SiC ceramics, Matović *et al.*<sup>64</sup> found that there is no amorphous phase or secondary phase at the phase boundary of the ultra-high pressure sintered  $B_4C$ -SiC ceramics without sintering aids. Both Zhang *et al.*<sup>136</sup> and Zhu *et al.*<sup>107</sup> observed that the phase boundary between  $B_4C$  and SiC grains in the pressureless sintered  $B_4C$ -SiC ceramics with the sintering aid of carbon black is clean and clear (Fig. 8). Both  $B_4C$  and SiC grains reveal lattice fringes up to the phase boundary, and  $B_4C$  and SiC grains are in direct mutual contact. Such phase boundary characteristics indicate that the bonding between  $B_4C$  and SiC is very strong. The reason for this phenomenon is that the interplanar spacing between  $B_4C$  lattice planes and SiC lattice planes matches, leading to the direct connection between lattice planes of  $B_4C$  crystals and lattice planes of SiC crystals. This suggests that similar lattice parameters result in a good interfacial structure. Such a phase boundary is an advantage when the mechanical properties of the composite ceramics are concerned, especially at high temperatures. Good phase boundary strength between  $B_4C$  and SiC plays an important role in the crack growth and mechanical properties of  $B_4C$ -SiC ceramics, which will be discussed in Section 4.1.1.

**3.5.2. Microstructure characteristics of  $B_4C$ -SiC ceramics prepared by reaction-bonded sintering.** The preparation method of reaction-bonded sintering is different from other preparation methods to obtain  $B_4C$ -SiC ceramics; thus, the microstructure of reaction-bonded  $B_4C$ -SiC ceramics has its own characteristics.

**3.5.2.1. Core-rim structure.** When liquid and solid phases participate in the microstructure evolution, the core-rim structure is a common phenomenon in composites produced by powder metallurgy. Hayun *et al.*<sup>137</sup> observed the core-rim structure characteristic of the  $B_4C$  particles in the reaction-bonded  $B_4C$ -SiC ceramics for the first time. After the infiltration process of a green  $B_4C$  compact with molten Si, the resulting  $B_4C$ -SiC ceramics are composed of  $B_4C$ ,  $B_{12}(B, C, Si)_3$ ,  $\beta$ -SiC, and some residual Si. It is interesting to note that the microstructure of  $B_4C$ -SiC ceramics exhibit a core-rim structure of the  $B_4C$  particles, with  $B_4C$  cores being surrounded by a 3–7  $\mu m$  thick  $B_{12}(B, C, Si)_3$  envelope (Fig. 9a). Furthermore, the bonding between  $B_4C$  and  $B_{12}(B, C, Si)_3$  is strong; no crack deflection occurs along the boundary between  $B_4C$  and  $B_{12}(B, C, Si)_3$  (Fig. 9b).<sup>138</sup>

For the formation of the  $B_{12}(B, C, Si)_3$  rim, different mechanisms are proposed. Hayun *et al.*<sup>137</sup> insisted that the original  $B_4C$  particles dissolve partially in molten Si during the infiltration process, and then the newly formed ternary  $B_{12}(B, C, Si)_3$  carbide phase, which is treated as a solid solution of Si in  $B_4C$ , precipitates



**Table 6** Effect of sintering aids on the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics

| Ceramics                                   | Raw material                              | Sintering method        | Sintering temperature (°C) | Sintering aid                                                                                                   | Relative density (%) | Phase composition                                                                          | Average grain size (μm)                   |
|--------------------------------------------|-------------------------------------------|-------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------|--------------------------------------------------------------------------------------------|-------------------------------------------|
| B <sub>4</sub> C-15 wt% SiC <sup>126</sup> | B <sub>4</sub> C (0.5 μm), SiC (0.5 μm)   | Spark plasma (75 MPa)   | 1700 (×3 min)              | No                                                                                                              | 99.4                 | B <sub>4</sub> C, SiC                                                                      | B <sub>4</sub> C: 0.53, SiC: 0.05–0.25    |
| B <sub>4</sub> C-15 wt% SiC <sup>126</sup> | B <sub>4</sub> C (0.5 μm), SiC (0.5 μm)   | Spark plasma (75 MPa)   | 1700 (×3 min)              | 2 wt% graphite                                                                                                  | 100.0                | B <sub>4</sub> C, SiC                                                                      | B <sub>4</sub> C: 0.61, SiC: 0.09–0.30    |
| B <sub>4</sub> C-10 wt% SiC <sup>127</sup> | B <sub>4</sub> C, SiC                     | Spark plasma (40 MPa)   | 1800 (×10 min)             | 3 wt% Al <sub>2</sub> O <sub>3</sub>                                                                            | 99.5                 | B <sub>4</sub> C, SiC, Al <sub>2</sub> O <sub>3</sub> , Al <sub>2</sub> SiO <sub>5</sub>   | B <sub>4</sub> C = 2.0–4.0, SiC = 1.0–2.0 |
| B <sub>4</sub> C-10 wt% SiC <sup>127</sup> | B <sub>4</sub> C, SiC                     | Spark plasma (40 MPa)   | 1800 (×10 min)             | 6 wt% Al <sub>2</sub> O <sub>3</sub>                                                                            | 99.1                 | B <sub>4</sub> C, SiC, Al <sub>2</sub> O <sub>3</sub> , Al <sub>2</sub> SiO <sub>5</sub>   | B <sub>4</sub> C = 2.0–4.0, SiC = 1.0–2.0 |
| B <sub>4</sub> C-5 vol% SiC <sup>96</sup>  | B <sub>4</sub> C, α-SiC                   | Spark plasma (40 MPa)   | 1750 (×5 min)              | No                                                                                                              | 98.0                 | B <sub>4</sub> C, SiC                                                                      | —                                         |
| B <sub>4</sub> C-5 vol% SiC <sup>96</sup>  | B <sub>4</sub> C, α-SiC                   | Spark plasma (40 MPa)   | 1750 (×5 min)              | 5 wt% Y <sub>2</sub> O <sub>3</sub>                                                                             | 98.3                 | B <sub>4</sub> C, SiC, YB <sub>4</sub> , YB <sub>2</sub> C <sub>2</sub>                    | —                                         |
| B <sub>4</sub> C-10 vol% SiC <sup>96</sup> | B <sub>4</sub> C, α-SiC                   | Spark plasma (40 MPa)   | 1750 (×5 min)              | No                                                                                                              | 98.0                 | B <sub>4</sub> C, SiC                                                                      | —                                         |
| B <sub>4</sub> C-10 vol% SiC <sup>96</sup> | B <sub>4</sub> C, α-SiC                   | Spark plasma (40 MPa)   | 1750 (×5 min)              | 5 wt% Y <sub>2</sub> O <sub>3</sub>                                                                             | 98.8                 | B <sub>4</sub> C, SiC, YB <sub>4</sub> , YB <sub>2</sub> C <sub>2</sub> , YBO <sub>3</sub> | —                                         |
| B <sub>4</sub> C-15 vol% SiC <sup>96</sup> | B <sub>4</sub> C, α-SiC                   | Spark plasma (40 MPa)   | 1750 (×5 min)              | No                                                                                                              | 97.8                 | B <sub>4</sub> C, SiC                                                                      | —                                         |
| B <sub>4</sub> C-15 vol% SiC <sup>96</sup> | B <sub>4</sub> C, α-SiC                   | Spark plasma (40 MPa)   | 1750 (×5 min)              | 5 wt% Y <sub>2</sub> O <sub>3</sub>                                                                             | 98.2                 | B <sub>4</sub> C, SiC, YB <sub>4</sub> , YB <sub>2</sub> C <sub>2</sub>                    | —                                         |
| B <sub>4</sub> C-10 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | No                                                                                                              | 81.3                 | B <sub>4</sub> C, α-SiC, (β-SiC)                                                           | —                                         |
| B <sub>4</sub> C-10 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | 10 vol% (Al <sub>2</sub> O <sub>3</sub> :Y <sub>2</sub> O <sub>3</sub> = 5:3, molar ratio)                      | 91.5                 | —                                                                                          | —                                         |
| B <sub>4</sub> C-10 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | 10 vol% (AlN:Y <sub>2</sub> O <sub>3</sub> = 3:2, molar ratio)                                                  | 93.4                 | —                                                                                          | —                                         |
| B <sub>4</sub> C-30 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | No                                                                                                              | 74.0                 | B <sub>4</sub> C, α-SiC, (β-SiC)                                                           | —                                         |
| B <sub>4</sub> C-30 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | 10 vol% (Al <sub>2</sub> O <sub>3</sub> :Y <sub>2</sub> O <sub>3</sub> = 5:3, molar ratio)                      | 78.5                 | —                                                                                          | —                                         |
| B <sub>4</sub> C-30 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | 10 vol% (AlN:Y <sub>2</sub> O <sub>3</sub> = 3:2, molar ratio)                                                  | 87.5                 | —                                                                                          | —                                         |
| B <sub>4</sub> C-50 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | No                                                                                                              | 67.5                 | B <sub>4</sub> C, α-SiC, (β-SiC)                                                           | —                                         |
| B <sub>4</sub> C-50 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | 10 vol% (Al <sub>2</sub> O <sub>3</sub> :Y <sub>2</sub> O <sub>3</sub> = 5:3, molar ratio)                      | 69.8                 | B <sub>4</sub> C, α-SiC                                                                    | —                                         |
| B <sub>4</sub> C-50 wt% SiC <sup>88</sup>  | B <sub>4</sub> C, β-SiC                   | Pressureless            | 2000                       | 10 vol% (AlN:Y <sub>2</sub> O <sub>3</sub> = 3:2, molar ratio)                                                  | 75.0                 | B <sub>4</sub> C, α-SiC                                                                    | —                                         |
| SiC-10 wt% B <sub>4</sub> C <sup>109</sup> | α-SiC (1.0 μm), B <sub>4</sub> C (0.5 μm) | Pressureless            | 1900                       | 10 wt% (Al <sub>2</sub> O <sub>3</sub> :La <sub>2</sub> O <sub>3</sub> = 1:1, molar ratio)                      | 96.8                 | SiC, B <sub>4</sub> C, LaAlO <sub>3</sub>                                                  | —                                         |
| SiC-5 wt% B <sub>4</sub> C <sup>74</sup>   | α-SiC (2.0 μm), B <sub>4</sub> C (0.5 μm) | Gas-pressure (0.08 MPa) | 1900                       | 8 wt% (Al <sub>2</sub> O <sub>3</sub> :Er <sub>2</sub> O <sub>3</sub> :SiO <sub>2</sub> = 1:1:0.5, molar ratio) | 94.2                 | SiC, B <sub>4</sub> C                                                                      | —                                         |
| SiC-10 wt% B <sub>4</sub> C <sup>74</sup>  | α-SiC (2.0 μm), B <sub>4</sub> C (0.5 μm) | Gas-pressure (0.08 MPa) | 1900                       | 8 wt% (Al <sub>2</sub> O <sub>3</sub> :Er <sub>2</sub> O <sub>3</sub> :SiO <sub>2</sub> = 1:1:0.5, molar ratio) | 93.4                 | SiC, B <sub>4</sub> C                                                                      | —                                         |
| SiC-15 wt% B <sub>4</sub> C <sup>74</sup>  | α-SiC (2.0 μm), B <sub>4</sub> C (0.5 μm) | Gas-pressure (0.08 MPa) | 1900                       | 8 wt% (Al <sub>2</sub> O <sub>3</sub> :Er <sub>2</sub> O <sub>3</sub> :SiO <sub>2</sub> = 1:1:0.5, molar ratio) | 91.7                 | SiC, B <sub>4</sub> C                                                                      | —                                         |
| SiC-20 wt% B <sub>4</sub> C <sup>74</sup>  | α-SiC (2.0 μm), B <sub>4</sub> C (0.5 μm) | Gas-pressure (0.08 MPa) | 1900                       | 8 wt% (Al <sub>2</sub> O <sub>3</sub> :Er <sub>2</sub> O <sub>3</sub> :SiO <sub>2</sub> = 1:1:0.5, molar ratio) | 88.9                 | SiC, B <sub>4</sub> C                                                                      | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>129</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)   | Pressureless            | 2150                       | No                                                                                                              | 85.8                 | B <sub>4</sub> C, SiC                                                                      | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>129</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)   | Pressureless            | 2150                       | 1 wt% CeO <sub>2</sub>                                                                                          | 91.2                 | B <sub>4</sub> C, SiC, CeB <sub>6</sub>                                                    | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>129</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)   | Pressureless            | 2150                       | 3 wt% CeO <sub>2</sub>                                                                                          | 92.6                 | B <sub>4</sub> C, SiC, CeB <sub>6</sub>                                                    | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>129</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)   | Pressureless            | 2150                       | 5 wt% CeO <sub>2</sub>                                                                                          | 96.4                 | B <sub>4</sub> C, SiC, CeB <sub>6</sub>                                                    | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>129</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)   | Pressureless            | 2150                       | 7 wt% CeO <sub>2</sub>                                                                                          | 94.6                 | B <sub>4</sub> C, SiC, CeB <sub>6</sub>                                                    | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>129</sup> | B <sub>4</sub> C (0.8 μm), SiC (0.5 μm)   | Pressureless            | 2150                       | 9 wt% CeO <sub>2</sub>                                                                                          | 93.4                 | B <sub>4</sub> C, SiC, CeB <sub>6</sub>                                                    | —                                         |
| B <sub>4</sub> C <sup>91</sup>             | B <sub>4</sub> C (3.5 μm)                 | Hot-press (30 MPa)      | 1950                       | No                                                                                                              | 91.7                 | B <sub>4</sub> C                                                                           | —                                         |
| B <sub>4</sub> C-15 wt% SiC <sup>91</sup>  | B <sub>4</sub> C (3.5 μm), PCS            | Hot-press (30 MPa)      | 1950                       | No                                                                                                              | 96.1                 | B <sub>4</sub> C, SiC                                                                      | SiC < 1.0                                 |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC                     | Pressureless            | 1950                       | 8 wt% Si                                                                                                        | 99.1                 | B <sub>4</sub> C, SiC                                                                      | B <sub>4</sub> C < 5.0, SiC < 2.0         |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC                     | Pressureless            | 1950                       | No                                                                                                              | 89.0                 | B <sub>4</sub> C, SiC                                                                      | —                                         |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC                     | Pressureless            | 1950                       | 2 wt% Si                                                                                                        | 88.0                 | B <sub>4</sub> C, SiC, Si                                                                  | —                                         |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC                     | Pressureless            | 1950                       | 5 wt% Si                                                                                                        | 89.0                 | B <sub>4</sub> C, SiC, Si                                                                  | —                                         |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC                     | Pressureless            | 1950                       | 10 wt% Si                                                                                                       | 92.0                 | B <sub>4</sub> C, SiC, Si                                                                  | —                                         |

Table 6 (continued)

| Ceramics                                   | Raw material          | Sintering method      | Sintering temperature (°C) | Sintering aid | Relative density (%) | Phase composition                            | Average grain size (μm) |
|--------------------------------------------|-----------------------|-----------------------|----------------------------|---------------|----------------------|----------------------------------------------|-------------------------|
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC | Pressureless          | 1950                       | 20 wt% Si     | 90.0                 | B <sub>4</sub> C, SiC, Si                    | —                       |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC | Spark plasma (50 MPa) | 1600 (×5 min)              | No            | 94.0                 | B <sub>4</sub> C, SiC                        | —                       |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC | Spark plasma (50 MPa) | 1350 (×5 min)              | 2 wt% Si      | 94.6                 | —                                            | —                       |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC | Spark plasma (50 MPa) | 1350 (×5 min)              | 5 wt% Si      | 96.3                 | B <sub>4</sub> C, SiC, Si, B <sub>3</sub> Si | —                       |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC | Spark plasma (50 MPa) | 1350 (×5 min)              | 10 wt% Si     | 98.0                 | B <sub>4</sub> C, SiC, Si, B <sub>3</sub> Si | —                       |
| B <sub>4</sub> C-60 wt% SiC <sup>131</sup> | B <sub>4</sub> C, SiC | Spark plasma (50 MPa) | 1350 (×5 min)              | 20 wt% Si     | 97.0                 | B <sub>4</sub> C, SiC, Si, B <sub>3</sub> Si | —                       |

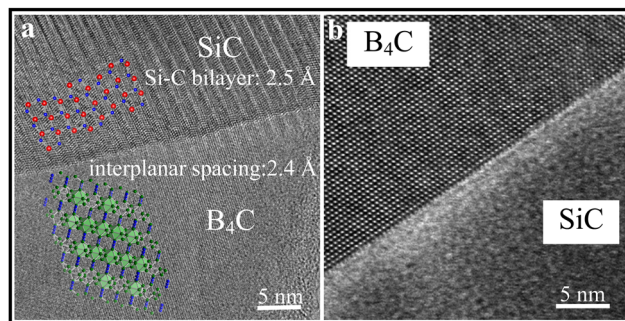


Fig. 8 HRTEM images of B<sub>4</sub>C–SiC ceramics prepared by solid-state sintering revealing the phase boundary characteristics between B<sub>4</sub>C and SiC: (a) B<sub>4</sub>C–40 wt% SiC ceramics with 3 wt% carbon black<sup>136</sup> (reprinted with permission, Copyright 2019, Elsevier) and (b) B<sub>4</sub>C–15 wt% SiC ceramics with 2 wt% carbon black<sup>107</sup> (reproduced with permission, Copyright 2019, Elsevier).

on the surface of original B<sub>4</sub>C particles when the solubility of B and C in molten Si becomes saturated, forming rim regions. This indicates that the formation of the B<sub>12</sub>(B, C, Si)<sub>3</sub> rim is the dissolution–precipitation process. This newly formed ternary phase B<sub>12</sub>(B, C, Si)<sub>3</sub> at the boundaries of neighboring B<sub>4</sub>C particles through dissolution–reprecipitation mechanism is also supported by Zhang *et al.*<sup>117</sup> in the reaction-bonded B<sub>4</sub>C–SiC ceramics. In contrast, Jannotti *et al.*<sup>139</sup> proposed a different view that the B<sub>12</sub>(B, C, Si)<sub>3</sub> phase is a Si-doped B<sub>4</sub>C phase. The Si substitutes for the C atoms on the ends of the linear chain and inserts into the icosahedrons in the B<sub>4</sub>C lattice, and C atoms react with liquid Si, generating SiC. Wang *et al.*<sup>140</sup> mentioned that the B<sub>12</sub>(B, C, Si)<sub>3</sub> rim surrounding B<sub>4</sub>C is generated by Si inward diffusion in B<sub>4</sub>C from a liquid. Sun *et al.*<sup>141</sup> put forward that there are two types of B<sub>12</sub>(B, C, Si)<sub>3</sub> phases in the reaction-bonded B<sub>4</sub>C–SiC ceramics. One is B<sub>12</sub>(B, C, Si)<sub>3</sub> with high Si content, derived from the reaction between Si and decomposed B<sub>4</sub>C (Si, B, and a part of C react to generate B<sub>12</sub>(B, C, Si)<sub>3</sub>, and the remaining C diffuses into the liquid Si, generating plate-like SiC; the other is B<sub>12</sub>(B, C, Si)<sub>3</sub> with low Si content, resulting from the diffusion of Si into B<sub>4</sub>C (solid solution process).

The core–rim structure of B<sub>4</sub>C is formed in the B<sub>4</sub>C–SiC ceramics produced *via* a conventional reaction-bonded sintering route; however, Thuault *et al.*<sup>63</sup> found that there is no core–rim structure of B<sub>4</sub>C in the reaction-bonded B<sub>4</sub>C–SiC ceramics prepared by the microwave assisted processing method in an Ar–H<sub>2</sub> atmosphere. The compositions of the obtained composite ceramics are B<sub>4</sub>C, β-SiC, and Si; there is no B<sub>12</sub>(B, C, Si)<sub>3</sub> phase. The reason why the core–rim structure is not formed is that the rapid heating generated by microwaves and the infiltration process under an Ar–H<sub>2</sub> gas flow at atmospheric pressure prevents the secondary reaction among Si, C, and B.

In addition, when the preform containing α-SiC is used to prepare reaction-bonded B<sub>4</sub>C–SiC ceramics, besides the core–rim structure of B<sub>4</sub>C surrounded by the B<sub>12</sub>(B, C, Si)<sub>3</sub> rim, the core–rim structure of primary α-SiC surrounded by the secondary β-SiC rim is also observed (Fig. 9c).<sup>85,140</sup> C first dissolves in molten Si and then diffuses to the vicinity of the original α-SiC



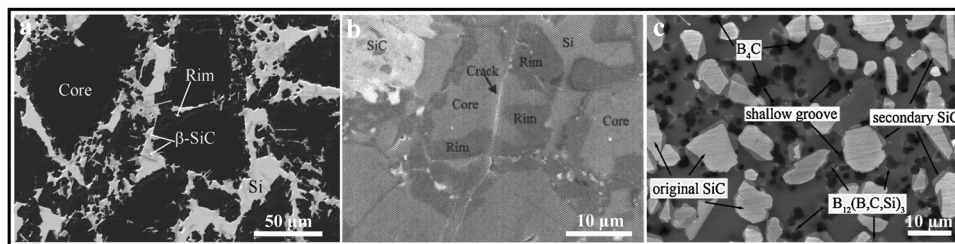


Fig. 9 SEM images of reaction-bonded  $B_4C$ -SiC ceramics exhibiting: (a) core-rim structure of  $B_4C$  particles<sup>137</sup> (reproduced with permission, Copyright 2009, Elsevier), (b) crack propagation path passing through the core-rim structure of  $B_4C$ <sup>138</sup> (reproduced with permission, Copyright 2010, John Wiley and Sons), and (c) core-rim structure of SiC particles<sup>85</sup> (reproduced with permission, Copyright 2016, Elsevier).

grains, forming supersaturated liquid  $Si[C]$ . Compared with the homogeneous nucleation in a liquid phase, the supersaturated liquid  $Si[C]$  is more prone to heterogeneously crystallize to form  $\beta$ -SiC attached to the original  $\alpha$ -SiC grains because of the relatively lower energy. The initial  $\alpha$ -SiC grains are interconnected by the newly formed  $\beta$ -SiC rim structure to generate a cluster of SiC grains. Because the  $\beta$ -SiC grows fast at a much lower temperature than that of the initial  $\alpha$ -SiC, many faults (twinning and lattice distortion) generate inside the  $\beta$ -SiC grains. Song *et al.*<sup>85</sup> considered that the dissolution process is exothermic, allowing the local temperature to increase at the dissolution sites. When the C gradually dissolves in molten Si, the C activity gradient within Si will cause a rapid diffusion of C away from the dissolution sites. The C diffuses to locally cooler sites (the initial SiC particles) until a supersaturation occurs in the molten Si and then the C precipitates as an epitaxial SiC rim.  $\beta$ -SiC cannot nucleate on  $B_4C$  with rim, which is attributed to the lattice mismatch between  $\beta$ -SiC and  $B_{12}(B, C, Si)_3$ .

**3.5.2.2. Morphology of SiC.** Reaction-bonded  $B_4C$ -SiC ceramics can be produced with or without free C in the preform. The C used to form SiC *in situ* can come from free C or/and C originally present in  $B_4C$ . When the free C is present in the preform, the siliconization chemical reaction (8) predominates.



The reaction (3) also occurs in parallel in the region where the free carbon concentration is locally reduced. However, when only  $B_4C$  is used as the C source, the formation of SiC is completely based on the reaction (3). Different C sources give rise to different morphologies of SiC grains *in situ* generated.

Hayun *et al.*<sup>137</sup> noted that the  $\beta$ -SiC particles have a plate-like shape (Fig. 10a) when  $B_4C$  acts as the sole source of C (without free C addition), while  $\beta$ -SiC particles show a polygonal shape (Fig. 10b) and only a small fraction of SiC displays a plate-like shape in the presence of 5 wt% free C, which is added by infiltration with an aqueous sugar solution. In the absence of free C, the gradual diffusion of C from  $B_4C$  favors the plate-like shape of the obtained secondary SiC. In fact, the polygonal  $\beta$ -SiC particles are built by mutually bonded plate-like particles; thus, a key factor that determines the morphology of the  $\beta$ -SiC particles is the available amount of C. Two C sources are available for  $\beta$ -SiC formation in the presence of free C, resulting in the formation of polygonal SiC particles. SiC particles precipitate at the melt/graphite interface after the dissolution of free C in the melt. Liquid Si continues to react with  $B_4C$  after the consumption of free C and some additional plate-like SiC particles are formed. Although the addition of C controls the morphology of the formed SiC particles, it is very interesting to note that the relative amounts of the SiC formed are similar for the  $B_4C$ -SiC ceramics produced with and without free C addition for a certain initial porosity of the preforms.<sup>142</sup> This indicates the following two points: (1) porosity of the preform is a key factor determining the amount of SiC formed. As the initial porosity of the preform increases from 20 to 40 vol%, the amount of SiC formed slightly increases from 8 to 12 vol%; and (2)  $B_4C$ -SiC ceramics can be produced by molten Si infiltration even in the absence of free C (external C source). Although secondary SiC particles with a plate-like morphology were observed by Hayun *et al.*<sup>137</sup> in the  $B_4C$ -SiC ceramics produced from the preform composed of sole  $B_4C$  without free C addition, Aroati *et al.*<sup>143</sup> found that no plate-like SiC particles are formed

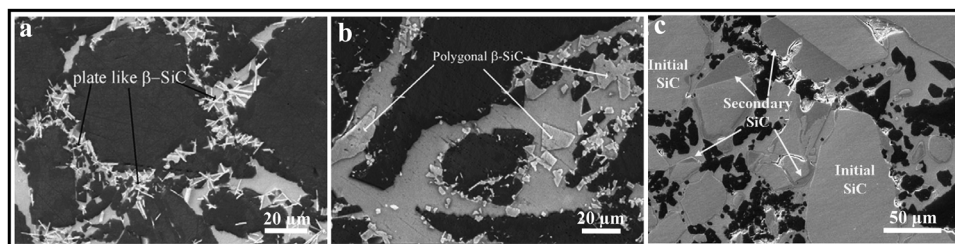


Fig. 10 Morphology of SiC grains in reaction-bonded  $B_4C$ -SiC ceramics produced from the preforms with different compositions: (a)  $B_4C$  without free C addition, (b)  $B_4C$  with 5 wt% free C addition<sup>137</sup> (reproduced with permission, Copyright 2009, Elsevier), and (c) the mixture of  $B_4C$  and SiC without free C addition<sup>143</sup> (reproduced with permission, Copyright 2010, Elsevier).



in the  $B_4C$ -SiC ceramics produced from the preform composed of a mixture of SiC and  $B_4C$  without free C addition (Fig. 10c). This is because there are SiC particles in the preform, so heterogeneous nucleation of secondary SiC occurs on the surface of these initial SiC particles.

**3.5.2.3. Particle size.** The particle sizes of  $B_4C$  and SiC in reaction-bonded  $B_4C$ -SiC ceramics are also related to C sources and contents. Gao *et al.*<sup>144</sup> reported that  $B_4C$ -SiC ceramics can be produced without the addition of C *via* reaction-bonded sintering; however, the particle sizes of  $B_4C$  and SiC are not uniform in the case of without adding C, which is attributed to the difficulty of  $B_4C$  sintering. The addition of C in the range of 5 to 10 vol% can make the particle sizes of  $B_4C$  and SiC smaller and make their particle size distributions more uniform. However, large-sized particles, which come from the aggregation of SiC formed, and Si spots are generated in the  $B_4C$ -SiC ceramics when the addition of C is more than 10 vol%. This indicates that the addition of excessive C will lead to the increase in the particle size of  $B_4C$ -SiC ceramics and less uniform phase distribution. Li *et al.*<sup>76</sup> also found that compared with no C addition, the grain sizes of SiC and Si are smaller in the case of carbon black addition, which may result from the decreased pore size in the preform as the content of carbon black increases.

The particle size of  $B_4C$  is affected by two competing factors; one is the dissolution and reaction of  $B_4C$  with liquid Si, consuming the  $B_4C$  particles and decreasing the particle size and the other is the precipitation of  $B_{12}(C, Si, B)_3$ , forming the coarsened  $B_4C$  particles and increasing the particle size. Meanwhile, the formed  $B_{12}(C, Si, B)_3$  promotes the generation of a sintering neck between neighboring  $B_4C$  grains. The distance between neighboring  $B_4C$  grains is decreased with further expansion of the sintering neck, allowing the neighboring  $B_4C$  grains to grow together and increasing the particle size of  $B_4C$ . Therefore, the formation of  $B_{12}(C, Si, B)_3$  results in the loss of  $B_4C$ , which reduces the hardness of  $B_4C$ -SiC ceramics, the aggregation and bonding of neighboring  $B_4C$  grains, and the consequent increase in particle size. In order to protect the  $B_4C$  grains from dissolution and reaction in liquid Si, several methods can be used to limit the formation of a large number of  $B_{12}(B, C, Si)_3$  phases.

First, the pre-production of C-coated  $B_4C$  particles. Zhang *et al.*<sup>101</sup> first used the phenolic resin as an external C source to prepare C (10 wt%)-coated  $B_4C$  particles by pyrolysis and carbonization, during which the phenolic resin uniformly attached to the  $B_4C$  particles is transformed into an amorphous C layer or C nanoparticles, which were then used to fabricate the reaction-bonded  $B_4C$ -SiC ceramics. As a result, the C layer acts a barrier between  $B_4C$  grains and molten Si, and the molten Si preferentially reacts with the C layer. The C-coating can effectively protect the  $B_4C$  grains from reacting with molten Si, reducing the dissolution and reaction loss of  $B_4C$ . Compared with the reaction-bonded  $B_4C$ -SiC ceramics prepared from a mixture of  $B_4C$  and carbon black powders (an external C source), which is formed only by the mechanical mixing of the two, the content of  $B_4C$  in the  $B_4C$ -SiC ceramics prepared from the C-coated  $B_4C$

particles is higher and the  $B_4C$  grains can maintain the initial irregular shape. In contrast, the  $B_4C$  grains in the  $B_4C$ -SiC ceramics prepared from uncoated  $B_4C$  particles change from irregular shape to faceted shape. It is reported that the  $B_4C$  grains will grow rapidly after they are transformed into the faceted shape;<sup>118</sup> thus, the grain size of  $B_4C$  in the  $B_4C$ -SiC ceramics prepared from the C-coated  $B_4C$  particles is smaller than the ones in the  $B_4C$ -SiC ceramics prepared from the mixture of uncoated  $B_4C$  and carbon black. On the other hand, *in situ* formed nano-SiC grains wrap the  $B_4C$  grains forming a nano-SiC grain-coating layer in the  $B_4C$ -SiC ceramics prepared from the C-coated  $B_4C$  particles; the neighboring  $B_4C$  grains can be bonded together with these nano-SiC grains, generating a continuous ceramic skeleton. In contrast, for the  $B_4C$ -SiC ceramics prepared from a mixture of uncoated  $B_4C$  and carbon black, most of the formed SiC grains with a size of 1  $\mu m$  are isolated in free Si, and many large-sized SiC zones of 50  $\mu m$  are formed, which is attributed to the nonuniform dispersion of the nano-carbon black. Although the pre-production of C-coated  $B_4C$  particles is relatively complex for the production of  $B_4C$ -SiC ceramics, this method can achieve not only a uniform distribution of  $B_4C$  and SiC but also a continuous ceramic skeleton composed of nano-SiC grain-coated and -bonded  $B_4C$  grains.

Second, the introduction of free B into the preform; free B dissolves in molten Si and decreases the Si activity towards  $B_4C$ .<sup>115</sup> This method increases the possibility that a mixture of boron silicides with varying stoichiometry will be present in the resulting ceramics, lowering the additive cracking resistance.<sup>115</sup>

Third, a decrease in the siliconization temperature to approximately 1450–1550 °C, at which the predominant process is reaction (8); an improvement in the sintering temperature to 1600 °C leads to an appreciable acceleration of reaction (3).<sup>115</sup> This method may increase the viscosity of molten Si and decrease the relative density, leading to the formation of residual C and deteriorated mechanical properties.

Actually, although these methods can protect the  $B_4C$  grains and limit the formation of  $B_{12}(B, C, Si)_3$ , their effects on the microstructure and other properties of  $B_4C$ -SiC ceramics should also be considered.

**3.5.2.4. Residue and morphology.**  $B_4C$ -SiC ceramics produced by reaction-bonded sintering often contain undesirable residual phases. If the ceramics have a Si deficit or are poorly homogenized, there will be some incompletely siliconized regions containing C in the resulting  $B_4C$ -SiC ceramics. Similarly, residual C also forms in cases where the porosity of the preform lies below the threshold for molten Si to flow through the porous preform, the sintering temperature is too low for molten Si to reach the required viscosity, or the holding time is too short. In contrast, residual Si will form in the case of a C deficit or excessive porosity. These residues affect the mechanical properties of  $B_4C$ -SiC ceramics, which will be discussed in Section 4.2.2.

The source of free C can not only come from carbon black, but also from carbon fibers. Two different sources of free C affect the morphology of residual Si. Song *et al.*<sup>85</sup> used carbon fibers as a carbon source to produce reaction-bonded  $B_4C$ -SiC



ceramics. The porous self-supporting interpenetrating network structure of carbon fibers is helpful for Si infiltration. During the Si infiltration, homogeneously and randomly distributed carbon fibers completely react with the molten Si, whose dominant mechanism is diffusion, and the residual Si particles occupy the original positions of carbon fibers, forming fiber-like extensions. This microstructure is different from that of the reaction-bonded  $B_4C$ -SiC ceramics using carbon black as the C source. The residual Si with fiber-like extensions is a revamped form of residual Si, and the residual Si is spread out throughout the matrix, reducing the dimensions of the Si islands. With the increase in carbon fiber content, the amount of newly formed  $\beta$ -SiC is increased and the amount of residual Si is reduced. Meanwhile, the formation of  $\beta$ -SiC during the siliconisation reaction between the carbon fibers and molten Si causes a large volume expansion, which is favorable for decreasing the space of residual Si.

## 4. Mechanical properties of $B_4C$ -SiC composite ceramics

The mechanical properties of  $B_4C$ -SiC ceramics are crucial for their applications. Hardness, fracture toughness, and bending strength are important mechanical properties of  $B_4C$ -SiC ceramics. Higher hardness will make  $B_4C$ -SiC ceramics a very interesting material for applications where high wear resistance is required, and higher bending strength will make  $B_4C$ -SiC ceramics an interesting material from the structural application point of view. For example, due to excellent mechanical and physical properties, *i.e.*, high hardness, high bending strength, relatively high fracture toughness, and low density,  $B_4C$ -SiC ceramics are one of the most potential candidates for novel bulletproof materials. To obtain desirable mechanical properties for polycrystalline  $B_4C$ -SiC ceramics, various aspects have been investigated. The research works focus on the effect of the microstructure, phase composition, raw materials, preparation process, and sintering aids on the mechanical properties of  $B_4C$ -SiC ceramics, which will be discussed in detail in this part.

### 4.1. Microstructure

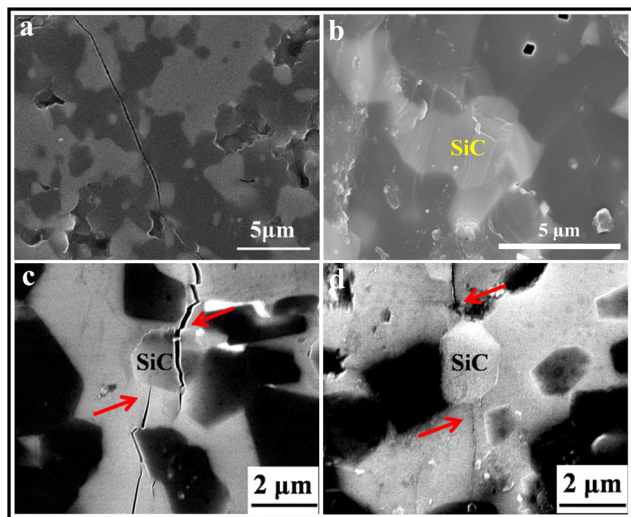
The good mechanical properties of  $B_4C$ -SiC ceramics are related to the control of the microstructure, which mainly includes the grain characteristics, grain boundary characteristics, pores, and flaws. In general, when the composition of the material is determined, the hardness is controlled by its relative density and grain size. To improve the hardness of  $B_4C$ -SiC ceramics, their grain size should be as low as possible, and their relative density should be as high as possible. The bending strength of  $B_4C$ -SiC ceramics is determined by the flaw size, and the bending strength increases with decreased flaw size. Generally, the flaws generated at the interface propagate to a maximum of up to one grain size.<sup>145</sup> Pores, as a major flaw, are also detrimental to the bending strength of  $B_4C$ -SiC ceramics. On the one hand, pores can reduce the cross-sectional areas across which a load is applied; on the other hand, pores act as

stress concentrators. Therefore, reducing the porosity is beneficial for improving the hardness and bending strength of  $B_4C$ -SiC ceramics. There are many methods to reduce the porosity to improve the mechanical properties of  $B_4C$ -SiC ceramics, such as refinement of raw materials, improvement of sintering temperature, and addition of sintering aids, *etc.*, which will be described later. The fracture toughness of  $B_4C$ -SiC ceramics is closely related to the crack propagation mode, which is decided through various factors, such as the phase boundary characteristics between  $B_4C$  and SiC grains (bonding strength of the interface), residual stress development, and grain morphology. In addition, dislocations, as a kind of crystal defect, can change the course of the crack when a crack runs into dislocations; also, complicated dislocation lines can be regarded as a second refinement on matrix grains.

**4.1.1. Phase boundary characteristics between  $B_4C$  and SiC.** For composite materials, the characteristics of the two-phase interface play a crucial role in the mechanical properties. For  $B_4C$ -SiC ceramics, the phase boundary characteristics decide the interfacial bonding between  $B_4C$  and SiC. Cracks always propagate along the weak joint in the stress field. If the interfacial bonding between  $B_4C$  and SiC is weak, cracks will extend along the phase boundary, causing an intergranular crack. In contrast, if the interfacial bonding is stronger than the cohesion strength of individual  $B_4C$  and SiC grains, a transgranular crack will be the predominant fracture mode. Intergranular fracture contributes to increasing fracture toughness, while transgranular fracture plays a positive role in strength. As reported in the liquid-phase sintered SiC ceramics, the aluminosilicate interphase provides a tortuous path for cracks and facilitates crack branching; the comparatively weak intergranular interphase is the preferential path for crack propagation, improving the fracture toughness.<sup>146</sup> Generally, the phase boundary of solid-state sintered  $B_4C$ -SiC ceramics is clean (Fig. 8); conversely, some secondary phase or amorphous layer exists between  $B_4C$  and SiC grains after liquid-phase sintering.

The clean phase boundary makes the bond between  $B_4C$  and SiC grains very strong. Zhang *et al.*<sup>98</sup> and Yaşar and Haber<sup>71</sup> found that cracks cross the  $B_4C$  and SiC grains, rather than propagating along the phase boundary, when cracks propagate in the hot-press sintered  $B_4C$ -50 wt% SiC ceramics without any sintering aid (Fig. 11a) and spark plasma sintered 10–50 wt%  $B_4C$ -SiC ceramics with a sintering aid of 1.5 wt% C, respectively. This indicates that interface cohesion between  $B_4C$  and SiC is powerful, and no crack deflection happens at the clean phase boundary. Normally, intergranular fracture plays a positive role in toughness. Although transgranular fracture is the predominant fracture mode of solid-state sintered  $B_4C$ -SiC ceramics, the fracture toughness of  $B_4C$ -SiC ceramics is higher than that of pure  $B_4C$  ceramics,<sup>98</sup> which solves the problem that the widespread application of pure  $B_4C$  ceramics is restricted due to their low fracture toughness. The powerful interfacial bonding between  $B_4C$  and SiC plays a key role in fracture toughness. For  $B_4C$ -SiC ceramics with transgranular cracks, the usual toughening mechanisms of crack propagation, such as crack bridging, deflection, and branching, are not applicable.





**Fig. 11** (a) Cracks in hot-press sintered  $B_4C$ -50 wt% SiC ceramics showing a transgranular mode<sup>98</sup> (reprinted with permission, Copyright 2013, Elsevier), (b) fracture surface of spark plasma sintered  $B_4C$ -20 vol% SiC ceramics exhibiting rougher SiC grains than  $B_4C$  grains,<sup>111</sup> and indentation crack propagation in reaction-bonded  $B_4C$ -SiC ceramics revealing: (c) crack branching and (d) crack bridging<sup>117</sup> (reprinted with permission, Copyright 2014, John Wiley and Sons).

With regard to the increased fracture toughness of  $B_4C$ -SiC ceramics, different mechanisms have been proposed by the researchers. The classical thermal expansion mismatch theory in toughening states that the fracture toughness is determined by the residual stress that can control the interaction between the composite microstructure and crack propagation;<sup>147</sup> the residual stress is caused because of the mismatch of thermal expansion coefficients between matrix and the second phase or inclusions. The release of residual stress plays an effective role in the improvement of fracture toughness. For  $B_4C$ -SiC ceramics, the residual stress is generated by a difference in the thermal expansion coefficients of  $B_4C$  and SiC. Zhang *et al.*<sup>98</sup> stated that the difference in thermal expansion coefficients of  $B_4C$  ( $5.73 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ ) and SiC ( $4.50 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ ) is not obvious, leading to the minimal residual thermal stress at their interface, which is inadequate to cause crack deflection or intergranular fracture. Hwang *et al.*<sup>87</sup> calculated the theoretical residual stress between the  $B_4C$  matrix and SiC particulate and verified experimentally by the Raman mapping that the compressive residual stress developed in the  $B_4C$  matrix around SiC particulates is small, whose value is between 27–64 MPa for  $\Delta T$  (temperature range over which stress is not relieved by a diffusive process) = 800–1900  $^\circ\text{C}$ . This means that the contribution of residual thermal stress to the toughening of  $B_4C$ -SiC ceramics is quite limited; thereby, the microstructure is responsible for the marked increase in fracture toughness. Small residual stress explains why cracks cross the  $B_4C$  and SiC grains, rather than crack deflection at the  $B_4C$ -SiC interface. Zhang *et al.*<sup>98</sup> claimed that the increased fracture toughness is attributed to the crack impeding mechanism rather than the crack deflection mechanism, and the SiC content is a more important factor than the residual stress. The fracture toughness of SiC is higher

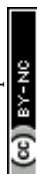
than that of  $B_4C$ , and cracks consume more energy when crossing SiC grains. This hypothesis was demonstrated by the observation of Wu *et al.*<sup>111</sup> that the SiC grains are rougher than  $B_4C$  grains on the fracture surface of the spark plasma sintered  $B_4C$ -20 vol% SiC ceramics (Fig. 11b). Therefore, the fracture toughness of  $B_4C$ -SiC ceramics is higher than that of pure  $B_4C$  ceramics. However, Moradkhani and Baharvandi<sup>80</sup> argued that the increased fracture toughness is related to residual stress. They observed that the fracture toughness of pressureless solid-state sintered  $B_4C$ -SiC ceramics increases with the addition of SiC from 2.5 to 10 vol%, and the fracture mode of  $B_4C$ -SiC ceramics changes from intergranular fracture to transgranular fracture with the increase in SiC content, which is ascribed to the formation of compressive residual stress around the reinforcing SiC particles and tensile stress in the matrix  $B_4C$  phase due to the unequal thermal expansion coefficients between  $B_4C$  and SiC. First, the compressive stress is transferred to the phase boundary between  $B_4C$  and SiC. When cracks move toward the phase boundary, the existing compressive stress at the phase boundary will divert the cracks toward the grain interior, consuming the energy of the crack. The compressive stress can increase the fracture toughness for  $B_4C$ -SiC ceramics by preventing crack nucleation and growth. Second, the release of residual stress will lead to the formation of dislocations around the reinforcing SiC particles and microcracks within grains. The generation of dislocations can make it difficult for cracks to propagate; the emergence of microcracks can increase the fracture toughness by microcrack toughening mechanism.

For the reaction-bonded  $B_4C$ -SiC ceramics produced *via* liquid-phase sintering, the crack propagation mode is different from that of  $B_4C$ -SiC ceramics with a clean phase boundary prepared by solid-state sintering. Crack bridging and crack branching, both of which are considered to enhance the fracture toughness of materials, are observed in the reaction-bonded  $B_4C$ -SiC ceramics (Fig. 11c and d).<sup>117</sup> SiC particles cause crack branching and also play a bridging role. Both crack branching and crack bridging can consume more energy and thus increase the resistance to crack propagation for  $B_4C$ -SiC ceramics.

**4.1.2. Grain morphology.** Grain morphology affects the mechanical properties of  $B_4C$ -SiC ceramics. The grain morphology of  $B_4C$ -SiC ceramics is mainly influenced by the raw material size, raw material specie, and parameters during sintering.

Moradkhani and Baharvandi<sup>80</sup> observed cleavage surfaces within grains (Fig. 2k and l) in the pressureless sintered  $B_4C$ -SiC ceramics. These cleavage surfaces can act as a crack path diverter, the generation of which is beneficial for improving the fracture toughness of  $B_4C$ -SiC ceramics.

As mentioned in Section 3.5.2, the grain morphology in the reaction-bonded  $B_4C$ -SiC ceramics is complex, which depends primarily on the C source, the addition of SiC, and the processing method. In the case of the conventional reaction-bonded sintering route,  $B_4C$  grains show a core-rim structure characteristic. There is a debate on the effect of the  $B_{12}(B, C, Si)_3$  phase in the form of rims generated on  $B_4C$  cores on the mechanical properties of  $B_4C$ -SiC ceramics. Hayun *et al.*<sup>84,138</sup> claimed that



Young's modulus and hardness of the  $B_{12}(B, C, Si)_3$  phase are slightly higher than those of  $B_4C$ . Jannotti *et al.*<sup>139</sup> reported that the  $B_{12}(B, C, Si)_3$  phase can yield improved mechanical properties for  $B_4C$ -SiC ceramics. However, Song *et al.*<sup>60,85</sup> argued that the  $B_{12}(B, C, Si)_3$  phase has high brittleness, which can be proved by the obvious grooves formed on the surface, resulting from the peeling off of the  $B_{12}(B, C, Si)_3$  phase during polishing. Therefore, the generation of a large number of  $B_{12}(B, C, Si)_3$  phases may increase the brittleness of  $B_4C$ -SiC ceramics, which is not conducive to improving the fracture toughness of the ceramics.<sup>115</sup> The contribution of the  $B_4C$  grains with a core-rim structure to the mechanical properties of  $B_4C$ -SiC ceramics needs to be further elucidated. Furthermore, from the view of grain size, coarse  $B_4C$  grains become the crack source during the fracture process; thus large-sized  $B_4C$  grains are unfavorable to improving the bending strength of  $B_4C$ -SiC ceramics.<sup>99</sup> On the other hand, when the reaction-bonded  $B_4C$ -SiC ceramics are prepared by a microwave-assisted processing method, no core-rim structure of  $B_4C$  is observed.<sup>63</sup> The hardness (22 GPa) of  $B_4C$ -SiC ceramics prepared by the microwave-assisted processing method is comparable to that prepared by the conventional reaction-bonded process, but Young's modulus (309 GPa) is lower than that obtained using the conventional process.

The C source (free C addition or C originating from  $B_4C$ ) directly affects the morphology of SiC grains formed *in situ* (Section 3.5.2.2), which in turn controls the mechanical properties of reaction-bonded  $B_4C$ -SiC ceramics.<sup>148</sup> Compared with the SiC with polygonal morphology, the SiC with plate-like morphology can provide higher bending strength, fracture toughness, and compressive strength for  $B_4C$ -SiC ceramics. The volume fraction of SiC formed is not dependent on the C source. The SiC grains with a polygonal morphology are coarser than those with plate-like morphology; thus, the density of plate-like SiC grains is higher than that of polygonal SiC grains. Therefore, the number of inter-particle boundaries which have to be crossed by a propagating crack is large in the  $B_4C$ -SiC ceramics with plate-like SiC grains, leading to increased fracture toughness. Dariel and Frage<sup>99</sup> also mentioned that the morphology of SiC grains has a strong effect on the bending strength and fracture toughness of  $B_4C$ -SiC ceramics. The  $B_4C$ -SiC ceramics with plate-like shaped SiC possess higher bending strength and fracture toughness than the  $B_4C$ -SiC ceramics with polygonal SiC. This phenomenon is attributed to the strengthening and toughening effects of SiC particles with a plate-like shape. The SiC particles with a plate-like shape have a high aspect ratio, and SiC grains with a plate-like morphology likely cause crack deflection compared to those with a polygonal morphology. These plate-like shaped SiC particles can affect crack propagation through the  $B_4C$ -SiC ceramics *via* a large number of boundaries that are crossed by cracks, which can cause larger crack energy losses. Although the plate-like morphology of SiC grains can improve the fracture toughness and bending strength of  $B_4C$ -SiC ceramics, it does not affect the hardness and stiffness of  $B_4C$ -SiC ceramics.

## 4.2. Phase composition

The mechanical properties of  $B_4C$ -SiC ceramics depend on the relative amount of phases present. For example, the intrinsic

hardness of the individual phase affects the hardness of  $B_4C$ -SiC ceramics. For  $B_4C$ -SiC ceramics prepared by solid-state sintering using  $B_4C$  and SiC as raw materials, an unexpected phase does not form during sintering. However, there are some unexpected residual phases in the  $B_4C$ -SiC ceramics prepared by reaction-bonded sintering, and these residual phases can affect the mechanical properties of  $B_4C$ -SiC ceramics.

**4.2.1. Ratio of  $B_4C$  to SiC.** The mechanical properties of  $B_4C$ -SiC ceramics are influenced by the ratio of  $B_4C$  to SiC. The intrinsic hardness of  $B_4C$  is higher than that of SiC; thus, according to the rule of mixture,  $B_4C$ -SiC ceramics with higher ratios of  $B_4C$  to SiC possess a higher hardness theoretically on the condition that the samples have the same relative density, and *vice versa*. On the other hand, the ratio of  $B_4C$  to SiC affects the sintering performance and microstructure of the ceramics (Section 3.1).  $B_4C$ -SiC ceramics with higher ratios of  $B_4C$  to SiC are prone to have more pores, and pores play a detrimental role in the mechanical properties; refined grains and dense microstructure, both of which are beneficial in improving the mechanical properties of  $B_4C$ -SiC ceramics, can be obtained by adjusting the ratio of  $B_4C$  to SiC. Therefore, the ratio of  $B_4C$  to SiC affects the mechanical properties of  $B_4C$ -SiC ceramics by regulating the microstructure and following the rule of mixtures, and it is necessary to balance the ratio of  $B_4C$  to SiC in order to obtain  $B_4C$ -SiC ceramics with excellent mechanical properties.

For  $B_4C$ -SiC ceramics produced by pressureless sintering, Magnani *et al.*<sup>68</sup> reported that the fracture toughness of SiC-5 vol%  $B_4C$  ceramics is similar to that of pure SiC ceramics; however, the hardness and bending strength of SiC-5 vol%  $B_4C$  ceramics are higher than those of pure SiC ceramics. Higher mechanical properties of SiC-5 vol%  $B_4C$  ceramics are attributed to the finer microstructure and less strength-controlling flaws like porosity as compared to pure SiC ceramics. Cho *et al.*<sup>69</sup> mentioned that the hardness reduces but the fracture toughness increases when the content of  $B_4C$  increases from 1 to 5 wt% in the SiC- $B_4C$  ceramics. The reduced hardness is attributed to the increased porosity of the ceramics, while the increased fracture toughness is caused by the toughening mechanisms of crack bridging, crack deflection, and crack branching, resulting from the presence of increased  $B_4C$  at the grain boundary. Zhang *et al.*<sup>70</sup> studied the mechanical properties of  $B_4C$ -SiC ceramics with the change of the ratio of  $B_4C$  to SiC ( $3/97 < B_4C \text{ wt\%/SiC wt\%} < 100/0$ ). The fracture toughness of  $B_4C$ -SiC ceramics does not show an obvious difference with a difference in the ratio of  $B_4C$  to SiC under the same sintering conditions. The fracture toughness of  $B_4C$ -SiC ceramics varies between 3.1 and 3.7 MPa m<sup>1/2</sup>, and the fracture toughness of  $B_4C$ -SiC ceramics is slightly lower than that of pure  $B_4C$  ceramics. The hardness of  $B_4C$ -SiC ceramics varies between 27 and 33 GPa, and the hardness of  $B_4C$ -SiC ceramics is higher than that of pure  $B_4C$  ceramics. SiC-40 wt%  $B_4C$  ceramics exhibit the highest hardness. When  $B_4C$  content is more than 40 wt%, excessive porosity caused by the worse sintering performance of  $B_4C$  leads to the decreased hardness for  $B_4C$ -SiC ceramics, despite the higher hardness of  $B_4C$  than SiC. Vandeperre and Teo<sup>108</sup> found that



the nanohardness of B<sub>4</sub>C–SiC ceramics (5/95 < B<sub>4</sub>C wt%/SiC wt% < 100/0) increases linearly from 29.3 to 33.3 GPa as the B<sub>4</sub>C content increases. The measured nanohardness values of the B<sub>4</sub>C–SiC ceramics are close to the average theoretical hardness of B<sub>4</sub>C and SiC because the indents made are relatively small compared to the scale of the microstructure. Furthermore, Young's modulus of B<sub>4</sub>C–SiC ceramics hardly varies with the increase in B<sub>4</sub>C content (356–375 GPa), which is consistent with the similar Young's modulus values of single crystal SiC (450 GPa<sup>149</sup>) and single crystal B<sub>4</sub>C (467 GPa<sup>150</sup>). The measured Young's modulus values are lower than the theoretical values, attributed to the residual porosity in the ceramics.

For B<sub>4</sub>C–SiC ceramics prepared *via* hot-press sintering, So *et al.*<sup>72</sup> noted that the hardness of B<sub>4</sub>C–SiC ceramics slightly increases with the increase in B<sub>4</sub>C content from 30 to 70 wt%; the fracture toughness decreases with the increase in B<sub>4</sub>C content, which is attributed to the decrease in the content of SiC with relatively high toughness. When the B<sub>4</sub>C content is 50 wt%, the ceramics achieve the highest bending strength, which is attributed to the smallest grain size, as mentioned in Section 3.1. Chen *et al.*<sup>79</sup> observed that the bending strength and fracture toughness of B<sub>4</sub>C–SiC ceramics increase with the increase in SiC content from 0 to 20 wt%, but the hardness of the ceramics slightly decreases. Tomohiro *et al.*<sup>78</sup> reported that the hardness of B<sub>4</sub>C–SiC ceramics decreases with the increase in SiC addition from 0 to 50 vol%, resulting from the lower hardness of SiC compared to B<sub>4</sub>C. However, both the bending strength and fracture toughness of the ceramics are maximum when the SiC content is 20 vol%. Crack deflection, bridging, and branching by SiC grains are the main toughening mechanisms for the B<sub>4</sub>C–SiC ceramics. Meanwhile, the microcrack caused by the difference in thermal expansion coefficients between B<sub>4</sub>C and SiC is also responsible for the increased fracture toughness. When the SiC content is more than 20 vol%, the grain size of SiC gradually increases from 2–3 μm to 5–6 μm; also, SiC grains agglomerate, leading to inhomogeneous dispersion of SiC grains in the ceramics. Thus, the bending strength and fracture toughness of the ceramics decrease. Keçeli *et al.*<sup>151</sup> found that the bending strength and hardness of SiC–B<sub>4</sub>C ceramics increase with the increase in B<sub>4</sub>C content from 0 to 15 wt%, which is attributed to the finer microstructure of the ceramics with the increased B<sub>4</sub>C content.

For spark plasma sintered B<sub>4</sub>C–SiC ceramics, Moshtaghioun *et al.*<sup>112</sup> found that the fracture toughness of B<sub>4</sub>C–15 wt% SiC ceramics is higher than that of pure B<sub>4</sub>C ceramics, which is attributed to the smaller grain sizes of B<sub>4</sub>C and SiC in the B<sub>4</sub>C–SiC ceramics than the grain size of B<sub>4</sub>C in pure B<sub>4</sub>C ceramics. Meanwhile, the addition of SiC changes the fracture mode of the ceramics from transgranular fracture to a mixture of transgranular and intergranular fracture. Crack bridging by the SiC grains is the main toughening mechanism. However, the hardness of B<sub>4</sub>C–15 wt% SiC ceramics is slightly lower than that of pure B<sub>4</sub>C ceramics because SiC is softer than B<sub>4</sub>C. Sahin *et al.*<sup>96</sup> observed that the hardness of B<sub>4</sub>C–SiC ceramics decreases from 34.4 to 31.1 GPa with the increase in SiC content from 5 to 15 vol%. Yaşar and Haber<sup>71</sup> found that with

the content of B<sub>4</sub>C in the composite ceramics increasing from 10 to 50 wt%, the hardness of SiC–B<sub>4</sub>C ceramics increases, but the fracture toughness, Poisson's ratio, and elastic modulus decrease.

For B<sub>4</sub>C–SiC ceramics fabricated by reaction-bonded sintering, Lee *et al.*<sup>152</sup> reported that the hardness of SiC–B<sub>4</sub>C ceramics increases from 15.4 to 30.0 GPa as the B<sub>4</sub>C content in the preform increases from 0 to 50 wt%. The increased hardness of SiC–B<sub>4</sub>C ceramics with an increase in B<sub>4</sub>C content is attributed to two aspects. First, B<sub>4</sub>C has higher hardness. Second, B<sub>4</sub>C provides more C due to partial decomposition during the reaction bonding because a locally exothermic reaction with Si and C will cause the temperature to exceed the heating temperature, reducing the residual Si content in the matrix by the reaction of C and Si. Han *et al.*<sup>153</sup> found that the reaction-bonded SiC–B<sub>4</sub>C ceramics exhibit higher hardness, bending strength, and fracture toughness compared to the reaction-bonded SiC ceramics; the mechanical properties of the reaction-bonded SiC–B<sub>4</sub>C ceramics linearly increase with an increase in B<sub>4</sub>C content from 5 to 30 wt%. Lin and Fang<sup>154</sup> researched the mechanical properties of SiC–B<sub>4</sub>C ceramics when the content of B<sub>4</sub>C in the green body varies between 20 and 40 wt%. It was also found that the hardness of SiC–B<sub>4</sub>C ceramics gradually increases with the increase in B<sub>4</sub>C content. Furthermore, the fracture toughness and bending strength first increase and then decrease with the increase in B<sub>4</sub>C content, both of which show the maximum values when the B<sub>4</sub>C content is 30 wt%. The decreased fracture toughness and bending strength are attributed to the higher porosity when the B<sub>4</sub>C content is more than 30 wt%, which is caused by the sintering difficulty of B<sub>4</sub>C. Sun *et al.*<sup>116</sup> also noted that the hardness of B<sub>4</sub>C–SiC ceramics increases with the increase in B<sub>4</sub>C content from 10 to 70 wt%; however, both the bending strength and the fracture toughness increase first and then decrease. The decreased bending strength is ascribed to the destruction of the continuous phase. The SiC phase in the ceramics is continuous, but the B<sub>4</sub>C phase is not bonded, existing in the form of a dispersion phase. Therefore, the SiC phase contacting each other in the form of a bridge is decreased with the increase in the non-bonded B<sub>4</sub>C phase, reducing the bending strength.

In addition, Matović *et al.*<sup>64</sup> reported that despite the highest relative density achieved for the ultra-high pressure sintered B<sub>4</sub>C–SiC ceramics with the equal-weighted contributions of B<sub>4</sub>C and SiC, the highest hardness is obtained for the B<sub>4</sub>C–SiC ceramics with the highest B<sub>4</sub>C content when the B<sub>4</sub>C content ranges from 25 to 75 wt%.

Some previous studies on the effect of the ratio of B<sub>4</sub>C to SiC on the mechanical properties of B<sub>4</sub>C–SiC ceramics are tabulated in Table 7.

**4.2.2. Residual phase.** For B<sub>4</sub>C–SiC ceramics produced by reaction-bonded sintering, there is some residual phase in the resulting ceramics, eventually in the presence of a C or Si excess. The addition of excessive C in the green body will lead to insufficient Si to completely react with C, forming residual C. In contrast, residual Si is formed when free C added is insufficient or Si is excessive. In the case of introducing free C, the



Table 7 Effect of the ratio of B<sub>4</sub>C to SiC on the mechanical properties of B<sub>4</sub>C–SiC ceramics

| Ceramics                                   | Raw material                                                                                         | Sintering method      | Sintering temperature (°C) | Sintering aid                                                              | Relative density (%) | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|--------------------------------------------|------------------------------------------------------------------------------------------------------|-----------------------|----------------------------|----------------------------------------------------------------------------|----------------------|----------------|--------------------------------------------|------------------------|-----------------------|
| SiC <sup>68</sup>                          | $\alpha$ -SiC (0.6 $\mu$ m)                                                                          | Pressureless          | 2150                       | 0.6 wt% B + 2 wt% carbon black                                             | 93.5                 | 27.5           | 4.25                                       | 333                    | —                     |
| SiC-5 vol% B <sub>4</sub> C <sup>68</sup>  | $\alpha$ -SiC (0.6 $\mu$ m), B <sub>4</sub> C (0.7–0.9 $\mu$ m)                                      | Pressureless          | 2150                       | 1 wt% carbon black                                                         | 96.0                 | 30.2           | 4.19                                       | 422                    | —                     |
| B <sub>4</sub> C <sup>70</sup>             | B <sub>4</sub> C (0.8 $\mu$ m)                                                                       | Pressureless          | 2300                       | 3 wt% carbon black                                                         | 94.4                 | 26.9           | 3.70                                       | 240                    | —                     |
| B <sub>4</sub> C-20 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.4 $\mu$ m)                                          | Pressureless          | 2300                       | 3 wt% carbon black                                                         | 93.8                 | 29.7           | 3.22                                       | —                      | —                     |
| B <sub>4</sub> C-40 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.4 $\mu$ m)                                          | Pressureless          | 2300                       | 3 wt% carbon black                                                         | 93.5                 | 30.4           | 3.19                                       | 390                    | —                     |
| B <sub>4</sub> C-60 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.4 $\mu$ m)                                          | Pressureless          | 2300                       | 3 wt% carbon black                                                         | 95.6                 | 33.1           | 3.33                                       | —                      | —                     |
| B <sub>4</sub> C-80 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.4 $\mu$ m)                                          | Pressureless          | 2300                       | 3 wt% carbon black                                                         | 96.5                 | 29.2           | 3.13                                       | —                      | —                     |
| B <sub>4</sub> C-97 wt% SiC <sup>70</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.4 $\mu$ m)                                          | Pressureless          | 2300                       | 3 wt% carbon black                                                         | 99.0                 | 28.3           | 3.18                                       | —                      | —                     |
| B <sub>4</sub> C-70 wt% SiC <sup>72</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.5 $\mu$ m)                                          | Hot-press (40 MPa)    | 2000                       | No                                                                         | 100.0                | 30.3           | 3.60                                       | 590                    | —                     |
| B <sub>4</sub> C-50 wt% SiC <sup>72</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.5 $\mu$ m)                                          | Hot-press (40 MPa)    | 2000                       | No                                                                         | 99.9                 | 30.5           | 3.02                                       | 645                    | —                     |
| B <sub>4</sub> C-30 wt% SiC <sup>72</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), $\alpha$ -SiC (0.5 $\mu$ m)                                          | Hot-press (40 MPa)    | 2000                       | No                                                                         | 99.8                 | 30.8           | 2.82                                       | 560                    | —                     |
| B <sub>4</sub> C <sup>79</sup>             | B <sub>4</sub> C (0.8 $\mu$ m)                                                                       | Hot-press (40 MPa)    | 1900                       | 6 wt% Al <sub>2</sub> O <sub>3</sub> + 4 wt% Y <sub>2</sub> O <sub>3</sub> | 98.2                 | 38.7           | 6.44                                       | 394                    | —                     |
| B <sub>4</sub> C-10 wt% SiC <sup>79</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), SiC (0.45 $\mu$ m)                                                   | Hot-press (40 MPa)    | 1900                       | 6 wt% Al <sub>2</sub> O <sub>3</sub> + 4 wt% Y <sub>2</sub> O <sub>3</sub> | 98.7                 | 34.9           | 6.78                                       | 407                    | —                     |
| B <sub>4</sub> C-20 wt% SiC <sup>79</sup>  | B <sub>4</sub> C (0.8 $\mu$ m), SiC (0.45 $\mu$ m)                                                   | Hot-press (40 MPa)    | 1900                       | 6 wt% Al <sub>2</sub> O <sub>3</sub> + 4 wt% Y <sub>2</sub> O <sub>3</sub> | 99.0                 | 32.6           | 7.21                                       | 448                    | —                     |
| B <sub>4</sub> C <sup>78</sup>             | B <sub>4</sub> C (0.72 $\mu$ m)                                                                      | Hot-press (30 MPa)    | 2200                       | No                                                                         | 99.9                 | 28.9           | 3.90                                       | 620                    | —                     |
| B <sub>4</sub> C-10 vol% SiC <sup>78</sup> | B <sub>4</sub> C (0.72 $\mu$ m), $\beta$ -SiC (0.3 $\mu$ m)                                          | Hot-press (30 MPa)    | 2200                       | No                                                                         | 99.9                 | 26.5           | 4.50                                       | 628                    | —                     |
| B <sub>4</sub> C-15 vol% SiC <sup>78</sup> | B <sub>4</sub> C (0.72 $\mu$ m), $\beta$ -SiC (0.3 $\mu$ m)                                          | Hot-press (30 MPa)    | 2200                       | No                                                                         | 99.9                 | 25.9           | 4.71                                       | 674                    | —                     |
| B <sub>4</sub> C-20 vol% SiC <sup>78</sup> | B <sub>4</sub> C (0.72 $\mu$ m), $\beta$ -SiC (0.3 $\mu$ m)                                          | Hot-press (30 MPa)    | 2200                       | No                                                                         | 99.9                 | 25.4           | 4.90                                       | 740                    | —                     |
| B <sub>4</sub> C-30 vol% SiC <sup>78</sup> | B <sub>4</sub> C (0.72 $\mu$ m), $\beta$ -SiC (0.3 $\mu$ m)                                          | Hot-press (30 MPa)    | 2200                       | No                                                                         | 99.9                 | 25.4           | 4.60                                       | 645                    | —                     |
| B <sub>4</sub> C-50 vol% SiC <sup>78</sup> | B <sub>4</sub> C (0.72 $\mu$ m), $\beta$ -SiC (0.3 $\mu$ m)                                          | Hot-press (30 MPa)    | 2200                       | No                                                                         | 99.9                 | 25.2           | 4.59                                       | 628                    | —                     |
| SiC <sup>151</sup>                         | SiC (0.11 $\mu$ m)                                                                                   | Hot-press (50 MPa)    | 2100                       | No                                                                         | 77.0                 | —              | —                                          | 65                     | —                     |
| SiC-5 wt% B <sub>4</sub> C <sup>151</sup>  | SiC (0.11 $\mu$ m), B <sub>4</sub> C (2.54 $\mu$ m)                                                  | Hot-press (50 MPa)    | 2100                       | No                                                                         | 77.0                 | —              | —                                          | 115                    | —                     |
| SiC-10 wt% B <sub>4</sub> C <sup>151</sup> | SiC (0.11 $\mu$ m), B <sub>4</sub> C (2.54 $\mu$ m)                                                  | Hot-press (50 MPa)    | 2100                       | No                                                                         | 79.0                 | —              | —                                          | 123                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>151</sup> | SiC (0.11 $\mu$ m), B <sub>4</sub> C (2.54 $\mu$ m)                                                  | Hot-press (50 MPa)    | 2100                       | No                                                                         | 80.0                 | —              | —                                          | 130                    | —                     |
| B <sub>4</sub> C <sup>112</sup>            | B <sub>4</sub> C (0.5 $\mu$ m)                                                                       | Spark plasma (75 MPa) | 1700 ( $\times$ 3 min)     | No                                                                         | 100.0                | 39.3           | 3.50                                       | —                      | —                     |
| B <sub>4</sub> C-15 wt% SiC <sup>112</sup> | B <sub>4</sub> C (0.5 $\mu$ m), $\beta$ -SiC (0.5 $\mu$ m)                                           | Spark plasma (75 MPa) | 1700 ( $\times$ 3 min)     | No                                                                         | 99.4                 | 36.2           | 5.70                                       | —                      | —                     |
| B <sub>4</sub> C-5 vol% SiC <sup>96</sup>  | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (40 MPa) | 1750 ( $\times$ 5 min)     | No                                                                         | 98.0                 | 34.4           | —                                          | —                      | —                     |
| B <sub>4</sub> C-10 vol% SiC <sup>96</sup> | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (40 MPa) | 1750 ( $\times$ 5 min)     | No                                                                         | 98.0                 | 33.4           | —                                          | —                      | —                     |
| B <sub>4</sub> C-15 vol% SiC <sup>96</sup> | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (40 MPa) | 1750 ( $\times$ 5 min)     | No                                                                         | 97.8                 | 31.1           | —                                          | —                      | —                     |
| SiC-10 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (50 MPa) | 1950 ( $\times$ 5 min)     | 1.5 wt% C                                                                  | 99.6                 | 26.1           | 2.89                                       | —                      | 415                   |
| SiC-20 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (50 MPa) | 1950 ( $\times$ 5 min)     | 1.5 wt% C                                                                  | 99.2                 | 28.8           | 2.79                                       | —                      | 409                   |
| SiC-30 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (50 MPa) | 1950 ( $\times$ 5 min)     | 1.5 wt% C                                                                  | 98.8                 | 29.5           | 2.74                                       | —                      | 402                   |
| SiC-40 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (50 MPa) | 1950 ( $\times$ 5 min)     | 1.5 wt% C                                                                  | 98.8                 | 30.0           | 2.66                                       | —                      | 392                   |
| SiC-50 wt% B <sub>4</sub> C <sup>71</sup>  | B <sub>4</sub> C, $\alpha$ -SiC                                                                      | Spark plasma (50 MPa) | 1950 ( $\times$ 5 min)     | 1.5 wt% C                                                                  | 98.9                 | 30.3           | 2.64                                       | —                      | 388                   |
| SiC <sup>152</sup>                         | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), carbon black, Si powder (1 mm)                                | Reaction              | 1650                       | No                                                                         | —                    | 15.4           | —                                          | —                      | —                     |
| SiC-50 wt% B <sub>4</sub> C <sup>152</sup> | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), B <sub>4</sub> C (15 $\mu$ m), carbon black, Si powder (1 mm) | Reaction              | 1650                       | No                                                                         | —                    | 30.0           | —                                          | —                      | —                     |
| SiC <sup>153</sup>                         | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), carbon black, Si powder (1 mm)                                | Reaction              | 1650                       | No                                                                         | —                    | 15.0           | —                                          | 108                    | —                     |
| SiC-5 wt% B <sub>4</sub> C <sup>153</sup>  | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), B <sub>4</sub> C (15 $\mu$ m), carbon black, Si powder (1 mm) | Reaction              | 1650                       | No                                                                         | —                    | 18.5           | —                                          | 129                    | —                     |
| SiC-10 wt% B <sub>4</sub> C <sup>153</sup> | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), B <sub>4</sub> C (15 $\mu$ m), carbon black, Si powder (1 mm) | Reaction              | 1650                       | No                                                                         | —                    | 20.9           | —                                          | 143                    | —                     |
| SiC-20 wt% B <sub>4</sub> C <sup>153</sup> | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), B <sub>4</sub> C (15 $\mu$ m), carbon black, Si powder (1 mm) | Reaction              | 1650                       | No                                                                         | —                    | 24.4           | —                                          | 200                    | —                     |
| SiC-30 wt% B <sub>4</sub> C <sup>153</sup> | $\alpha$ -SiC (44 $\mu$ m, 3 $\mu$ m), B <sub>4</sub> C (15 $\mu$ m), carbon black, Si powder (1 mm) | Reaction              | 1650                       | No                                                                         | —                    | 27.5           | —                                          | 289                    | —                     |
| SiC-20 wt% B <sub>4</sub> C <sup>154</sup> | B <sub>4</sub> C (5 $\mu$ m), SiC (11 $\mu$ m), carbon black (10 $\mu$ m), Si                        | Reaction              | 1600                       | No                                                                         | 99.9                 | 31.0           | 3.60                                       | 458                    | —                     |
| SiC-30 wt% B <sub>4</sub> C <sup>154</sup> | B <sub>4</sub> C (5 $\mu$ m), SiC (11 $\mu$ m), carbon black (10 $\mu$ m), Si                        | Reaction              | 1600                       | No                                                                         | 99.8                 | 32.0           | 3.80                                       | 475                    | —                     |



Table 7 (continued)

| Ceramics                                   | Raw material                                                                     | Sintering method            | Sintering temperature (°C) | Sintering aid | Relative density (%) | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|--------------------------------------------|----------------------------------------------------------------------------------|-----------------------------|----------------------------|---------------|----------------------|----------------|--------------------------------------------|------------------------|-----------------------|
|                                            | B <sub>4</sub> C (5 µm), SiC (11 µm), carbon black (10 µm), Si                   |                             |                            |               |                      |                |                                            |                        |                       |
| SiC-40 wt% B <sub>4</sub> C <sup>154</sup> | B <sub>4</sub> C (5 µm), SiC (11 µm), carbon black (10 µm), Si                   | Reaction                    | 1600                       | No            | 99.7                 | 32.5           | 3.10                                       | 400                    | —                     |
| SiC-10 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 µm), α-SiC (7 µm), phenolic resin, carbon black, Si powder | Reaction                    | 1750                       | No            | —                    | 28.4           | 4.15                                       | 423                    | —                     |
| SiC-20 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 µm), α-SiC (7 µm), phenolic resin, carbon black, Si powder | Reaction                    | 1750                       | No            | —                    | —              | 4.71                                       | 458                    | —                     |
| SiC-30 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 µm), α-SiC (7 µm), phenolic resin, carbon black, Si powder | Reaction                    | 1750                       | No            | —                    | 30.2           | 5.07                                       | 487                    | —                     |
| SiC-50 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 µm), α-SiC (7 µm), phenolic resin, carbon black, Si powder | Reaction                    | 1750                       | No            | —                    | 34.0           | 4.50                                       | 430                    | —                     |
| SiC-70 wt% B <sub>4</sub> C <sup>116</sup> | B <sub>4</sub> C (1.5 µm), α-SiC (7 µm), phenolic resin, carbon black, Si powder | Reaction                    | 1750                       | No            | —                    | 35.5           | 3.85                                       | 394                    | —                     |
| B <sub>4</sub> C-75 wt% SiC <sup>64</sup>  | B <sub>4</sub> C (2.5 µm), β-SiC (0.6 µm)                                        | Ultra-high pressure (4 GPa) | 1500 (×1 min)              | No            | 96.4                 | 23.1           | —                                          | —                      | —                     |
| B <sub>4</sub> C-50 wt% SiC <sup>64</sup>  | B <sub>4</sub> C (2.5 µm), β-SiC (0.6 µm)                                        | Ultra-high pressure (4 GPa) | 1500 (×1 min)              | No            | 98.0                 | 27.0           | —                                          | —                      | —                     |
| B <sub>4</sub> C-25 wt% SiC <sup>64</sup>  | B <sub>4</sub> C (2.5 µm), β-SiC (0.6 µm)                                        | Ultra-high pressure (4 GPa) | 1500 (×1 min)              | No            | 96.9                 | 31.2           | —                                          | —                      | —                     |

presence of residual Si means the complete consumption of C initially added to the green body, and the quantity of infiltrated Si is enough to react with the introduced free C. The amount of Si introduced is related to the original porosity present in the preform before infiltration; thus, the amount of residual Si mainly depends on the amount of C and initial porosity of the preform.

The content and distribution of residual Si play an important role in the mechanical properties of B<sub>4</sub>C–SiC ceramics. First, Si is a brittle phase with lower hardness (7 GPa) and strength than B<sub>4</sub>C and SiC. Second, the thermal stress is developed by the thermal expansion coefficient mismatch between the matrix and Si at weak interfacial sites during cooling.<sup>155</sup> Third, the bonding strength of the interface in the ceramics is reduced due to the existence of residual Si, which does not help in improving the bending strength of B<sub>4</sub>C–SiC ceramics. Fourth, large-sized Si pools that are crack sources will be generated from residual Si, which can reduce the strength of B<sub>4</sub>C–SiC ceramics. Hayun *et al.*<sup>156</sup> found that the mechanical properties of B<sub>4</sub>C–SiC ceramics depend on the amount of residual Si. The B<sub>4</sub>C preforms without the addition of free C achieve 30 and 20 vol% porosity after pre-infiltration sintering at 2000 and 2100 °C, respectively. For the B<sub>4</sub>C preform with 20 vol% porosity, the amount of residual Si in the resulting ceramics is 7 vol%. For the B<sub>4</sub>C preform with 30 vol% porosity, the amount of residual Si in the resulting ceramics is 13 vol%. The B<sub>4</sub>C–SiC ceramics with less residual Si amount has higher hardness and Young's modulus, which is attributed to the increased fraction of the ceramic phases within the ceramics. Chhillar *et al.*<sup>157</sup> reported that the hardness, bending strength, and Young's modulus of the B<sub>4</sub>C–SiC ceramics decrease with the increase in residual Si content, but its fracture toughness increases as the residual Si content increases. The decreased hardness and Young's modulus are attributed to the relatively low hardness and stiffness of residual Si, respectively; the decreased bending strength is caused by the larger critical flaw size in the ceramics with greater Si content; the increased fracture toughness results from ductile-like failure of the Si phase, and more tortuous fracture paths and more Si phase deformation occur in the ceramics with more Si content. Hayun *et al.*<sup>148</sup> pointed out that the amount of residual Si affects not only the static mechanical properties but also the dynamic mechanical properties. The stress at the Hugoniot elastic limit of the B<sub>4</sub>C–SiC ceramics monotonically reduces with the increasing amount of residual Si. In addition, as armor materials, the compressive strength of ceramics is also an important parameter. Patel *et al.*<sup>158</sup> reported that the reaction-bonded B<sub>4</sub>C–SiC ceramics fail in a typical brittle failure under compressive load, and the compressive strength of the reaction-bonded B<sub>4</sub>C–SiC ceramics increases with the increase in the strain rate, the trend of which is similar to that of hot-pressed B<sub>4</sub>C ceramics. However, the compressive strength of the reaction-bonded B<sub>4</sub>C–SiC ceramics (700 MPa) is lower than those of hot-pressed B<sub>4</sub>C ceramics (3.52 GPa) and hot-pressed SiC ceramics (5.46 GPa),<sup>159</sup> which is attributed to 20 vol% residual Si. The weak residual Si interface between the B<sub>4</sub>C grains is the main reason for the low compressive strength of the reaction-bonded B<sub>4</sub>C–SiC ceramics.



Besides the amount of residual Si, the size of residual Si also affects the mechanical properties of B<sub>4</sub>C–SiC ceramics. When the Si region is small (< 5 μm), the Si phase is under a state of residual compressive stress due to thermal mismatch between Si and the matrix during the cooling, which can improve the fracture toughness because of increased resistance to crack propagation in the Si phase.<sup>100</sup> In contrast, when the Si region is large (> 5 μm) and irregularly shaped, the Si phase attains a state of tensile stress, promoting easy transgranular cracking with the Si region as the size of residual Si increases beyond a critical level.<sup>100</sup> Li *et al.*<sup>76</sup> reported that the hardness of B<sub>4</sub>C–SiC ceramics increases with a decrease in residual Si size.

Although B<sub>4</sub>C–SiC ceramics can be produced by reaction-bonded sintering, due to the inhomogeneous structure and presence of abundant residual Si, the reliability and mechanical properties of products, especially at high temperatures, are inferior. For example, soft spots left by residual Si can detract from the overall ballistic efficiency of B<sub>4</sub>C–SiC ceramics. The products lose the partial superior properties of B<sub>4</sub>C–SiC ceramics. Therefore, it is meaningful to decrease the amount of residual Si in the reaction-bonded B<sub>4</sub>C–SiC ceramics. Several approaches have been attempted, such as the use of a powder mixture with an appropriate multimodal particle size distribution to decrease the initial porosity of the green body (Section 3.2.1),<sup>76,84</sup> infiltration of the partially sintered preform to increase the relative density of the preform,<sup>142,156</sup> the addition of elements that react with Si to form stable silicides,<sup>160</sup> and addition of elements (Ti and Fe) or compounds (TiC) that react with B<sub>4</sub>C and release an additional amount of free C.<sup>161–163</sup>

As to the effect of residual C, Lin and Fang<sup>154</sup> reported that the residual C in the B<sub>4</sub>C–SiC ceramics produced *via* the addition of free C can worsen the mechanical properties of B<sub>4</sub>C–SiC ceramics even more seriously than residual Si. The mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics first increase and then decrease with the increase in carbon black addition from 10 to 30 wt%.

In order to improve the mechanical properties of B<sub>4</sub>C–SiC ceramics, the amount of residual phase needs to be reduced as much as possible. Some previous studies on the effect of the residual phase on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics are tabulated in Table 8.

#### 4.3. Raw material

As mentioned in Section 3.2, the characteristics of raw materials affect the sintering performance and microstructure of B<sub>4</sub>C–SiC ceramics, which in turn can affect the mechanical properties of B<sub>4</sub>C–SiC ceramics. The particle size and species of raw materials have a great influence on the mechanical properties of B<sub>4</sub>C–SiC ceramics.

**4.3.1. Particle size.** For the B<sub>4</sub>C–SiC ceramics produced by reaction-bonded sintering, the particle size of initial B<sub>4</sub>C powders significantly affects the mechanical properties of B<sub>4</sub>C–SiC ceramics.<sup>164</sup> Various findings have been put forward. Hayun *et al.*<sup>84</sup> reported that using B<sub>4</sub>C powders with a suitable particle size distribution as raw materials can improve the relative density of the green body and reduce the amount of residual Si; thus, the mechanical properties of the obtained B<sub>4</sub>C–SiC ceramics are increased. Dariel and Frage<sup>99</sup> mentioned that coarse B<sub>4</sub>C grains are unfavorable for improving the bending strength of B<sub>4</sub>C–SiC ceramics, while the effect of initial size of the B<sub>4</sub>C particles on fracture toughness is minor. Zhai *et al.*<sup>165</sup> found that the hardness, fracture toughness, and bending strength of B<sub>4</sub>C–SiC ceramics increase first and then decrease with the increase in particle size of B<sub>4</sub>C (1, 2.5, 8, 15, 17, and 34 μm). When the particle size of B<sub>4</sub>C is 17 μm, the mechanical properties of B<sub>4</sub>C–SiC ceramics reach the maximum, which is attributed to the closed packing effect of the green body. Barick *et al.*<sup>166</sup> noted that the smaller the particle size of B<sub>4</sub>C powders in the range of 18.7–63.4 μm, the greater the fracture toughness and bending strength of B<sub>4</sub>C–SiC ceramics will be. For the fracture toughness of reaction-bonded SiC ceramics, Chakrabarti *et al.*<sup>167</sup> stated that the number of grains for crack propagation that will pass through is dependent on the average grain size and intergranular Si thickness. Similarly, the ratio of grain size to Si thickness decreases with the increase in particle size of B<sub>4</sub>C powders in the reaction-bonded B<sub>4</sub>C–SiC ceramics, which indicates that the crack propagates a longer distance for the B<sub>4</sub>C–SiC ceramics with smaller particle size. Furthermore, the interfacial debonding mechanism dominates over transgranular fracture as the grain size decreases, and the debonding at B<sub>4</sub>C–Si and SiC–Si interfaces can further improve fracture toughness for B<sub>4</sub>C–SiC ceramics as compared to transgranular fracture. Therefore, the B<sub>4</sub>C–SiC ceramics produced from the

**Table 8** Effect of the residual phase on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics

| Ceramics                                    | Raw material                                                             | Sintering temperature (°C) | Relative density (%) | Residual phase | Content of residual phase | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|---------------------------------------------|--------------------------------------------------------------------------|----------------------------|----------------------|----------------|---------------------------|----------------|--------------------------------------------|------------------------|-----------------------|
| B <sub>4</sub> C-13 vol% SiC <sup>156</sup> | B <sub>4</sub> C, Si                                                     | 1480                       | —                    | Si             | 7 vol%                    | 22.5           | 5.5                                        | 390                    | 410                   |
| B <sub>4</sub> C-17 vol% SiC <sup>156</sup> | B <sub>4</sub> C, Si                                                     | 1480                       | —                    | Si             | 13 vol%                   | 20.3           | 7.9                                        | 415                    | 370                   |
| B <sub>4</sub> C–SiC <sup>157</sup>         | B <sub>4</sub> C, resin, Si                                              | —                          | —                    | Si             | 5 vol%                    | 19.5           | 4.4                                        | 324                    | 432                   |
| B <sub>4</sub> C–SiC <sup>157</sup>         | B <sub>4</sub> C, resin, Si                                              | —                          | —                    | Si             | 10 vol%                   | 16.7           | 4.8                                        | 280                    | 406                   |
| B <sub>4</sub> C–SiC <sup>157</sup>         | B <sub>4</sub> C, resin, Si                                              | —                          | —                    | Si             | 14 vol%                   | 15.3           | 5.0                                        | 276                    | 380                   |
| B <sub>4</sub> C-70 wt% SiC <sup>154</sup>  | B <sub>4</sub> C (5 μm), SiC (11 μm),<br>10 wt% carbon black (10 μm), Si | 1600                       | 99.9                 | Si             | —                         | 30.0           | 3.4                                        | 415                    | —                     |
| B <sub>4</sub> C-60 wt% SiC <sup>154</sup>  | B <sub>4</sub> C (5 μm), SiC (11 μm),<br>20 wt% carbon black (10 μm), Si | 1600                       | 99.9                 | Si             | —                         | 31.0           | 3.6                                        | 458                    | —                     |
| B <sub>4</sub> C-50 wt% SiC <sup>154</sup>  | B <sub>4</sub> C (5 μm), SiC (11 μm),<br>30 wt% carbon black (10 μm), Si | 1600                       | 99.8                 | C              | —                         | 28.5           | 2.1                                        | 370                    | —                     |



B<sub>4</sub>C powders with smaller particle sizes exhibit higher fracture toughness. As to bending strength, residual thermal stress formed due to thermal expansion mismatch between the matrix and Si during cooling can generate flaws or cracks in weak interfacial zones. On the one hand, the probability of the formation of flaws with larger sizes is higher for the B<sub>4</sub>C–SiC ceramics with larger grain size owing to the larger scale of the interfacial area between B<sub>4</sub>C and Si grains; on the other hand, these flaws can propagate maximum up to one-grain size. Thereby, the B<sub>4</sub>C–SiC ceramics with a larger grain size have flaws with a larger size. According to the Griffith equation:

$$\sigma_f = (2\gamma Y / \Pi C)^{1/2} \quad (9)$$

where  $\sigma_f$  is the bending strength (MPa),  $\gamma$  is the fracture surface energy (J m<sup>−2</sup>),  $Y$  is Young's modulus (GPa), and  $C$  is half of the crack length (μm);<sup>168</sup> the larger the flaw size, the lower the bending strength is. As a result, the B<sub>4</sub>C–SiC ceramics produced from B<sub>4</sub>C powders with larger particle sizes show lower bending strength. However, the hardness of B<sub>4</sub>C–SiC ceramics decreases with the decrease in particle size of B<sub>4</sub>C powders. This is because the reaction-bonded B<sub>4</sub>C–SiC ceramics with fine particle size have a larger interface boundary area, which is a weak zone. The larger the interface boundary area, the larger the volume fraction of the weak interfacial zone is. Therefore, the B<sub>4</sub>C–SiC ceramics produced from B<sub>4</sub>C powders with a smaller particle size exhibit lower hardness.<sup>166</sup> Furthermore, the smaller size of B<sub>4</sub>C grains is beneficial for increasing the compressive strength of the reaction-bonded B<sub>4</sub>C–SiC ceramics.<sup>148</sup> Based on these findings, adjusting the size of raw materials is one of the effective means to control the mechanical properties of B<sub>4</sub>C–SiC ceramics.

Some previous studies on the effect of particle size of raw materials on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics are tabulated in Table 9.

**4.3.2. Species.** As mentioned in Section 3.2.3, the species of raw materials control the microstructure of the obtained B<sub>4</sub>C–SiC ceramics, which in turn gives rise to different mechanical properties of B<sub>4</sub>C–SiC ceramics.

When β-SiC is used as the raw material, the microstructure of the resulting B<sub>4</sub>C–SiC ceramics is different from that of B<sub>4</sub>C–SiC ceramics prepared using α-SiC as the raw material; due to the partial transformation of β → α-SiC during sintering, platelet-shaped SiC grains are formed. Excessive platelet-shaped SiC grains in B<sub>4</sub>C–SiC ceramics are not favorable for improving the densification of the ceramics; however, these platelet-shaped SiC grains can act as a factor for enhancing the fracture toughness of B<sub>4</sub>C–SiC ceramics, which plays an equally important role in obtaining lightweight ballistic material.

In addition to directly mixing commercial B<sub>4</sub>C and SiC raw powders to fabricate B<sub>4</sub>C–SiC ceramics, other raw materials can also be used to prepare B<sub>4</sub>C–SiC ceramics.

PCS is widely used as the precursor of SiC. The generation of fine SiC grains from PCS can reduce the size and density of structural defects that deteriorate the mechanical properties of B<sub>4</sub>C–SiC ceramics by filling the pores and voids. Also, these fine SiC grains affect the crack propagation; when a crack

**Table 9** Effect of particle size of raw materials on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics

| Ceramics                            | Raw material                                                                              | Particle size of B <sub>4</sub> C (μm)  | Relative density of green body (%) | Sintering temperature (°C) | Relative density (%) | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|-------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------|------------------------------------|----------------------------|----------------------|----------------|--------------------------------------------|------------------------|-----------------------|
| B <sub>4</sub> C–SiC <sup>84</sup>  | B <sub>4</sub> C, Si                                                                      | 66 vol%130.0 + 15 vol%13.0 + 19 vol%1.0 | 74.2                               | 1450                       | 99.9                 | 22.6           | —                                          | 318                    | 400                   |
| B <sub>4</sub> C–SiC <sup>165</sup> | B <sub>4</sub> C, α-SiC (9 μm), carbon black (0.56 μm), phenolic resin, Si powder (50 μm) | 1.0                                     | —                                  | 1560                       | —                    | 18.6           | 3.03                                       | 274                    | —                     |
| B <sub>4</sub> C–SiC <sup>165</sup> | B <sub>4</sub> C, α-SiC (9 μm), carbon black (0.56 μm), phenolic resin, Si powder (50 μm) | 2.5                                     | —                                  | 1560                       | —                    | 18.9           | 3.56                                       | 289                    | —                     |
| B <sub>4</sub> C–SiC <sup>165</sup> | B <sub>4</sub> C, α-SiC (9 μm), carbon black (0.56 μm), phenolic resin, Si powder (50 μm) | 8.0                                     | —                                  | 1560                       | —                    | 21.5           | 3.84                                       | 319                    | —                     |
| B <sub>4</sub> C–SiC <sup>165</sup> | B <sub>4</sub> C, α-SiC (9 μm), carbon black (0.56 μm), phenolic resin, Si powder (50 μm) | 15.0                                    | —                                  | 1560                       | —                    | 24.6           | 4.20                                       | 346                    | —                     |
| B <sub>4</sub> C–SiC <sup>165</sup> | B <sub>4</sub> C, α-SiC (9 μm), carbon black (0.56 μm), phenolic resin, Si powder (50 μm) | 17.0                                    | —                                  | 1560                       | —                    | 28.2           | 4.49                                       | 376                    | —                     |
| B <sub>4</sub> C–SiC <sup>165</sup> | B <sub>4</sub> C, α-SiC (9 μm), carbon black (0.56 μm), phenolic resin, Si powder (50 μm) | 34.0                                    | —                                  | 1560                       | —                    | 24.3           | 3.89                                       | 340                    | —                     |
| B <sub>4</sub> C–SiC <sup>166</sup> | B <sub>4</sub> C, phenolic resin, carbon black                                            | 18.7                                    | 55.9                               | 1550                       | —                    | 12.4           | 5.76                                       | 403                    | —                     |
| B <sub>4</sub> C–SiC <sup>166</sup> | B <sub>4</sub> C, phenolic resin, carbon black                                            | 33.7                                    | 58.9                               | 1550                       | —                    | 13.6           | 5.00                                       | 359                    | —                     |
| B <sub>4</sub> C–SiC <sup>166</sup> | B <sub>4</sub> C, phenolic resin, carbon black                                            | 63.4                                    | 62.7                               | 1550                       | —                    | 16.4           | 3.40                                       | 265                    | —                     |



encounters these fine SiC grains, either it has to break them or bypass them to continue the propagation, both of which consume the crack propagation energy. On the other hand, the thermal decomposition of PCS yields not only SiC but also free C. The C impurity has an effect on the hardness, strength, and oxidation resistance of B<sub>4</sub>C–SiC ceramics. Therefore, different from the direct use of SiC powders, the use of PCS will have a certain impact on the mechanical properties of B<sub>4</sub>C–SiC ceramics. Du *et al.*<sup>91</sup> used B<sub>4</sub>C and PCS as raw materials to prepare B<sub>4</sub>C–SiC ceramics by hot-press sintering. The hardness and fracture toughness of B<sub>4</sub>C–15 wt% SiC ceramics are higher than those of pure B<sub>4</sub>C ceramics. The improvement in hardness is attributed to the reduction of residual porosity in B<sub>4</sub>C–SiC ceramics. The enhancement of fracture toughness is ascribed to two aspects. First, the layered structure and dislocation defects are generated in SiC grains (Fig. 3). Dislocation has a passivated effect on the crack tip. When cracks propagate to the dislocation zone, dislocation can absorb partial crack propagation energy by self-deformation and pin the crack, which is similar to microcrack toughening. Thereby, the layered structure and dislocation can consume much crack propagation energy, forming effective barriers for crack propagation. Second, SiC grains formed from the pyrolysis of PCS have a particle size in the range of nanometers to micrometers. Although transgranular fracture is still the main fracture mode of B<sub>4</sub>C–SiC ceramics, SiC grains of micron size cause crack bridging and nano-sized SiC grains within B<sub>4</sub>C grains induce crack deflection, both of which increase the fracture toughness of B<sub>4</sub>C–SiC ceramics. Crack deflection is related to the tensile residual stress field induced by nano or quasi-nano SiC grains in the B<sub>4</sub>C matrix. B<sub>4</sub>C and SiC have similar thermal expansion coefficients; however, the thermal expansion properties of SiC may be changed greatly because of the nanometer size effect as SiC grain size reduces to nanoscale or quasi-nanoscale. As a result, a thermal residual stress field around nano or quasi-nano SiC grains is induced by the mismatch in the thermal expansion coefficients between the B<sub>4</sub>C matrix and SiC grains during cooling. Hwang *et al.*<sup>87</sup> also observed the layered microstructure (or planar defects) and/or subgrains in the PCS pyrolyzed SiC grains. This microstructure can further improve the fracture toughness of the spark plasma sintered B<sub>4</sub>C–SiC ceramics because cracks frequently deflect within SiC grains generated from PCS pyrolysis (Fig. 12a), which results from either the grain boundary between subgrains or the layered structure of grains (Fig. 12b). As a result, the toughening mechanism of SiC grains generated from PCS pyrolysis for the B<sub>4</sub>C–SiC ceramics is a combination of crack deflection within SiC grains and crack impeding by SiC grains. It is noteworthy that the fracture toughness (indentation K<sub>IC</sub>) of spark plasma sintered B<sub>4</sub>C–SiC ceramics (2.7 MPa m<sup>1/2</sup>) prepared from the pyrolysis of PCS is lower than the fracture toughness reported for the spark plasma sintered B<sub>4</sub>C–SiC ceramics (5.7 MPa m<sup>1/2</sup>) produced from SiC powders (Table 7), which is attributed to the residual C from the conversion of PCS to SiC, the difference in grain size, or other unknown factors; however, it is not recommended to compare the values of fracture toughness between different ceramic systems due to the complex crack tip arrest environment.<sup>169</sup> Furthermore, the hardness of spark plasma

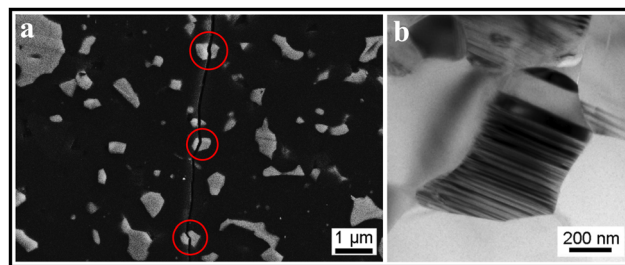


Fig. 12 (a) Cracks in spark plasma sintered B<sub>4</sub>C–SiC ceramics whose SiC is generated from PCS pyrolysis showing frequent deflection and (b) SiC grain generated from PCS pyrolysis in the B<sub>4</sub>C–SiC ceramics showing a layered structure (or planar defects)<sup>87</sup> (reprinted with permission, Copyright 2018, Elsevier).

sintered B<sub>4</sub>C–SiC ceramics decreases with the increased content of SiC formed by PCS pyrolysis. Besides the rule of mixtures that the hardness of SiC is lower than that of B<sub>4</sub>C, the amount of residual C generated accompanied by the pyrolysis of PCS to form SiC also gradually increases, which can also lead to the reduction of hardness. Meanwhile, the hardness of spark plasma sintered B<sub>4</sub>C–SiC ceramics (~29 GPa) prepared from the pyrolysis of PCS is lower than the hardness reported for the spark plasma sintered B<sub>4</sub>C–SiC ceramics (31–36 GPa) produced from SiC powders (Table 7), resulting from the residual C accompanied by the PCS conversion to SiC. The introduction of an appropriate amount of Si can convert residual C into SiC, thus increasing the hardness of B<sub>4</sub>C–SiC ceramics.<sup>91</sup> In addition, Zhou *et al.*<sup>170</sup> utilized PCS as a SiC precursor to prepare reaction-bonded B<sub>4</sub>C–SiC ceramics from the green body composed of graded B<sub>4</sub>C powders and PCS. Compared with the reaction-bonded B<sub>4</sub>C–SiC ceramics produced from the green body composed of B<sub>4</sub>C without the addition of PCS, the reaction-bonded B<sub>4</sub>C–SiC ceramics prepared from the green body composed of B<sub>4</sub>C with the addition of 5–10 wt% PCS exhibit higher bending strength, which is attributed to their lower porosity. The formed β-SiC and C particles by PCS pyrolysis can segment the large pores in the preform, decreasing the median pore diameter, which can increase the capillary force and is beneficial for the infiltration process. However, the excessive addition of PCS will reduce the bending strength of reaction-bonded B<sub>4</sub>C–SiC ceramics because Si accumulation areas are generated in the ceramics, leading to the formation of residual stress in weak interfacial zones and flaws with large sizes. The layered structure of SiC derived from PCS pyrolysis is also observed in the reaction-bonded B<sub>4</sub>C–SiC ceramics.<sup>117</sup>

Moreover, SiC can be formed *in situ* through some chemical reactions of two raw materials, which can cause a different effect on the mechanical properties of B<sub>4</sub>C–SiC ceramics. Zhang *et al.*<sup>94,95</sup> used B<sub>4</sub>C, Si, and amorphous carbon powders to produce B<sub>4</sub>C–SiC ceramics *via* high-energy ball milling by hot-press sintering or spark plasma sintering. It was found that the hardness and fracture toughness of the obtained B<sub>4</sub>C–SiC ceramics are higher than those of B<sub>4</sub>C–SiC ceramics produced from B<sub>4</sub>C and PCS as raw materials<sup>91</sup> or produced directly from B<sub>4</sub>C and SiC powders *via* high-energy ball milling.<sup>98</sup> For the B<sub>4</sub>C–SiC ceramics made from B<sub>4</sub>C, Si, and amorphous carbon



*via* hot-press sintering, a number of nano-sized SiC and B<sub>4</sub>C grains (100–200 nm) exist within the B<sub>4</sub>C grains (1–3 μm). During high-energy ball milling, some smaller SiC and B<sub>4</sub>C particles are embedded into the larger B<sub>4</sub>C particles. Thereby, these smaller SiC and B<sub>4</sub>C particles are trapped into the larger B<sub>4</sub>C particles during sintering because of the fast diffusion speed, which is attributed to the disordered structure of B<sub>4</sub>C–SiC composite powders formed during high-energy ball milling. This intragranular structure, which can generate intracrystalline boundaries and stress, is helpful in improving the mechanical properties of B<sub>4</sub>C–SiC ceramics, especially the fracture toughness. The transgranular fracture is still the main fracture mode; however, when cracks cross the B<sub>4</sub>C grains and reach intragranular particles within B<sub>4</sub>C grains, the cracks are deflected along the intracrystalline boundary, rather than crossing the intragranular particles, which is ascribed to the small-size and high-strength intragranular crystals that can consume crack extension energy. Therefore, the intragranular grains (including B<sub>4</sub>C and SiC grains) induce crack deflection; the intragranular structure changes the fracture mode from the single transgranular fracture to a combination of transgranular fracture and intergranular fracture, improving the fracture toughness of B<sub>4</sub>C–SiC ceramics. Furthermore, the hardness and fracture toughness of B<sub>4</sub>C–SiC ceramics produced from B<sub>4</sub>C, Si, and amorphous carbon powders *via* spark plasma sintering are slightly higher than those of B<sub>4</sub>C–SiC ceramics produced from the same raw materials *via* hot-press sintering, which is attributed to the smaller grain size resulting from the lower sintering temperature and shorter holding time as well as to the sufficient utilization of high sintering activity of B<sub>4</sub>C and SiC composite powders produced *via* high-energy ball milling resulting from the fast heating rate by the spark plasma sintering, which can lead to the production of abundant energy from the disorder–order transformation of SiC and B<sub>4</sub>C to induce densification. Wei *et al.*<sup>171,172</sup> used Si powders ( $D_{50} = 1 \mu\text{m}$ ) and B<sub>4</sub>C containing free C (0.9%) powders ( $D_{50} = 1.5 \mu\text{m}$ ) as raw materials to produce B<sub>4</sub>C–SiC ceramics. At high temperatures, free C can react with Si, synthesizing SiC *in situ*. Only B<sub>4</sub>C and SiC phases are detected in the resulting B<sub>4</sub>C–SiC ceramics, which indicates that no free Si exists in the ceramics after adding different contents of Si powders (4–12 wt%). The residual Si after reaction with free C is fully solid soluted into the B<sub>4</sub>C lattice, resulting in increased lattice parameters of B<sub>4</sub>C. The Si powders can melt above 1400 °C; thus the existence of a liquid phase promotes the sintering and improves the densification, reducing the number and size of pores acting as the origin of fracture. Therefore, the bending strength of B<sub>4</sub>C–SiC ceramics is higher than that of pure B<sub>4</sub>C ceramics without adding Si powders. The formation of SiC in B<sub>4</sub>C ceramics, on the one hand, is beneficial for increasing the relative density of the ceramics, and on the other hand, changes the fracture mode of the ceramics from transgranular fracture to a combination of transgranular fracture and intergranular fracture, resulting in the increased fracture toughness compared to pure B<sub>4</sub>C ceramics. However, the addition of excessive Si powders (12 wt%) will cause a certain degree of decrease in the strength and toughness of B<sub>4</sub>C–SiC ceramics because the excessive SiC particles formed *in situ* aggregate,

leading to a much bigger grain size. Sahin *et al.*<sup>96</sup> used B<sub>4</sub>C, SiO<sub>2</sub>, and carbon black as raw materials to produce B<sub>4</sub>C–SiC ceramics *via* spark plasma sintering according to reaction (1). The formation of SiC using SiO<sub>2</sub> and carbon black as raw materials is accompanied by the generation of gas; thus, the hardness of the resulting B<sub>4</sub>C–SiC ceramics decreases with the increase in *in situ* formed SiC content from 5 to 20 vol%, which is attributed to the gradually decreased relative density.

SiC whiskers (SiC<sub>w</sub>) with high strength and high elastic modulus are considered to be an excellent toughening phase; different researchers studied the effect of SiC addition in the form of whiskers (SiC<sub>w</sub>) on the mechanical properties of B<sub>4</sub>C–SiC ceramics. To improve the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics, Wang *et al.*<sup>173</sup> added SiC in the form of a whisker into the green body composed of B<sub>4</sub>C and C. The stacking density of the mixed powders in the preform decreases with the increase in SiC<sub>w</sub> addition from 0 to 24 wt%, resulting in the gradually decreased relative density of the preform. The fracture roughness of the reaction-bonded B<sub>4</sub>C–SiC ceramics increases with the increase in SiC<sub>w</sub> content from 0 to 24 wt%; the main toughening mechanism is the pulling out of SiC<sub>w</sub> from the matrix, which is an energy-consuming process. However, the hardness and bending strength of the reaction-bonded B<sub>4</sub>C–SiC ceramics decrease with the increase in SiC<sub>w</sub> content from 0 to 24 wt%. The reduced hardness is attributed to the decreased proportion of B<sub>4</sub>C in the ceramics; the decreased bending strength is ascribed to the dissolution of SiC<sub>w</sub> and transformation to SiC particles during molten Si infiltration, the formation of microcracks within the ceramics resulting from the mismatch of thermal expansion coefficients between B<sub>4</sub>C and SiC<sub>w</sub>, and the weakening of interface bonding strength between B<sub>4</sub>C and SiC<sub>w</sub> due to the increased defects such as the porosity and the non-uniformity distribution of SiC<sub>w</sub>. Tamari *et al.*<sup>174</sup> studied the effect of SiC whisker content in the range of 10 to 30 vol% on the mechanical properties of hot-press sintered B<sub>4</sub>C–SiC<sub>w</sub> ceramics. There was no pulling-out of the SiC whiskers and no crack deflection during fracture, which is opposite to what Wang *et al.*<sup>173</sup> found; thus, the fracture toughness of B<sub>4</sub>C–SiC<sub>w</sub> ceramics increases slightly with the increase in SiC whisker content. In contrast, the bending strength of B<sub>4</sub>C–SiC<sub>w</sub> ceramics decreases with the increase in SiC whisker content. The hardness and elastic modulus are independent of SiC whisker content.

Some previous studies on the effect of species of raw material on the mechanical properties of B<sub>4</sub>C–SiC ceramics are tabulated in Table 10.

#### 4.3.3. Use of C/SiC in the reaction-bonded B<sub>4</sub>C–SiC ceramics.

The addition of free C in the preform will help control the morphology of SiC grains formed (Section 3.5.2.2) and SiC phase volume fraction, which in turn will affect the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics. Furthermore, the use of C can affect the sintering performance and microstructure of reaction-bonded B<sub>4</sub>C–SiC ceramics; thus, the mechanical properties of B<sub>4</sub>C–SiC ceramics can be enhanced by adjusting the initial free C content. Gao *et al.*,<sup>144</sup> Zhang *et al.*,<sup>75</sup> and Lin *et al.*<sup>175</sup> reported that the addition of 5–10 vol% carbon powders, 8–10 wt%





**Table 10** Effect of species of raw material on the mechanical properties of B<sub>4</sub>C–SiC ceramics

| Ceramics                                   | Raw material                                                                        | Sintering method      | Sintering temperature (°C) | Sintering aid | Relative density (%) | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|--------------------------------------------|-------------------------------------------------------------------------------------|-----------------------|----------------------------|---------------|----------------------|----------------|--------------------------------------------|------------------------|-----------------------|
| B <sub>4</sub> C <sup>91</sup>             | B <sub>4</sub> C (3.5 μm)                                                           | Hot-press (30 MPa)    | 1950                       | No            | 91.7                 | 24.1           | 3.34                                       | —                      | —                     |
| B <sub>4</sub> C-15 wt% SiC <sup>91</sup>  | B <sub>4</sub> C (3.5 μm), PCS                                                      | Hot-press (30 MPa)    | 1950                       | No            | 96.1                 | 26.6           | 4.98                                       | —                      | —                     |
| B <sub>4</sub> C-15 wt% SiC <sup>91</sup>  | B <sub>4</sub> C (3.5 μm), PCS                                                      | Hot-press (30 MPa)    | 1950                       | 8 wt% Si      | 99.1                 | 33.5           | 5.57                                       | —                      | —                     |
| B <sub>4</sub> C <sup>87</sup>             | B <sub>4</sub> C (0.3–0.6 μm)                                                       | Spark plasma (50 MPa) | 1900 (×5 min)              | No            | —                    | 29.7           | 2.00                                       | —                      | 409                   |
| B <sub>4</sub> C-10 wt% SiC <sup>87</sup>  | B <sub>4</sub> C (0.3–0.6 μm), PCS                                                  | Spark plasma (50 MPa) | 1900 (×5 min)              | No            | 99.7                 | 29.1           | 2.36                                       | —                      | 416                   |
| B <sub>4</sub> C-20 wt% SiC <sup>87</sup>  | B <sub>4</sub> C (0.3–0.6 μm), PCS                                                  | Spark plasma (50 MPa) | 1900 (×5 min)              | No            | 99.5                 | 28.5           | 2.68                                       | —                      | 408                   |
| B <sub>4</sub> C-SiC <sup>170</sup>        | B <sub>4</sub> C (139.0 μm, 2.01 μm), Si powder                                     | Reaction              | 1500                       | No            | 99.1                 | 15.1           | 4.26                                       | 260                    | 348                   |
| B <sub>4</sub> C-SiC <sup>170</sup>        | B <sub>4</sub> C (139.0 μm, 2.01 μm), 5 wt% PCS, Si powder                          | Reaction              | 1500                       | No            | 99.8                 | 17.3           | 4.35                                       | 319                    | 402                   |
| B <sub>4</sub> C-SiC <sup>170</sup>        | B <sub>4</sub> C (139.0 μm, 2.01 μm), 10 wt% PCS, Si powder                         | Reaction              | 1500                       | No            | 99.8                 | 17.2           | —                                          | 281                    | 393                   |
| B <sub>4</sub> C-SiC <sup>170</sup>        | B <sub>4</sub> C (139.0 μm, 2.01 μm), 15 wt% PCS, Si powder                         | Reaction              | 1500                       | No            | 99.6                 | 16.9           | —                                          | 242                    | 403                   |
| B <sub>4</sub> C-20 wt% SiC <sup>94</sup>  | B <sub>4</sub> C (3 μm), Si (–200 mesh), amorphous carbon (1 μm)                    | Hot-press (30 MPa)    | 1900                       | No            | 97.2                 | 30.1           | 6.10                                       | —                      | —                     |
| B <sub>4</sub> C-20 wt% SiC <sup>94</sup>  | B <sub>4</sub> C (3 μm), Si (–200 mesh), amorphous carbon (1 μm)                    | Hot-press (30 MPa)    | 1950                       | No            | 98.6                 | 34.3           | 6.00                                       | —                      | —                     |
| B <sub>4</sub> C-20 wt% SiC <sup>95</sup>  | B <sub>4</sub> C (3 μm), Si (–200 mesh), amorphous carbon (1 μm)                    | Spark plasma (30 MPa) | 1700 (×5 min)              | No            | 96.7                 | 28.8           | 5.75                                       | —                      | —                     |
| B <sub>4</sub> C-20 wt% SiC <sup>95</sup>  | B <sub>4</sub> C (3 μm), Si (–200 mesh), amorphous carbon (1 μm)                    | Spark plasma (30 MPa) | 1750 (×5 min)              | No            | 98.3                 | 33.4           | 6.50                                       | —                      | —                     |
| B <sub>4</sub> C-20 wt% SiC <sup>95</sup>  | B <sub>4</sub> C (3 μm), Si (–200 mesh), amorphous carbon (1 μm)                    | Spark plasma (30 MPa) | 1800 (×5 min)              | No            | 99.2                 | 35.8           | 6.80                                       | —                      | —                     |
| B <sub>4</sub> C-50 wt% SiC <sup>98</sup>  | B <sub>4</sub> C, SiC, mean particle size of 0.7 μm                                 | Hot-press (30 MPa)    | 1900                       | No            | 96.4                 | 24.0           | 4.60                                       | 430                    | —                     |
| B <sub>4</sub> C <sup>171</sup>            | B <sub>4</sub> C (1 μm)                                                             | Hot-press (60 MPa)    | 1850                       | No            | —                    | —              | 4.25                                       | 175                    | —                     |
| B <sub>4</sub> C-SiC <sup>171</sup>        | B <sub>4</sub> C (1 μm), Si (1.5 μm)                                                | Hot-press (60 MPa)    | 1850                       | 4 wt% Si      | —                    | —              | 4.37                                       | 283                    | —                     |
| B <sub>4</sub> C-SiC <sup>171</sup>        | B <sub>4</sub> C (1 μm), Si (1.5 μm)                                                | Hot-press (60 MPa)    | 1850                       | 8 wt% Si      | —                    | —              | 5.04                                       | 354                    | —                     |
| B <sub>4</sub> C-SiC <sup>171</sup>        | B <sub>4</sub> C (1 μm), Si (1.5 μm)                                                | Hot-press (60 MPa)    | 1850                       | 12 wt% Si     | —                    | —              | 4.76                                       | 302                    | —                     |
| B <sub>4</sub> C-5 vol% SiC <sup>96</sup>  | B <sub>4</sub> C, SiO <sub>2</sub> (1 μm), carbon black                             | Spark plasma (40 MPa) | 1750 (×5 min)              | No            | 97.7                 | 35.0           | —                                          | —                      | —                     |
| B <sub>4</sub> C-10 vol% SiC <sup>96</sup> | B <sub>4</sub> C, SiO <sub>2</sub> (1 μm), carbon black                             | Spark plasma (40 MPa) | 1750 (×5 min)              | No            | 93.8                 | 34.5           | —                                          | —                      | —                     |
| B <sub>4</sub> C-15 vol% SiC <sup>96</sup> | B <sub>4</sub> C, SiO <sub>2</sub> (1 μm), carbon black                             | Spark plasma (40 MPa) | 1750 (×5 min)              | No            | 91.2                 | 33.1           | —                                          | —                      | —                     |
| B <sub>4</sub> C-20 vol% SiC <sup>96</sup> | B <sub>4</sub> C, SiO <sub>2</sub> (1 μm), carbon black                             | Spark plasma (40 MPa) | 1750 (×5 min)              | No            | 88.3                 | 32.1           | —                                          | —                      | —                     |
| B <sub>4</sub> C-SiC <sup>173</sup>        | B <sub>4</sub> C (125 μm: 12.8 μm = 2:1), carbon black, Si                          | Reaction              | 1500                       | No            | —                    | 31.2           | 4.49                                       | 322                    | —                     |
| B <sub>4</sub> C-SiC <sup>173</sup>        | B <sub>4</sub> C (125 μm: 12.8 μm = 2:1), carbon black, 6 vol% SiC whisker, Si      | Reaction              | 1500                       | No            | —                    | 31.0           | 4.64                                       | 285                    | —                     |
| B <sub>4</sub> C-SiC <sup>173</sup>        | B <sub>4</sub> C (125 μm: 12.8 μm = 2:1), carbon black, 12 vol% SiC whisker, Si     | Reaction              | 1500                       | No            | —                    | 30.4           | 4.67                                       | 265                    | —                     |
| B <sub>4</sub> C-SiC <sup>173</sup>        | B <sub>4</sub> C (125 μm: 12.8 μm = 2:1), carbon black, 18 vol% SiC whisker, Si     | Reaction              | 1500                       | No            | —                    | 28.9           | 4.73                                       | 254                    | —                     |
| B <sub>4</sub> C-SiC <sup>173</sup>        | B <sub>4</sub> C (125 μm: 12.8 μm = 2:1), carbon black, 24 vol% SiC whisker, Si     | Reaction              | 1500                       | No            | —                    | 27.6           | 4.88                                       | 243                    | —                     |
| B <sub>4</sub> C-SiC <sup>174</sup>        | B <sub>4</sub> C (0.24 μm), 10 vol% SiC whisker (diameter = 1.1 μm, length = 45 μm) | Hot-press (30 MPa)    | 2100                       | No            | >99%                 | 30.0           | 3.89                                       | 877                    | 439                   |
| B <sub>4</sub> C-SiC <sup>174</sup>        | B <sub>4</sub> C (0.24 μm), 20 vol% SiC whisker (diameter = 1.1 μm, length = 45 μm) | Hot-press (30 MPa)    | 2100                       | No            | >99%                 | 31.1           | 3.89                                       | 812                    | 429                   |
| B <sub>4</sub> C-SiC <sup>174</sup>        | B <sub>4</sub> C (0.24 μm), 30 vol% SiC whisker (diameter = 1.1 μm, length = 45 μm) | Hot-press (30 MPa)    | 2100                       | No            | >99%                 | 30.0           | 4.23                                       | 760                    | 426                   |

nano-carbon black, or microporous carbon can improve the mechanical properties of reaction-bonded  $B_4C$ -SiC ceramics, respectively. The addition of C can promote the sintering of  $B_4C$ -SiC ceramics; therefore, the increase in hardness and bending strength is attributed to the decrease in porosity of  $B_4C$ -SiC ceramics and a more uniform microstructure. The fracture mode of  $B_4C$ -SiC ceramics changes from a combination of intergranular and transgranular fracture to transgranular fracture only with the increase in C content from 0 to 10 vol%. However, excessive C (>10 vol% or >10 wt%) will lead to a decrease in mechanical properties for  $B_4C$ -SiC ceramics. The excessive C leads to the formation of larger-sized individual particles resulting from the aggregation of SiC and the formation of holes, which is attributed to the blockage of the channels from Si infiltration caused by the aggregation of SiC. Both the increase in grain size and the formation of holes deteriorate the mechanical properties of  $B_4C$ -SiC ceramics. Different from the research results mentioned above, Lee *et al.*<sup>152</sup> found that the hardness of SiC-30 wt%  $B_4C$  ceramics increases linearly with the increase in carbon black from 10 to 40 wt%. The increase in C content can increase the reactivity with Si, reducing the residual Si content in the final  $B_4C$ -SiC ceramics. Zhang *et al.*<sup>101</sup> introduced C in the form of a C layer deposited on  $B_4C$  particles into the preform. The mechanical properties of  $B_4C$ -SiC ceramics prepared from the C-coated  $B_4C$  particles are higher than those prepared from the mixture of uncoated  $B_4C$  and nano-carbon black. The C layer on  $B_4C$  particles can prevent the dissolution and reaction of  $B_4C$  grains in molten Si effectively; thus, the better mechanical properties of  $B_4C$ -SiC ceramics prepared from the C-coated  $B_4C$  particles are attributed to the higher relative density, higher  $B_4C$  content, the smaller grain size of  $B_4C$ , and the formation of many nano-SiC grains as well as a continuous ceramic skeleton of the nano-SiC grains-coated and -bonded  $B_4C$  grains, as mentioned in Section 3.5.2.3.

Furthermore, C can also be introduced in the form of fibers. On the one hand, carbon fibers can be used as a C source, and on the other hand, carbon fibers can also be used as a toughening phase.  $B_4C$ -SiC ceramics exhibit isotropic mechanical properties due to the homogeneous dispersion of the chopped carbon fibers. The main toughening mechanisms of carbon fibers in  $B_4C$ -SiC ceramics are considered to be fiber pullout and fiber debonding. Carbon fibers not only provide sufficient C for forming a ceramic skeleton structure but also control the distribution of residual Si. Song *et al.*<sup>85</sup> noted that the fracture toughness and bending strength of  $B_4C$ -SiC ceramics increase with an increase in carbon fibers content from 0 to 40 vol%. Carbon fibers can completely react with molten Si during Si infiltration, and there are no carbon fibers in the final  $B_4C$ -SiC ceramics. The residual Si content is decreased with the increase in carbon fibers content; also, the residual Si particles occupy the original positions of carbon fibers, forming fiber-like extensions, which is beneficial for lowering the defect sensitivity of the residual Si and controlling the size of the formed Si islands. However, the addition of an excess of carbon fibers (50 vol%) will generate too many  $\beta$ -SiC particles, causing a relatively high volume expansion, leading to the blockage of Si capillary channels and the formation of residual carbon fibers;

thus, the mechanical properties are reduced. It is worth noting that if carbon fibers are only used as a C source, it is unnecessary to take measures to protect the carbon fibers. In contrast, if carbon fibers are used as a toughening material, the structure and mechanical properties of carbon fibers are inevitably degraded due to the interfacial reaction during the infiltration; adding carbon black in the preform can protect the carbon fibers from erosion to some extent since the molten Si will preferentially react with the carbon black due to its higher specific surface area.<sup>176</sup>

Moreover, the addition of SiC in the preform can form the core-rim structure of primary  $\alpha$ -SiC surrounded by a secondary  $\beta$ -SiC rim (Section 3.5.2.1). Song *et al.*<sup>60</sup> mentioned that the mechanical properties of  $B_4C$ -SiC ceramics produced from the preform with the addition of SiC are higher than those of  $B_4C$ -SiC ceramics produced from the preform without the addition of SiC. This is because the formed SiC cannot nucleate and grow on the  $B_4C$  particles in the preform without the addition of SiC; thus, SiC formed and  $B_4C$  particles are distributed independently; a continuous ceramic skeleton is not formed. In contrast, in the preform with the addition of SiC, SiC formed can connect the original SiC particles to form a continuous ceramic skeleton, improving the mechanical properties.

Although better mechanical properties of reaction-bonded  $B_4C$ -SiC ceramics are achieved by generating the plate-like shaped SiC grains without adding free C in the preform, the addition of free C can improve the mechanical properties of  $B_4C$ -SiC ceramics by promoting the sintering performance and enhancing the microstructure. Therefore, the effect of free C on the mechanical properties of reaction-bonded  $B_4C$ -SiC ceramics is a competitive factor, which depends on the amount, form, *etc.* Some previous studies on the effect of C/SiC added in the preform on the mechanical properties of reaction-bonded  $B_4C$ -SiC ceramics are tabulated in Table 11.

#### 4.4. Preparation process

In addition to optimizing raw material formulations, some efforts have been devoted to studying how to improve the mechanical properties of  $B_4C$ -SiC ceramics by adjusting process parameters. The preparation process affects the mechanical properties of  $B_4C$ -SiC ceramics mainly by changing the microstructure.

**4.4.1. Preparation of the green body.** Pores in the green body affect the mechanical properties of the obtained  $B_4C$ -SiC ceramics. Compaction pressure can control the porosity and pore size of the green body. Meanwhile, adjusting the porosity and pore size of the green body can help control the content and size of residual Si in the reaction-bonded  $B_4C$ -SiC ceramics. Zong *et al.*<sup>177</sup> investigated the effect of forming pressure on the mechanical properties of reaction-bonded  $B_4C$ -SiC ceramics. With the increase in forming pressure from 50 to 200 MPa, the porosity of the green body decreases, leading to the decreased porosity of the obtained reaction-bonded  $B_4C$ -SiC ceramics and the decreased content of free Si filled in the remaining pores, both of which are beneficial for improving the mechanical properties of  $B_4C$ -SiC ceramics. However, when the forming pressure exceeds 200 MPa, the pores in the

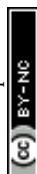


Table 11 Effect of C/SiC added in the preform on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics

| Ceramics                                   | Raw material                                                                                                          | Amount of C/SiC added (°C) | Sintering temperature (°C) | Residual Si content (%) | Relative density (%) | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|--------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|----------------------------|----------------------------|-------------------------|----------------------|----------------|--------------------------------------------|------------------------|-----------------------|
| B <sub>4</sub> C–SiC <sup>144</sup>        | B <sub>4</sub> C (5 µm), Si                                                                                           | 0 vol% C                   | 1650                       | —                       | 99.7                 | 17.1           | 2.70                                       | 268                    | —                     |
| B <sub>4</sub> C–SiC <sup>144</sup>        | B <sub>4</sub> C (5 µm), carbon black, Si                                                                             | 5 vol% C                   | 1650                       | —                       | 99.6                 | 18.9           | 3.96                                       | 305                    | —                     |
| B <sub>4</sub> C–SiC <sup>144</sup>        | B <sub>4</sub> C (5 µm), carbon black, Si                                                                             | 10 vol% C                  | 1650                       | —                       | 99.8                 | 19.6           | 3.83                                       | 358                    | —                     |
| B <sub>4</sub> C–SiC <sup>144</sup>        | B <sub>4</sub> C (5 µm), carbon black, Si                                                                             | 20 vol% C                  | 1650                       | —                       | 99.2                 | 15.3           | 3.10                                       | 226                    | —                     |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 µm), Si                                                                                        | 0 wt% C                    | 1550                       | —                       | 99.9                 | 19.2           | 3.65                                       | 267                    | —                     |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 µm), carbon black, Si                                                                          | 6 wt% C                    | 1550                       | —                       | 99.9                 | 21.3           | 4.30                                       | 318                    | —                     |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 µm), carbon black, Si                                                                          | 8 wt% C                    | 1550                       | —                       | 99.4                 | 24.0           | 4.74                                       | 336                    | —                     |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 µm), carbon black, Si                                                                          | 10 wt% C                   | 1550                       | —                       | 99.1                 | 24.4           | 4.41                                       | 361                    | —                     |
| B <sub>4</sub> C–SiC <sup>75</sup>         | B <sub>4</sub> C (4.08 µm), carbon black, Si                                                                          | 12 wt% C                   | 1550                       | —                       | 98.7                 | 19.0           | 4.20                                       | 275                    | —                     |
| B <sub>4</sub> C–SiC <sup>175</sup>        | B <sub>4</sub> C, microporous carbon, Si powder (200 mesh)                                                            | —                          | 1600                       | —                       | 98.4                 | 22.6           | 4.74                                       | 286                    | 332                   |
| SiC-30 wt% B <sub>4</sub> C <sup>152</sup> | α-SiC (77 µm : 3 µm = 7 : 3), B <sub>4</sub> C (15 µm), carbon black, Si powder (1 mm)                                | 10 wt% C                   | 1650                       | —                       | —                    | 25.0           | —                                          | —                      | —                     |
| SiC-30 wt% B <sub>4</sub> C <sup>152</sup> | α-SiC (77 µm : 3 µm = 7 : 3), B <sub>4</sub> C (15 µm), carbon black, Si powder (1 mm)                                | 20 wt% C                   | 1650                       | —                       | —                    | 27.6           | —                                          | —                      | —                     |
| SiC-30 wt% B <sub>4</sub> C <sup>152</sup> | α-SiC (77 µm : 3 µm = 7 : 3), B <sub>4</sub> C (15 µm), carbon black, Si powder (1 mm)                                | 30 wt% C                   | 1650                       | —                       | —                    | 34.5           | —                                          | —                      | —                     |
| SiC-30 wt% B <sub>4</sub> C <sup>152</sup> | α-SiC (77 µm : 3 µm = 7 : 3), B <sub>4</sub> C (15 µm), carbon black, Si powder (1 mm)                                | 40 wt% C                   | 1650                       | —                       | —                    | 37.3           | —                                          | —                      | —                     |
| B <sub>4</sub> C–SiC <sup>101</sup>        | C-coated B <sub>4</sub> C particles prepared via the pyrolysis and carbonization of phenolic resin, Si lump (5–10 mm) | 10 wt% C                   | 1600                       | —                       | 99.9                 | 24.0           | 4.80                                       | 316                    | —                     |
| B <sub>4</sub> C–SiC <sup>101</sup>        | B <sub>4</sub> C (2.14 µm), carbon black (22 mm), Si lump (5–10 mm)                                                   | 10 wt% C                   | 1600                       | —                       | 99.7                 | 19.0           | 3.50                                       | 457                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>85</sup>  | α-SiC (14 µm), B <sub>4</sub> C (1.5 µm), Si                                                                          | 0 wt% C                    | 1600                       | 39.0 wt%                | —                    | —              | 2.83                                       | 291                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>85</sup>  | α-SiC (14 µm), B <sub>4</sub> C (1.5 µm), carbon fibers (diameter = 6 µm, length = 3 mm), Si                          | 10 wt% C                   | 1600                       | 28.6 wt%                | —                    | —              | 3.24                                       | 320                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>85</sup>  | α-SiC (14 µm), B <sub>4</sub> C (1.5 µm), carbon fibers (diameter = 6 µm, length = 3 mm), Si                          | 20 wt% C                   | 1600                       | 19.9 wt%                | —                    | —              | 4.50                                       | 375                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>85</sup>  | α-SiC (14 µm), B <sub>4</sub> C (1.5 µm), carbon fibers (diameter = 6 µm, length = 3 mm), Si                          | 30 wt% C                   | 1600                       | 14.2 wt%                | —                    | —              | 6.58                                       | 414                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>85</sup>  | α-SiC (14 µm), B <sub>4</sub> C (1.5 µm), carbon fibers (diameter = 6 µm, length = 3 mm), Si                          | 40 wt% C                   | 1600                       | 7.1 wt%                 | —                    | —              | 7.50                                       | 465                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>85</sup>  | α-SiC (14 µm), B <sub>4</sub> C (1.5 µm), carbon fibers (diameter = 6 µm, length = 3 mm), Si                          | 50 wt% C                   | 1600                       | 5.3 wt%                 | —                    | —              | 2.89                                       | 262                    | —                     |
| B <sub>4</sub> C–SiC <sup>60</sup>         | B <sub>4</sub> C (14 µm), phenolic resin, Si                                                                          | 0 wt% SiC                  | 1600                       | —                       | —                    | —              | —                                          | 332                    | —                     |
| SiC-5 wt% B <sub>4</sub> C <sup>60</sup>   | B <sub>4</sub> C (14 µm), α-SiC (14 µm), carbon black, phenolic resin, Si                                             | 68 wt% SiC                 | 1600                       | 15.6 vol%               | —                    | —              | 4.06                                       | 325                    | —                     |
| SiC-15 wt% B <sub>4</sub> C <sup>60</sup>  | B <sub>4</sub> C (14 µm), α-SiC (14 µm), carbon black, phenolic resin, Si                                             | 58 wt% SiC                 | 1600                       | 14.8 vol%               | —                    | —              | 4.35                                       | 357                    | —                     |
| SiC-25 wt% B <sub>4</sub> C <sup>60</sup>  | B <sub>4</sub> C (14 µm), α-SiC (14 µm), carbon black, phenolic resin, Si                                             | 48 wt% SiC                 | 1600                       | 13.2 vol%               | —                    | —              | 4.58                                       | 407                    | —                     |
| SiC-35 wt% B <sub>4</sub> C <sup>60</sup>  | B <sub>4</sub> C (14 µm), α-SiC (14 µm), carbon black, phenolic resin, Si                                             | 38 wt% SiC                 | 1600                       | 13.7 vol%               | —                    | —              | 4.80                                       | 379                    | —                     |
| SiC-45 wt% B <sub>4</sub> C <sup>60</sup>  | B <sub>4</sub> C (14 µm), α-SiC (14 µm), carbon black, phenolic resin, Si                                             | 28 wt% SiC                 | 1600                       | 14.9 vol%               | —                    | —              | 5.12                                       | 367                    | —                     |



green body become too narrow to be penetrated by molten Si because of the occupation of the newly formed SiC particles, increasing the porosity of the obtained reaction-bonded B<sub>4</sub>C–SiC ceramics, thus decreasing the bending strength and fracture toughness. Besides the number of pores in the green body, the pore size in the green body can also affect the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics. Li *et al.*<sup>76</sup> stated that the porosity and pore size of the green body correspond to the volumetric fraction and size of the Si phase, respectively; the hardness of B<sub>4</sub>C–SiC ceramics increases with the decrease in residual Si size. Therefore, decreasing the pore size in the green body can also increase the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics.

Moreover, preliminary sintering for preforms before infiltration with molten Si can increase the relative density of preforms;<sup>142,156</sup> an additional step, namely, the preliminary sintering of preforms, is added, and a product with decreased Si content is obtained. However, Dariel and Frage<sup>99</sup> found that the preliminary sintering of preforms has little effect on the mechanical properties of the obtained reaction-bonded B<sub>4</sub>C–SiC ceramics, which is attributed to the rim structure connecting the original B<sub>4</sub>C grains in both the preliminary sintered preforms and the green preforms. Hayun *et al.*<sup>148</sup> also noted that the preliminary sintering of preforms has no effect on the static mechanical properties and on the dynamic response of the resulting reaction-bonded B<sub>4</sub>C–SiC ceramics, although preliminary sintering can lead to the formation of a continuous preform skeleton. This phenomenon is attributed to the similar final microstructures between the B<sub>4</sub>C–SiC ceramics produced from the preforms with and without preliminary sintering, *i.e.*, the rim regions composed of B<sub>12</sub>(B, C, Si)<sub>3</sub> connect the B<sub>4</sub>C grains in both types of reaction-bonded B<sub>4</sub>C–SiC ceramics.

In addition, the forming technique for the green body can affect the mechanical properties of the resulting B<sub>4</sub>C–SiC ceramics. Xu *et al.*<sup>100</sup> used the conventional compression molding method and gel-casting method to produce preforms composed of B<sub>4</sub>C and C, respectively, and found that the mechanical properties of the obtained reaction-bonded B<sub>4</sub>C–SiC ceramics produced by the gel-casting method are higher than those of the reaction-bonded B<sub>4</sub>C–SiC ceramics produced by the conventional compression molding method after the same liquid Si infiltration process. The higher mechanical properties are attributed to the microstructure of the obtained B<sub>4</sub>C–SiC ceramics, *viz.*, the continuous SiC-bonded B<sub>4</sub>C skeleton structure and decreased size of residual Si in the ceramics, resulting from the 3D-interconnected porous structure in the preform produced *via* the gel-casting route. Furthermore, residual Si inevitably exists in the reaction-bonded B<sub>4</sub>C–SiC ceramics; however, it is possible to improve their mechanical properties as far as possible by controlling the size of residual Si. Non-uniform residual stress distributes throughout if the residual Si size is larger than 5 µm, leading to defect generation due to the presence of anomalous tensile stress in the interior of residual Si.<sup>178</sup> Ren *et al.*<sup>103</sup> observed that adjusting the content of the catalyst Na<sub>2</sub>CO<sub>3</sub> in the resorcinol–formaldehyde gel system can help control the pore characteristics of the preform prepared by gel-

casting, which can improve the mechanical properties of the reaction-bonded B<sub>4</sub>C–SiC ceramics by controlling the content and size of residual Si. With an increase in catalyst content, on the one hand, the residual Si content is reduced; on the other hand, carbon particle size in the preform decreases, resulting in the decreased size of the SiC particles formed. However, as the size of carbon particles decreases to a nanometre size, nano-sized carbon particles undergo aggregation, leading to the formation of large-sized SiC particles and subsequent deterioration of mechanical properties due to the large residual stress during cooling. Also, the pore structure of the preform changes from a single macroporous or mesoporous structure to a hierarchical macroporous–mesoporous structure with the increase in catalyst content. The preform with a single mesoporous structure exhibits the best mechanical properties. Using the gel-casting method to produce the green body is a feasible and novel way to improve the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics.

Some previous studies on the effect of forming pressure and forming technique for the green body on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics are tabulated in Table 12.

**4.4.2. Parameters during sintering.** Parameters during sintering mainly affect the mechanical properties of B<sub>4</sub>C–SiC ceramics by changing their microstructure. Generally, fine grains are helpful in improving the mechanical properties of B<sub>4</sub>C–SiC ceramics. Meanwhile, high relative density, which can be achieved by increasing sintering temperature, prolonging holding time, and enhancing sintering pressure (if any), allows B<sub>4</sub>C–SiC ceramics to achieve better mechanical properties. It is worth noting that increasing the sintering temperature or prolonging the holding time can lead to grain coarsening, which is not conducive to improving the mechanical properties of B<sub>4</sub>C–SiC ceramics.

**4.4.2.1. Sintering temperature.** For B<sub>4</sub>C–SiC ceramics produced *via* pressureless sintering, Zhu *et al.*<sup>107</sup> reported that the hardness, bending strength, and fracture toughness of B<sub>4</sub>C–15 wt% SiC ceramics first increase and then decrease with an increase in sintering temperature in the range of 2100 to 2200 °C. When the sintering temperature is 2150 °C, the mechanical properties of B<sub>4</sub>C–SiC ceramics reach the maximum. With the increase in sintering temperature to 2150 °C, the improvement in mechanical properties of B<sub>4</sub>C–SiC ceramics is attributed to the following aspects: (1) the porosity of the ceramics is reduced, and the pores are mostly round or regular polygons, the characteristics of which can reduce stress concentration and increase the bending strength; (2) clean phase boundaries between B<sub>4</sub>C and SiC grains indicate that the bonding between B<sub>4</sub>C and SiC is strong (Fig. 8b), which has an vital influence on the mechanical properties of B<sub>4</sub>C–SiC ceramics; (3) graphite formed due to the crystallisation of the sintering aid of carbon black can hinder the movement of grain boundaries at the high temperature stage, improving the mechanical properties; (4) the phase boundary between B<sub>4</sub>C and graphite is clean and narrow, and such a semi-coherent interface with low stress results in a high bending strength; (5) the existence of SiC particles can cause crack deflection (Fig. 13a)



Table 12 Effect of forming pressure and forming technique for the green body on the mechanical properties of reaction-bonded B<sub>4</sub>C–SiC ceramics

| Ceramics                            | Raw material                                      | Forming technique of preform | Forming pressure (MPa) | Open porosity of the green body (%) | Sintering temperature (°C) | Open porosity (%) | Residual Si content (vol%) | Hardness (GPa) | Fracture toughness (MPa m <sup>1/2</sup> ) | Bending strength (MPa) | Young's modulus (GPa) |
|-------------------------------------|---------------------------------------------------|------------------------------|------------------------|-------------------------------------|----------------------------|-------------------|----------------------------|----------------|--------------------------------------------|------------------------|-----------------------|
| B <sub>4</sub> C–SiC <sup>177</sup> | B <sub>4</sub> C, carbon black, Si lump           | Compression molding          | 50                     | 49.4                                | 1550                       | 0.95              | 38.5                       | 16.8           | 3.80                                       | 246                    | —                     |
| B <sub>4</sub> C–SiC <sup>177</sup> | B <sub>4</sub> C, carbon black, Si lump           | Compression molding          | 100                    | 46.3                                | 1550                       | 0.40              | 32.8                       | 18.2           | 4.05                                       | 263                    | —                     |
| B <sub>4</sub> C–SiC <sup>177</sup> | B <sub>4</sub> C, carbon black, Si lump           | Compression molding          | 150                    | 44.3                                | 1550                       | 0.23              | 30.6                       | 21.9           | 4.28                                       | 283                    | —                     |
| B <sub>4</sub> C–SiC <sup>177</sup> | B <sub>4</sub> C, carbon black, Si lump           | Compression molding          | 200                    | 42.3                                | 1550                       | 0.19              | 28.8                       | 24.0           | 4.90                                       | 319                    | —                     |
| B <sub>4</sub> C–SiC <sup>177</sup> | B <sub>4</sub> C, carbon black, Si lump           | Compression molding          | 250                    | 41.7                                | 1550                       | 0.30              | 26.8                       | 24.6           | 4.59                                       | 310                    | —                     |
| B <sub>4</sub> C–SiC <sup>100</sup> | B <sub>4</sub> C (2.41 μm), carbon black, Si lump | Compression molding          | 200                    | 39.1                                | 1480                       | —                 | —                          | 17.4           | 3.61                                       | 330                    | —                     |
| B <sub>4</sub> C–SiC <sup>100</sup> | B <sub>4</sub> C (2.41 μm), carbon black, Si lump | Gel-casting                  | —                      | 37.7                                | 1480                       | —                 | —                          | 19.4           | 4.37                                       | 389                    | —                     |

that may occur because of the layered structure within SiC grains, crack branching (Fig. 13b), and crack bridging (Fig. 13c), prolonging the crack-propagation, inhibiting crack-tip propagation, and increasing the energy consumption; thus, the fracture toughness of the B<sub>4</sub>C–SiC ceramics is increased. However, a higher sintering temperature will lead to abnormal grain growth and increased porosity caused by the rapid movement of grain boundaries, which can deteriorate the mechanical properties of B<sub>4</sub>C–SiC ceramics.

For B<sub>4</sub>C–SiC ceramics prepared by hot-press sintering, Shi *et al.*<sup>83</sup> found that the hardness and bending strength of B<sub>4</sub>C–20 vol% SiC ceramics increase with an increase in sintering temperature from 1900 to 2100 °C, which is attributed to the reduced porosity with an increase in sintering temperature. The bending strength of B<sub>4</sub>C–SiC ceramics strongly depends on porosity, and the relationship between porosity ( $\theta$ ) and bending strength ( $\sigma_w$ ) of B<sub>4</sub>C–20 vol% SiC ceramics can be expressed as  $\sigma_w = 257 \exp(-2.18\theta)$ . Compared with pure B<sub>4</sub>C ceramics, the B<sub>4</sub>C–20 vol% SiC ceramics exhibit higher hardness after different sintering temperatures; however, the bending strength of B<sub>4</sub>C–20 vol% SiC ceramics is higher than that of pure B<sub>4</sub>C ceramics only after sintering at 1900 °C, and the bending strength of B<sub>4</sub>C–20 vol% SiC ceramics is slightly lower than that of pure B<sub>4</sub>C ceramics after sintering at 2000 and 2100 °C. Zhang *et al.*<sup>98</sup> stated that the hardness and bending strength of B<sub>4</sub>C–50 wt% SiC ceramics increase linearly with the increase in sintering temperature in the range of 1800–1950 °C, which is attributed to the gradually increased densification; however, the fracture roughness of the ceramics first increases and then decreases. When the sintering temperature is 1850 °C, the fracture toughness reaches the maximum because there are a number of pores inside the ceramics sintered at that temperature and these pores can consume fracture energy when cracks pass through them. Chen *et al.*<sup>110</sup> reported that the mechanical properties of B<sub>4</sub>C–20 wt% SiC ceramics increase with the increase in sintering temperature from 1800 to 1900 °C, which is attributed to the smaller grains and denser microstructure at higher sintering temperatures. The B<sub>4</sub>C–20 wt% SiC ceramics exhibit better mechanical properties than the pure B<sub>4</sub>C ceramics. The fracture mode of the B<sub>4</sub>C–20 wt% SiC ceramics is mainly transgranular fracture at any temperature; however, partial crack deflection and grain pullout are enhanced with an increase in sintering temperature (Fig. 14).

For spark plasma sintered B<sub>4</sub>C–SiC ceramics, Wu *et al.*<sup>111</sup> observed that the hardness and fracture toughness of B<sub>4</sub>C–20 vol% SiC ceramics increase with the increase in sintering temperature from 1900 to 2000 °C. The improved mechanical properties are attributed to the increased relative density with the increase in sintering temperature, independent of the phase change because no new phases are formed during sintering. When the sintering temperature is higher than 2000 °C, the change in mechanical properties of B<sub>4</sub>C–20 vol% SiC ceramics is not obvious. The increased sintering temperature does not change the mode of crack propagation, that is, the fracture mechanism of the ceramics sintered at different sintering temperatures is the transgranular fracture. However, the number of



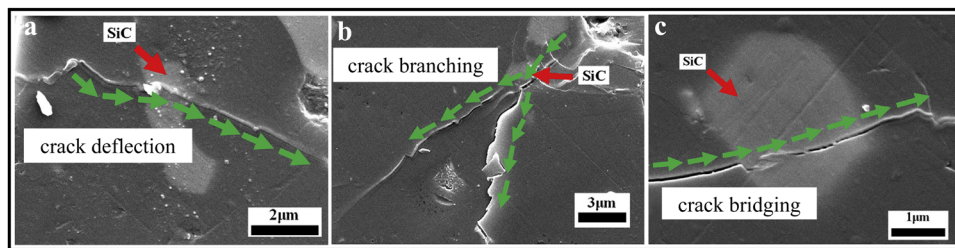


Fig. 13 Crack propagation on the surface of pressureless sintered  $B_4C$ -15 wt% SiC ceramics: (a) crack deflection, (b) crack branching, and (c) crack bridging<sup>107</sup> (reprinted with permission, Copyright 2019, Elsevier).

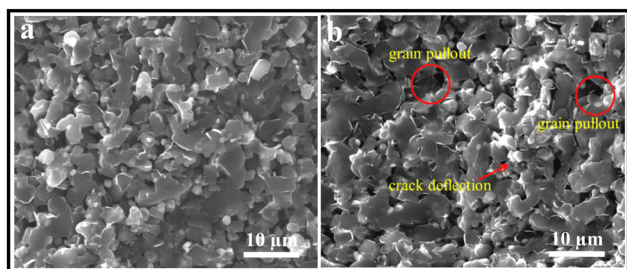


Fig. 14 Fracture surfaces of hot-press sintered  $B_4C$ -20 wt% SiC ceramics at different sintering temperatures: (a) 1800 °C and (b) 1900 °C.<sup>110</sup>

pores in the ceramics gradually decreases with the increase in sintering temperature; thus, the crack propagation is more hindered. Also, the reduction of porosity can increase the probability of cracks passing through the SiC grains, resulting in a significant increase in fracture toughness.

For  $B_4C$ -SiC ceramics fabricated by reaction-bonded sintering, sintering temperature can alter phase volume fractions. Zhang *et al.*<sup>117</sup> found that the hardness, fracture toughness, and bending strength of  $B_4C$ -SiC ceramics increase with the increase in infiltration temperature from 1450 to 1600 °C. The improved hardness and bending strength are attributed to the gradually decreased porosity, and the increased fracture toughness is caused by the increased *in situ* formed SiC with a layered structure. When the infiltration temperature is more than 1600 °C, the fracture toughness increases continuously; however, the hardness and bending strength decrease, resulting from the increased porosity and the larger flaws due to the increased grain size of  $B_4C$  particles and the presence of large SiC zones.

**4.4.2.2. Holding time.** Tomohiro *et al.*<sup>78</sup> reported that the bending strength and fracture toughness of the hot-press sintered  $B_4C$ -15 vol% SiC ceramics decrease with the increase in holding time from 0.5 to 2 h when the sintering temperature is 2200 °C, which is attributed to the increased grain size and the increased flaw size in the ceramics with the increase in holding time.

**4.4.2.3. Sintering pressure.** Chen *et al.*<sup>122</sup> noted that the mechanical properties of hot-press sintered  $B_4C$ -20 wt% SiC ceramics increase with the increase in sintering pressure from 30 to 40 MPa, which is attributed to the increased relative density and decreased grain size of the  $B_4C$ -SiC ceramics with the increase in sintering pressure. The fracture mode of the  $B_4C$ -SiC ceramics

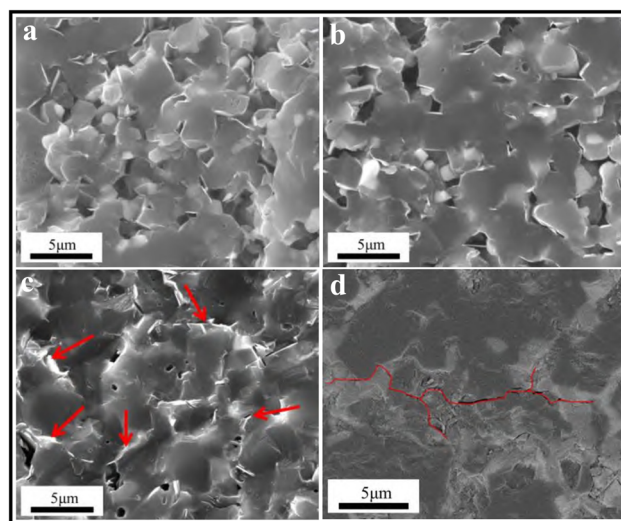


Fig. 15 Fracture surfaces of hot-press sintered  $B_4C$ -20 wt% SiC ceramics produced at different sintering pressures: (a) 30 MPa, (b) 35 MPa, and (c) 40 MPa.<sup>122</sup> (d) Indentation crack deflection in hot-press sintered  $B_4C$ -20 wt% SiC ceramics produced at a sintering pressure of 40 MPa.<sup>122</sup>

is mainly transgranular fracture at different sintering pressures (Fig. 15a-c); however, cracks tend to deflect with the increase in sintering pressure. The residual stress is caused due to different thermal expansion coefficients between  $B_4C$  and SiC during hot-press sintering, forming the microcracks at the weak interface between  $B_4C$  and SiC because the hot-press sintered  $B_4C$ -20 wt% SiC ceramics are produced by liquid-phase sintering with  $Al_2O_3$  and  $Y_2O_3$  as sintering aids. When the sintering pressure is low, the microstructure is loose; thus, it is difficult to generate a crack deflection effect, leading to lower fracture toughness. However, under high sintering pressure, when the fracture crack extends to the microcrack, it will preferentially orient in the direction of the microcrack (Fig. 15d), so that the fracture crack will deflect and bifurcate, improving the fracture toughness.

Some previous studies on the effect of parameters during sintering on the mechanical properties of  $B_4C$ -SiC ceramics are tabulated in Table 13.

## 4.5. Sintering aids

The addition of sintering aids can promote the sintering of  $B_4C$ -SiC ceramics *via* solid-state sintering or liquid-phase sintering





**Table 13** Effect of parameters during sintering on the mechanical properties of  $B_4C-SiC$  ceramics

| Ceramics                  | Raw material                                         | Sintering method | Sintering temperature (°C) | Holding time | Sintering pressure (MPa) | Sintering aid                 | Relative density (%) | Hardness (GPa) | Fracture toughness ( $MPa\ m^{1/2}$ ) | Bending strength (MPa) | Young's modulus (GPa) |
|---------------------------|------------------------------------------------------|------------------|----------------------------|--------------|--------------------------|-------------------------------|----------------------|----------------|---------------------------------------|------------------------|-----------------------|
| $B_4C-15\ wt\% SiC^{107}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Pressureless     | 2100                       | 1 h          | No                       | 2 wt% carbon black            | 91.6                 | 16.2           | 2.20                                  | 145                    | —                     |
| $B_4C-15\ wt\% SiC^{107}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Pressureless     | 2125                       | 1 h          | No                       | 2 wt% carbon black            | 93.6                 | 22.1           | 2.60                                  | 231                    | —                     |
| $B_4C-15\ wt\% SiC^{107}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Pressureless     | 2150                       | 1 h          | No                       | 2 wt% carbon black            | 95.3                 | 25.5           | 2.81                                  | 296                    | —                     |
| $B_4C-15\ wt\% SiC^{107}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Pressureless     | 2175                       | 1 h          | No                       | 2 wt% carbon black            | 93.1                 | 22.0           | 2.40                                  | 193                    | —                     |
| $B_4C^{83}$               | $B_4C$ (10.22 $\mu m$ )                              | Hot-press        | 1900                       | 1 h          | 20                       | No                            | 71.9                 | 3.2            | —                                     | 134                    | —                     |
| $B_4C-20\ vol\% SiC^{83}$ | $B_4C$ (10.22 $\mu m$ ), $\beta-SiC$ (1.07 $\mu m$ ) | Hot-press        | 1900                       | 1 h          | 20                       | No                            | 73.7                 | 3.7            | —                                     | 150                    | —                     |
| $B_4C^{83}$               | $B_4C$ (10.22 $\mu m$ )                              | Hot-press        | 2000                       | 1 h          | 20                       | No                            | 77.0                 | 5.0            | —                                     | 164                    | —                     |
| $B_4C-20\ vol\% SiC^{83}$ | $B_4C$ (10.22 $\mu m$ ), $\beta-SiC$ (1.07 $\mu m$ ) | Hot-press        | 2000                       | 1 h          | 20                       | No                            | 77.8                 | 6.1            | —                                     | 153                    | —                     |
| $B_4C^{83}$               | $B_4C$ (10.22 $\mu m$ )                              | Hot-press        | 2100                       | 1 h          | 20                       | No                            | 87.9                 | 11.5           | —                                     | 196                    | —                     |
| $B_4C-20\ vol\% SiC^{83}$ | $B_4C$ (10.22 $\mu m$ ), $\beta-SiC$ (1.07 $\mu m$ ) | Hot-press        | 2100                       | 1 h          | 20                       | No                            | 87.0                 | 12.8           | —                                     | 194                    | —                     |
| $B_4C-50\ wt\% SiC^{98}$  | $B_4C$ , $SiC$ , mean particle size of 0.7 $\mu m$   | Hot-press        | 1800                       | 0.5 h        | 30                       | No                            | 74.0                 | 6.0            | 3.20                                  | 214                    | —                     |
| $B_4C-50\ wt\% SiC^{98}$  | $B_4C$ , $SiC$ , mean particle size of 0.7 $\mu m$   | Hot-press        | 1850                       | 0.5 h        | 30                       | No                            | 79.2                 | 8.0            | 5.20                                  | 263                    | —                     |
| $B_4C-50\ wt\% SiC^{98}$  | $B_4C$ , $SiC$ , mean particle size of 0.7 $\mu m$   | Hot-press        | 1900                       | 0.5 h        | 30                       | No                            | 89.2                 | 18.0           | 4.90                                  | 366                    | —                     |
| $B_4C-50\ wt\% SiC^{98}$  | $B_4C$ , $SiC$ , mean particle size of 0.7 $\mu m$   | Hot-press        | 1950                       | 0.5 h        | 30                       | No                            | 96.4                 | 24.0           | 4.60                                  | 430                    | —                     |
| $B_4C^{110}$              | $B_4C$ (0.8 $\mu m$ )                                | Hot-press        | 1800                       | 0.5 h        | 30                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 97.2                 | 8.2            | 2.58                                  | 257                    | —                     |
| $B_4C-20\ wt\% SiC^{110}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.45 $\mu m$ )         | Hot-press        | 1800                       | 0.5 h        | 30                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 94.0                 | 12.0           | 3.28                                  | 237                    | —                     |
| $B_4C^{110}$              | $B_4C$ (0.8 $\mu m$ )                                | Hot-press        | 1900                       | 0.5 h        | 30                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 98.6                 | 20.0           | 4.01                                  | 264                    | —                     |
| $B_4C-20\ wt\% SiC^{111}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.45 $\mu m$ )         | Hot-press        | 1900                       | 0.5 h        | 30                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 98.5                 | 17.0           | 4.79                                  | 313                    | —                     |
| $B_4C-20\ wt\% SiC^{111}$ | $B_4C$ (3.5 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Spark plasma     | 1900                       | 10 min       | 40                       | No                            | 90.1                 | 16.7           | 3.93                                  | —                      | —                     |
| $B_4C-20\ wt\% SiC^{111}$ | $B_4C$ (3.5 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Spark plasma     | 1950                       | 10 min       | 40                       | No                            | 91.0                 | 17.2           | 4.12                                  | —                      | —                     |
| $B_4C-20\ wt\% SiC^{111}$ | $B_4C$ (3.5 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Spark plasma     | 2000                       | 10 min       | 40                       | No                            | 96.3                 | 32.4           | 4.78                                  | —                      | —                     |
| $B_4C-20\ wt\% SiC^{111}$ | $B_4C$ (3.5 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Spark plasma     | 2050                       | 10 min       | 40                       | No                            | 96.6                 | 32.9           | 4.74                                  | —                      | —                     |
| $B_4C-20\ wt\% SiC^{111}$ | $B_4C$ (3.5 $\mu m$ ), $SiC$ (0.5 $\mu m$ )          | Spark plasma     | 2100                       | 10 min       | 40                       | No                            | 96.8                 | 33.4           | 4.68                                  | —                      | —                     |
| $B_4C-SiC^{117}$          | $B_4C$ (4.08 $\mu m$ ), carbon black, Si lump        | Reaction         | 1450                       | 1 h          | No                       | No                            | 99.8                 | 15.0           | 3.33                                  | 312                    | —                     |
| $B_4C-SiC^{117}$          | $B_4C$ (4.08 $\mu m$ ), carbon black, Si lump        | Reaction         | 1500                       | 1 h          | No                       | No                            | 99.8                 | 16.9           | 3.63                                  | 315                    | —                     |
| $B_4C-SiC^{117}$          | $B_4C$ (4.08 $\mu m$ ), carbon black, Si lump        | Reaction         | 1550                       | 1 h          | No                       | No                            | 99.9                 | 17.0           | 3.66                                  | 319                    | —                     |
| $B_4C-SiC^{117}$          | $B_4C$ (4.08 $\mu m$ ), carbon black, Si lump        | Reaction         | 1600                       | 1 h          | No                       | No                            | 99.9                 | 19.0           | 3.80                                  | 344                    | —                     |
| $B_4C-SiC^{117}$          | $B_4C$ (4.08 $\mu m$ ), carbon black, Si lump        | Reaction         | 1650                       | 1 h          | No                       | No                            | 99.8                 | 13.7           | 3.97                                  | 290                    | —                     |
| $B_4C-15\ vol\% SiC^{78}$ | $B_4C$ (0.72 $\mu m$ ), $\beta-SiC$ (0.3 $\mu m$ )   | Hot-press        | 2200                       | 0.5 h        | 30                       | No                            | 99.7                 | —              | 4.73                                  | 680                    | —                     |
| $B_4C-15\ vol\% SiC^{78}$ | $B_4C$ (0.72 $\mu m$ ), $\beta-SiC$ (0.3 $\mu m$ )   | Hot-press        | 2200                       | 1 h          | 30                       | No                            | 99.7                 | —              | 4.70                                  | 553                    | —                     |
| $B_4C-15\ vol\% SiC^{78}$ | $B_4C$ (0.72 $\mu m$ ), $\beta-SiC$ (0.3 $\mu m$ )   | Hot-press        | 2200                       | 2 h          | 30                       | No                            | 99.7                 | —              | 4.20                                  | 396                    | —                     |
| $B_4C-15\ vol\% SiC^{78}$ | $B_4C$ (0.72 $\mu m$ ), $\beta-SiC$ (0.3 $\mu m$ )   | Hot-press        | 1900                       | 0.5 h        | 30                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 98.5                 | 17.0           | 4.79                                  | 313                    | —                     |
| $B_4C-20\ wt\% SiC^{122}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.45 $\mu m$ )         | Hot-press        | 1900                       | 0.5 h        | 35                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 98.6                 | 25.7           | 6.94                                  | 366                    | —                     |
| $B_4C-20\ wt\% SiC^{122}$ | $B_4C$ (0.8 $\mu m$ ), $SiC$ (0.45 $\mu m$ )         | Hot-press        | 1900                       | 0.5 h        | 40                       | 10 wt% ( $Al_2O_3 + Y_2O_3$ ) | 99.0                 | 32.6           | 7.21                                  | 448                    | —                     |

(Section 3.4). In general, under the liquid-phase sintering mechanism, amorphous secondary phases remain at the phase boundary of the composite ceramics. Accordingly, numerous processes, such as creep, diffusion, crack growth, oxidation, and corrosion will occur during the applications depending on the amount and the composition of boundary phases, which can affect the performance, especially at high temperatures, and even shorten the service life of ceramics.<sup>179</sup> Compared with liquid-phase sintering, the ceramics can achieve better high-temperature performance under the solid-state sintering mechanism. Different sintering aids have different effects on the mechanical properties of  $B_4C$ -SiC ceramics. Some types of sintering aids benefit only the densification of  $B_4C$ -SiC ceramics, not their mechanical properties.

**4.5.1. C.** Moshtaghioun *et al.*<sup>112</sup> reported that the graphite sintering aid can promote the densification of the spark plasma sintered  $B_4C$ -15 wt% SiC ceramics; however, the addition of graphite increases the sizes of both  $B_4C$  and SiC grains, thus decreasing the hardness and fracture toughness of the ceramics. Meanwhile, the residual graphite softens the  $B_4C$ -SiC ceramics and weakens the interface between the  $B_4C$  and SiC grains.

In addition, the graphite sintering aid also has an effect on the creep resistance of  $B_4C$ -SiC ceramics at high temperatures.<sup>126</sup> The total deformation of  $B_4C$ -SiC ceramics with 2 wt% graphite and without graphite is 25% and 30%, respectively. In the case of  $B_4C$ -SiC ceramics with graphite after deformation, the cavitation that is created during deformation occurs in the ceramics; however, the complicated networks of dislocations, twinning, and trapped dislocations in twins are the main characteristics in the  $B_4C$ -SiC ceramics without graphite. In the absence of graphite, the  $B_4C$ -SiC ceramics show a similar plastic behavior as pure  $B_4C$  polycrystalline ceramics. In the presence of graphite, the deformation of  $B_4C$ -SiC ceramics is controlled by either solution-precipitation or grain sliding controlled by the viscosity of the glassy phase. The creep resistance of  $B_4C$ -SiC ceramics is strongly dependent on the presence of a graphite layer along the grain boundary. For the  $B_4C$ -SiC ceramics with graphite, grain boundary sliding is a more favorable process under creep, permitting ductility to be increased to a greater strain value. Therefore, due to an enhanced creep resistance,  $B_4C$ -SiC ceramics with graphite opens up new perspectives of structural materials with complex shapes for high-temperature applications.

**4.5.2. Oxide.** Jamale and Kumar<sup>127</sup> studied the effect of  $Al_2O_3$  addition on the mechanical properties of spark plasma sintered  $B_4C$ -10 wt% SiC ceramics. With an increase in the amount of relatively softer  $Al_2O_3$  from 3 to 6 wt%, the hardness of  $B_4C$ -10 wt% SiC ceramics slightly decreases, but the fracture toughness increases. Transgranular fracture is still the dominant fracture mode in the  $B_4C$ -10 wt% SiC ceramics after the addition of  $Al_2O_3$ , resulting from the minor difference in thermal expansion coefficients between  $B_4C$  and SiC. Sahin *et al.*<sup>96</sup> observed that the addition of 5 wt%  $Y_2O_3$  can slightly enhance the hardness of spark plasma sintered  $B_4C$ -SiC ceramics, which is attributed to the improved relative density resulting from the formation of glassy phases. Rocha and Melo<sup>88</sup> found that the pressureless sintered  $B_4C$ -10 wt% SiC ceramics with the addition

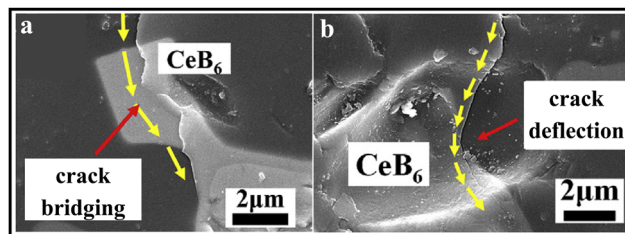


Fig. 16 Crack propagating on the surface of pressureless sintered  $B_4C$ -15 wt% SiC ceramics with the sintering aid of 5 wt%  $CeO_2$ : (a) crack bridging and (b) crack deflection<sup>129</sup> (reproduced with permission, Copyright 2013, Elsevier).

of sintering aids of  $AlN$ - $Y_2O_3$  can achieve higher hardness than that with the addition of sintering aids of  $Al_2O_3$ - $Y_2O_3$ , which is attributed to the higher relative density of  $B_4C$ -10 wt% SiC ceramics after the addition of  $AlN$ - $Y_2O_3$ . Zhu *et al.*<sup>129</sup> reported that an appropriate amount of sintering aid  $CeO_2$  can improve the mechanical properties of pressureless sintered  $B_4C$ -15 wt% SiC ceramics. On the one hand,  $CeB_6$  grains formed *in situ* via the reaction between  $B_4C$  and  $CeO_2$  disperse on the  $B_4C$  grain boundaries; these  $CeB_6$  grains can inhibit the movement of grain boundary, which is beneficial for inhibiting grain growth and refining grains. On the other hand, a residual stress field is formed around the  $CeB_6$  grains during the cooling process due to the higher thermal expansion coefficient of  $CeB_6$  than that of SiC and  $B_4C$ ,<sup>180</sup> contributing to improved fracture toughness for  $B_4C$ -SiC ceramics. The toughening mechanisms are crack deflection owing to the thermal expansion mismatch between  $CeB_6$  and  $B_4C$  and crack bridging at the crack tip by the  $CeB_6$  grain (Fig. 16). However, the addition of excessive  $CeO_2$  will increase the porosity of  $B_4C$ -SiC ceramics, leading to the reduction in mechanical properties.

**4.5.3. Si.** Du *et al.*<sup>132</sup> stated that the addition of sintering aid Si can improve the mechanical properties of hot-press sintered  $B_4C$ -15 wt% SiC ceramics, in which SiC is obtained from PCS after pyrolyzing. On the one hand, Si forms a liquid phase at high temperatures, promoting densification and decreasing residual porosity; on the other hand, Si can react with residual C generated from the pyrolysis of PCS to form SiC, removing the soft C-rich phase that can reduce the hardness of  $B_4C$ -SiC ceramics. However, Sahani and Chaira<sup>131</sup> found that the addition of sintering aid Si in the range of 2–20 wt% cannot enhance the hardness of  $B_4C$ -60 wt% SiC ceramics produced by pressureless sintering or spark plasma sintering, although the relative density of the  $B_4C$ -60 wt% SiC ceramics is increased after the addition of Si. The hardness of  $B_4C$ -60 wt% SiC ceramics containing 10 wt% Si is close to that of  $B_4C$ -60 wt% SiC ceramics without Si, which is attributed to the reduced pore size and refined microstructure resulting from the sufficient Si addition. The addition of excessive Si will produce a large amount of residual Si in the matrix, reducing the hardness of the  $B_4C$ -60 wt% SiC ceramics.

Some previous studies on the effect of sintering aids on the mechanical properties of  $B_4C$ -SiC ceramics are tabulated in Table 14.

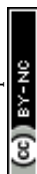


Table 14 Effect of sintering aids on the mechanical properties of  $B_4C-SiC$  ceramics

| Ceramics                   | Raw material                                      | Sintering aid                                       | Sintering method      | Sintering temperature (°C) | Relative density (%) | Hardness (GPa) | Fracture toughness ( $MPa\ m^{1/2}$ ) | Bending strength (MPa) | Young's modulus (GPa) |
|----------------------------|---------------------------------------------------|-----------------------------------------------------|-----------------------|----------------------------|----------------------|----------------|---------------------------------------|------------------------|-----------------------|
| $B_4C-15\ wt\%\ SiC^{112}$ | $B_4C$ (0.5 $\mu m$ ), $\beta-SiC$ (0.5 $\mu m$ ) | No                                                  | Spark plasma (75 MPa) | 1650 ( $\times 3$ min)     | 96.6                 | 30.3           | 6.0                                   | —                      | —                     |
| $B_4C-15\ wt\%\ SiC^{112}$ | $B_4C$ (0.5 $\mu m$ ), $\beta-SiC$ (0.5 $\mu m$ ) | 2 wt% graphite                                      | Spark plasma (75 MPa) | 1650 ( $\times 3$ min)     | 98.8                 | 25.7           | 5.5                                   | —                      | —                     |
| $B_4C-15\ wt\%\ SiC^{112}$ | $B_4C$ (0.5 $\mu m$ ), $\beta-SiC$ (0.5 $\mu m$ ) | No                                                  | Spark plasma (75 MPa) | 1700 ( $\times 3$ min)     | 99.4                 | 36.2           | 5.7                                   | —                      | —                     |
| $B_4C-15\ wt\%\ SiC^{112}$ | $B_4C$ (0.5 $\mu m$ ), $\beta-SiC$ (0.5 $\mu m$ ) | 2 wt% graphite                                      | Spark plasma (75 MPa) | 1700 ( $\times 3$ min)     | 100.0                | 29.3           | 5.3                                   | —                      | —                     |
| $B_4C-10\ wt\%\ SiC^{127}$ | $B_4C$ , SiC                                      | 3 wt% $Al_2O_3$                                     | Spark plasma (40 MPa) | 1800 ( $\times 10$ min)    | 99.5                 | 35.1           | 5.9                                   | —                      | —                     |
| $B_4C-10\ wt\%\ SiC^{127}$ | $B_4C$ , SiC                                      | 6 wt% $Al_2O_3$                                     | Spark plasma (40 MPa) | 1800 ( $\times 10$ min)    | 99.1                 | 33.7           | 6.5                                   | —                      | —                     |
| $B_4C-5\ vol\%\ SiC^{96}$  | $B_4C$ , $\alpha-SiC$                             | No                                                  | Spark plasma (40 MPa) | 1750 ( $\times 5$ min)     | 98.0                 | 34.4           | —                                     | —                      | —                     |
| $B_4C-5\ vol\%\ SiC^{96}$  | $B_4C$ , $\alpha-SiC$                             | 5 wt% $Y_2O_3$                                      | Spark plasma (40 MPa) | 1750 ( $\times 5$ min)     | 98.3                 | 35.3           | —                                     | —                      | —                     |
| $B_4C-10\ vol\%\ SiC^{96}$ | $B_4C$ , $\alpha-SiC$                             | No                                                  | Spark plasma (40 MPa) | 1750 ( $\times 5$ min)     | 98.0                 | 33.4           | —                                     | —                      | —                     |
| $B_4C-10\ vol\%\ SiC^{96}$ | $B_4C$ , $\alpha-SiC$                             | 5 wt% $Y_2O_3$                                      | Spark plasma (40 MPa) | 1750 ( $\times 5$ min)     | 98.8                 | 34.4           | —                                     | —                      | —                     |
| $B_4C-15\ vol\%\ SiC^{96}$ | $B_4C$ , $\alpha-SiC$                             | No                                                  | Spark plasma (40 MPa) | 1750 ( $\times 5$ min)     | 97.8                 | 31.1           | —                                     | —                      | —                     |
| $B_4C-15\ vol\%\ SiC^{96}$ | $B_4C$ , $\alpha-SiC$                             | 5 wt% $Y_2O_3$                                      | Spark plasma (40 MPa) | 1750 ( $\times 5$ min)     | 98.2                 | 33.0           | —                                     | —                      | —                     |
| $B_4C-10\ wt\%\ SiC^{88}$  | $B_4C$ , $\beta-SiC$                              | 10 vol% ( $Al_2O_3 : Y_2O_3 = 5 : 3$ , molar ratio) | Pressureless          | 2000                       | 91.5                 | 29.5           | —                                     | —                      | —                     |
| $B_4C-10\ wt\%\ SiC^{88}$  | $B_4C$ , $\beta-SiC$                              | 10 vol% (AIN : $Y_2O_3 = 3 : 2$ , molar ratio)      | Pressureless          | 2000                       | 93.4                 | 30.3           | —                                     | —                      | —                     |
| $B_4C-15\ wt\%\ SiC^{129}$ | $B_4C$ (0.8 $\mu m$ ), SiC (0.5 $\mu m$ )         | No                                                  | Pressureless          | 2150                       | 85.8                 | 19.8           | 2.40                                  | 194                    | —                     |
| $B_4C-15\ wt\%\ SiC^{129}$ | $B_4C$ (0.8 $\mu m$ ), SiC (0.5 $\mu m$ )         | 1 wt% $CeO_2$                                       | Pressureless          | 2150                       | 91.2                 | 26.0           | 3.25                                  | 270                    | —                     |
| $B_4C-15\ wt\%\ SiC^{129}$ | $B_4C$ (0.8 $\mu m$ ), SiC (0.5 $\mu m$ )         | 3 wt% $CeO_2$                                       | Pressureless          | 2150                       | 92.6                 | 29.4           | 3.59                                  | 330                    | —                     |
| $B_4C-15\ wt\%\ SiC^{129}$ | $B_4C$ (0.8 $\mu m$ ), SiC (0.5 $\mu m$ )         | 5 wt% $CeO_2$                                       | Pressureless          | 2150                       | 96.4                 | 32.2           | 4.32                                  | 380                    | —                     |
| $B_4C-15\ wt\%\ SiC^{129}$ | $B_4C$ (0.8 $\mu m$ ), SiC (0.5 $\mu m$ )         | 7 wt% $CeO_2$                                       | Pressureless          | 2150                       | 94.6                 | 29.0           | 4.19                                  | 350                    | —                     |
| $B_4C-15\ wt\%\ SiC^{129}$ | $B_4C$ (0.8 $\mu m$ ), SiC (0.5 $\mu m$ )         | 9 wt% $CeO_2$                                       | Pressureless          | 2150                       | 93.4                 | 27.0           | 4.00                                  | 330                    | —                     |
| $B_4C-15\ wt\%\ SiC^{132}$ | $B_4C$ (3.5 $\mu m$ ), PCS                        | No                                                  | Hot-press (30 MPa)    | 1950                       | 95.4                 | 24.0           | 4.96                                  | 265                    | —                     |
| $B_4C-15\ wt\%\ SiC^{132}$ | $B_4C$ (3.5 $\mu m$ ), PCS                        | 4 wt% Si                                            | Hot-press (30 MPa)    | 1950                       | 95.8                 | 26.4           | 5.06                                  | 260                    | —                     |
| $B_4C-15\ wt\%\ SiC^{132}$ | $B_4C$ (3.5 $\mu m$ ), PCS                        | 8 wt% Si                                            | Hot-press (30 MPa)    | 1950                       | 97.8                 | 29.8           | 5.34                                  | 324                    | —                     |
| $B_4C-15\ wt\%\ SiC^{132}$ | $B_4C$ (3.5 $\mu m$ ), PCS                        | 11.4 wt% Si                                         | Hot-press (30 MPa)    | 1950                       | 99.2                 | 33.2           | 5.64                                  | 389                    | —                     |
| $B_4C-15\ wt\%\ SiC^{132}$ | $B_4C$ (3.5 $\mu m$ ), PCS                        | 15 wt% Si                                           | Hot-press (30 MPa)    | 1950                       | 98.3                 | 31.0           | 5.40                                  | 350                    | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | No                                                  | Pressureless          | 1950                       | 89.0                 | 20.0           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 2 wt% Si                                            | Pressureless          | 1950                       | 88.0                 | 14.0           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 5 wt% Si                                            | Pressureless          | 1950                       | 89.0                 | 16.2           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 10 wt% Si                                           | Pressureless          | 1950                       | 92.0                 | 18.1           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 20 wt% Si                                           | Pressureless          | 1950                       | 90.0                 | 15.0           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | No                                                  | Spark plasma (50 MPa) | 1600 ( $\times 5$ min)     | 94.0                 | 28.0           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 2 wt% Si                                            | Spark plasma (50 MPa) | 1350 ( $\times 5$ min)     | 94.6                 | 22.0           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 5 wt% Si                                            | Spark plasma (50 MPa) | 1350 ( $\times 5$ min)     | 96.3                 | 24.4           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 10 wt% Si                                           | Spark plasma (50 MPa) | 1350 ( $\times 5$ min)     | 98.0                 | 27.8           | —                                     | —                      | —                     |
| $B_4C-60\ wt\%\ SiC^{131}$ | $B_4C$ , SiC                                      | 20 wt% Si                                           | Spark plasma (50 MPa) | 1350 ( $\times 5$ min)     | 97.0                 | 24.0           | —                                     | —                      | —                     |

## 5. Future development trend

$B_4C$ -SiC composite ceramics have emerged as a novel structural ceramic material for engineering applications. Looking forward, several aspects need to be further researched to enhance the understanding and fulfill their wide applications.

### 5.1. Investigation of high-temperature performance and other properties

$B_4C$ -SiC ceramics are dimensionally and structurally stable against a wide range of temperature variations due to chemical inertness and high-temperature resistance. High-temperature-resistant ceramics have the potential to have a significant impact on improving energy efficiency. The application of lightweight ceramics can lead to energy saving in various fields like the chemical industry, environment, automobile, aircraft engine parts, and power. As a potential high-temperature structural component, the mechanical properties of  $B_4C$ -SiC ceramics at high temperatures need to be further investigated.

Currently, the investigation for  $B_4C$ -SiC ceramics is mostly focused on conventional mechanical properties evaluation, and other mechanical properties are seldom reported. For example, as bulletproof materials,  $B_4C$ -SiC ceramics are used against high-speed armor-piercing projectiles and hard steel-core bullets; thus, the compressive strength and impact strength of  $B_4C$ -SiC ceramics also need to be investigated deeply. Although the bending strength and hardness of the SiC- $B_4C$  ceramics increase with the increase in  $B_4C$  content from 0 to 15 wt%, their impact strength exhibits the highest value as the  $B_4C$  content is 5 wt%.<sup>151</sup> Therefore, all the mechanical property parameters need to be considered comprehensively. In addition,  $B_4C$ -SiC ceramics have received considerable scientific attention for direct conversion between thermal and electric energy applications.<sup>181,182</sup> Accordingly, the thermal properties and electrical properties of  $B_4C$ -SiC ceramics need to be evaluated.

### 5.2. Development of new sintering aids

To date, the sintering performance of  $B_4C$ -SiC ceramics can be enhanced by using sintering aids. However, some sintering aids only benefit densification or fracture toughness, not strength or hardness, and even deteriorate mechanical properties. To mitigate or overcome this disadvantage, new sintering aids should be developed to increase the fracture toughness while maintaining a high hardness for  $B_4C$ -SiC ceramics. Moreover, the use of current sintering aids may cause a reduction in the high-temperature mechanical properties of  $B_4C$ -SiC ceramics. Therefore, the development of new sintering aids for high-performance applications of  $B_4C$ -SiC ceramics at low and high temperatures is still a severe challenge.

### 5.3. Research on $B_4C$ -SiC nanocomposite ceramics

Due to the nanometer size effect,  $B_4C$ -SiC nanocomposite ceramics exhibit better performance and have wider application prospects. However, one of the problems is that it is difficult and costly to produce  $B_4C$ -SiC nanocomposite ceramics by directly mixing commercial nano-sized  $B_4C$  and SiC

powders and subsequent sintering. New ways and technologies should be explored to fabricate  $B_4C$ -SiC nanocomposite ceramics, enabling us to further broaden the application fields of  $B_4C$ -SiC ceramics. From the point of view of special properties and potential applications, the research on  $B_4C$ -SiC nanocomposite ceramics is meaningful.

### 5.4. Preparation of new forms of ceramics composed of $B_4C$ -SiC

In addition to the traditional dense  $B_4C$ -SiC block ceramics with uniform composition, the  $B_4C$ -SiC component can also be used to prepare other forms of ceramic materials, such as gradient ceramics, laminated ceramics, porous ceramics, and ceramic hollow microspheres. Furthermore, due to the excellent performance of the  $B_4C$ -SiC binary system, it is estimated that more and more new forms of ceramics composed of  $B_4C$ -SiC will gradually appear.

**5.4.1. Gradient ceramics/laminated ceramics.** Gradient ceramics are a kind of inhomogeneous composite ceramics with at least two phases. One of the important characteristics of gradient ceramics is that the microstructure and performance present gradual gradient change along the thickness direction due to the continuous change of the component.<sup>183</sup> As a result, the specific performance in a specific direction of the gradient ceramics is superior to homogeneous counterparts composed of similar components.<sup>184</sup> Therefore, gradient ceramics are a potential material that can be applied in a wide range of engineering fields, such as nuclear reactions, aerospace, and internal combustion engines.<sup>185</sup>  $B_4C$  and SiC are the preferred materials for producing gradient ceramics owing to their excellent properties. Zhang *et al.*<sup>186</sup> successfully prepared  $B_4C$ -SiC gradient ceramics with six layers structure. The composition of the prepared  $B_4C$ -SiC gradient ceramics exhibits obvious gradient characteristics, the interface between adjacent layers is well combined and there are no cracks at the interface, resulting from the good physical and chemical compatibility between  $B_4C$  and SiC as well as their little difference in thermal expansion coefficients. Meanwhile, the mechanical properties of  $B_4C$ -SiC gradient ceramics show the characteristics of gradient transition along the thickness direction of gradient layers. Especially, the  $B_4C$ -SiC gradient ceramics have excellent thermal shock resistance, which is ascribed to the tight bonding between different layers and the unique multi-layer gradient structure. Microcracks can be generated at the interface layer under the action of the shear stress between the gradient layers, which is caused by the different thermal expansion coefficients between layers due to the different composition ratios of each layer. When the main cracks formed during the thermal shock pass through the interface layer, these cracks can be passivated by the microcracks at the interface. The  $B_4C$ -SiC gradient ceramics can decrease the damage by enhancing thermal conductivity, thermal shock resistance, and brittleness under the condition of temperature gradients. Therefore, the  $B_4C$ -SiC ceramics in the form of composition gradient distribution have better effects on some properties than homogeneous  $B_4C$ -SiC block ceramics.



In order to improve the fracture toughness of ceramics, a laminated bionic design can be applied. Generally, there are two toughening mechanisms of laminated ceramics based on the bonding strength of the interface between the layers. One is the residual compressive stress owing to the thermal mismatch at the strong interface, and the other is the delamination and deflection of cracks at the weak interface. Sun *et al.*<sup>141</sup> prepared a kind of laminated B<sub>4</sub>C–SiC ceramics by tape casting. Compared with the fracture toughness of the block B<sub>4</sub>C–SiC ceramics, the laminated B<sub>4</sub>C–SiC ceramics possess higher fracture toughness, which is attributed to the strong interface bond between the layers resulting from the residual compressive stress in the laminated ceramics; also, the laminated B<sub>4</sub>C–SiC ceramics have bending strength than the block B<sub>4</sub>C–SiC ceramics. Therefore, the layered structure design can improve the mechanical properties of B<sub>4</sub>C–SiC ceramics.

**5.4.2. Porous ceramics.** Porous ceramics are a kind of material with open pores and high open porosity. It is suitable for precise filtration and separation of various media; thus, it is often prepared as ceramic membranes. Compared with traditional porous ceramic membrane supports, membrane supports composed of SiC–B<sub>4</sub>C porous ceramics can exhibit better corrosion resistance in hot acidic and alkaline solutions.<sup>187</sup> Also, SiC–B<sub>4</sub>C porous ceramics have higher flexural strength than pure SiC porous ceramics, which is attributed to the microstructure of interpenetrated networks formed by large plate-like SiC grains interpenetrating with equiaxed SiC grains in the SiC–B<sub>4</sub>C porous ceramics.<sup>187</sup> Compared with dense SiC–B<sub>4</sub>C block ceramics, SiC–B<sub>4</sub>C porous ceramics are a new form of SiC–B<sub>4</sub>C composites.

**5.4.3. Ceramic hollow microspheres.** The ceramic hollow microspheres are an important engineering material, which can be applied as fillers in composites, ignition targets for inertial confinement fusion, and catalyst supports.<sup>188</sup> In particular, inertial confinement fusion is a sustainable, clean energy and is considered as an effective solution to energy crisis. The ignition target, a vital component for inertial confinement fusion, needs to meet many strict requirements in term of material, surface roughness, and sphericity.<sup>189,190</sup> Due to their high melting point, high thermal conductivity, and excellent thermal stability, B<sub>4</sub>C and SiC are estimated as the ignition target materials for inertial confinement fusion.<sup>191</sup> Yan *et al.*<sup>192</sup> used a combination of slurry-coating and precursor conversion methods to prepare B<sub>4</sub>C–SiC hollow microspheres with a smooth surface and high crush load. The obtained B<sub>4</sub>C–SiC hollow microspheres possess a diameter of 1.6–1.9 mm and a wall thickness of 10–60 μm; the B<sub>4</sub>C–SiC hollow microspheres have a high sphericity of 99.6%. Compared with pure B<sub>4</sub>C hollow microspheres prepared by the CVD method, whose wall thickness can hardly reach 20 μm, the B<sub>4</sub>C–SiC hollow microspheres obtained through a combination of slurry-coating and precursor conversion method exhibit higher wall thickness. B<sub>4</sub>C–SiC ceramics with other complex shapes can also be produced by this method.

### 5.5. Exploration of new material of ternary systems or quaternary systems based on B<sub>4</sub>C–SiC binary ceramics

B<sub>4</sub>C–SiC binary ceramics exhibit better sinterability and mechanical properties than pure B<sub>4</sub>C and SiC ceramics. Recently, the

performance of ternary or quaternary systems based on B<sub>4</sub>C–SiC binary ceramics has attracted much attention, such as B<sub>4</sub>C–SiC–TiB<sub>2</sub>,<sup>193–205</sup> B<sub>4</sub>C–SiC–CrB<sub>2</sub>,<sup>206</sup> B<sub>4</sub>C–SiC–NbB<sub>2</sub>,<sup>207</sup> B<sub>4</sub>C–SiC–MoB<sub>2</sub>,<sup>208</sup> B<sub>4</sub>C–SiC–HfB<sub>2</sub>,<sup>209,210</sup> B<sub>4</sub>C–SiC–ZrB<sub>2</sub>,<sup>211,212</sup> B<sub>4</sub>C–SiC–WC,<sup>213</sup> B<sub>4</sub>C–SiC–Al<sub>2</sub>O<sub>3</sub>,<sup>214</sup> B<sub>4</sub>C–SiC–rGO,<sup>215</sup> B<sub>4</sub>C–SiC–carbon nanotubes,<sup>216</sup> B<sub>4</sub>C–SiC–carbon fiber,<sup>217</sup> B<sub>4</sub>C–SiC–Si,<sup>218,219</sup> B<sub>4</sub>C–SiC–Mo,<sup>220</sup> B<sub>4</sub>C–SiC–Al,<sup>221–223</sup> B<sub>4</sub>C–SiC–Al<sub>2</sub>O<sub>3</sub>–MgB<sub>2</sub>,<sup>224</sup> and B<sub>4</sub>C–SiC–Si–TiB<sub>2</sub>.<sup>225</sup> The demand for B<sub>4</sub>C–SiC with good performance promotes further exploration of new materials of ternary or quaternary systems with improved properties based on B<sub>4</sub>C–SiC binary ceramics.

### 5.6. Study on the combination of mechanical properties and tribological properties

As a novel ceramic material with low friction and low wear, B<sub>4</sub>C–SiC ceramics exhibit satisfactory tribological properties under both unlubricated and water-lubricated sliding conditions.<sup>226–232</sup> However, the tribological properties of the solid-state sintered B<sub>4</sub>C–SiC ceramics under high load need to be further improved due to the relatively low fracture toughness.<sup>233</sup> Therefore, how to improve the tribological properties of B<sub>4</sub>C–SiC ceramics under harsh conditions by controlling their mechanical properties remains to be further studied.

## 6. Conclusions

B<sub>4</sub>C–SiC composite ceramics are a very promising alternative to pure B<sub>4</sub>C ceramics and pure SiC ceramics. B<sub>4</sub>C–SiC ceramics exhibit a combination of the desirable performance of B<sub>4</sub>C and SiC. The mechanical properties of B<sub>4</sub>C–SiC ceramics are determined by a number of factors, as mentioned in this review. Some values of mechanical properties of B<sub>4</sub>C–SiC ceramics reported in the literature vary considerably, and some research conclusions are not uniform so far. The measurement of mechanical properties is strongly dependent on the measuring method, instrument, and operator. The comparison of mechanical properties reported in different literature studies can only be regarded as a reference, even for the B<sub>4</sub>C–SiC ceramics prepared by the same preparation process. Design and exploration of novel advanced ceramic materials for high-performance applications are important to accelerate the development of modern material engineering. B<sub>4</sub>C–SiC ceramics are a potentially promising material for a variety of applications. This review is of practical significance for the promotion and application of B<sub>4</sub>C–SiC ceramics.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

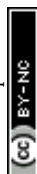
The author would like to express his gratitude to his grandfather and grandmother. The author was brought up by his grandfather and grandmother from birth. The author's grandfather passed away 13 years ago, and the author's grandmother



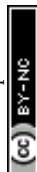
died 5 years ago. The author would like to use this article as a way to commemorate his grandfather and grandmother and express his yearning.

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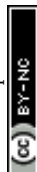
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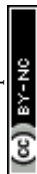
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