Mechanical properties and tribological characteristics of B₄C-SiC ceramic composite in artificial seawater

Chen Wei⁴⁻⁵, Hao Wenhui⁶, Zhao ziqiang⁶, He Nairu⁵, Li xiuqing⁴, Li Huaqiang⁶

(a, National Joint Engineering Research Center for abrasion control and molding of metal materials, Henan University of Science and Technology, 471000, China; b, College of Mechanical and Electrical Engineering, Shaanxi University of Science &Technology, 710021, China; c, State key laboratory of electrical insulation and power equipment, Xi’an Jiaotong University, 710049, China)

Author Information:

Dr. Chen Wei

Address:

a College of Mechanical and Electrical Engineering,
Shaanxi University of Science &Technology
263 Kaiyuan Avenue
Luoyang, Henan Province 471023, P. R. China

b College of Mechanical and Electrical Engineering,
Shaanxi University of Science & Technology
6 Xuefu Middle Road
Xi’an, Shaanxi Province 710049, P. R. China

E-mail: chenweijd@sust.edu.cn
Tel: +86-29-86168806
Fax: +86-29-86168806

Mr. Hao Wenhui
Address:
College of Mechanical and Electrical Engineering,
Shaanxi University of Science & Technology
6 Xuefu Middle Road
Xi’an, Shaanxi Province 710049, P. R. China

Mr. Zhao ziqiang
Address:
College of Mechanical and Electrical Engineering,
Shaanxi University of Science & Technology
6 Xuefu Middle Road
Xi’an, Shaanxi Province 710049, P. R. China

Dr. He Nairu
Address:
College of Mechanical and Electrical Engineering,
Shaanxi University of Science & Technology
6 Xuefu Middle Road
Xi’an, Shaanxi Province 710049, P. R. China

Dr. Li Xiuqing
Address:
College of Mechanical and Electrical Engineering,
Shaanxi University of Science & Technology
263 Kaiyuan Avenue
Luoyang, Henan Province 471023, P. R. China

**Dr. Li Huaqiang**

School of electrical engineering

Xi’an Jiaotong University

28 Xianning West Road

Xi’an, Shaanxi Province 710049, P. R. China
Mechanical properties and tribological characteristics of B₄C-SiC ceramic composite in artificial seawater

Chen Wei⁺, Hao Wenhui⁺, Zhao ziqiang⁺, He Nairu⁺, Li xiuqing⁺, Li Huaqiang⁺

(a, National Joint Engineering Research Center for abrasion control and molding of metal materials, Henan University of Science and Technology, 471000, China; b, College of Mechanical and Electrical Engineering, Shaanxi University of Science &Technology, 710021, China; c, State key laboratory of electrical insulation and power equipment, Xi’an Jiaotong University, 710049, China)

Abstract

To improve the mechanical properties and tribological characteristics of boron carbide (SiC) ceramic, silicon carbide as incorporation phase was added into boron carbide (B₄C) matrix. The results showed that the incorporation of SiC phase led to denser microstructure and lower porosity. When the content of SiC was 20 wt.%, the composite presented higher bending strength of 447.6MPa and fracture toughness of 7.21 MPa·m¹/₂. Meanwhile, when the composite slid against PEEK in seawater, lower friction coefficient of 0.052 and wear rate were obtained. The excellent tribological performance would be attributed to the denser ceramic structure, weakened abrasive wear and tribo-chemical removal.

Key Words: Boron carbide; Silicon carbide; toughness; friction; wear; seawater

1 Introduction

It is well-known that the moving components (such as sealing element, bearing, valve seat, pump body and plunger) operating are usually subjected to the combined actions of friction and wear during service. Especially, the seals in seawater are usually susceptible to
the combined action of wear and corrosion. It is an effective way to improve the stability and reliability of the moving component to apply the materials with anti-wear corrosion and self-healing properties [1-4]. Meanwhile, ceramic materials possess a series of interesting properties, such as high hardness, high strength, high chemical stability, good wear resistance. At present, the application of ceramic materials to seals in seawater environment has attracted increasing attention [5-7].

Boron carbide (B₄C) ceramics possess excellent mechanical properties, chemical stability in acid and alkali environment and unique nuclear shielding properties [8-9]. However, boron carbide ceramic materials represent low fracture and poor tribological properties as engineering friction materials, which limits their further expanded application [10-11]. The scholars improved the strength, toughness and tribological characteristics of the boron carbide ceramics by adding the second phase. Ojalvo[12] added Ti-Al powders into ceramic matrix in order to improve the toughness and wear resistance of B₄C ceramics. And the test results showed that the friction coefficients of B₄C/diamond-coated SiC reached to a range of 0.04-0.05, while its toughness was only 3.5 MPa·m⁰.₅. Meanwhile, Li [13-14] added hBN as incorporateion phase into B₄C ceramic matrix and fabricated B₄C-hBN ceramics by hot-press sintering. And, the experimental results showed that the incorporation of hBN could effectively reduce the dry friction coefficients of B₄C-hBN/B₄C to 0.321, while the incorporation of hBN significantly deteriorates the toughness of B₄C ceramics (from 5.62 MPa·m⁰.₅ for B₄C to 3.85 MPa·m⁰.₅ for B₄C-hBN). Moreover, Sedlák [15] added GPLs into B₄C ceramic matrix and found that the incorporation of GPLs could slightly improve the tribological properties, but the hardness significantly decreased from 30.35 GPa to 18.21 GPa.
As discussed above, it is necessary to further study how to improve the mechanical and tribological properties of boron carbide ceramics at the same time.

In recent years, the SiC particles has been added into B₄C ceramic matrix to enhance the mechanical properties of B₄C ceramic[16-18]. Chawon[19] fabricated the B₄C-preceramic polymer derived SiC composite, and the results showed that the mechanical properties of the composite were similar to those of single-phase ceramics. Meanwhile, Sung [20] fabricated B₄C-SiC ceramic composites by hot pressing sintering, and the experimental results showed the fracture toughness was only 3.59 MPa-m¹/² when the sintering temperature was 2000℃ and the pressure was 40 MPa. Similarly, Du[21] fabricated the B₄C-SiC ceramic composites with high density by hot-press sintering at the sintering temperature of 1950 ℃ and pressure of 30 MPa, and the study results indicated that their hardness and fracture toughness could reach to 33.2 GPa and 5.64 MPa·m¹/², respectively. Obviously, the mechanical properties of B₄C-SiC ceramic composites were influenced by the process and process parameters. Moreover, there are relatively few reports on the tribology of B₄C-SiC ceramic, and no unified conclusion has been reached.

Based on the mentioned above, this paper systematically studied the mechanical properties and tribological performance of B₄C-SiC ceramic composites in seawater environment. The special plastic Polyetheretherketone (PEEK) was selected as the mating materials due to its corrosion resistance in seawater [22]. The pin-on-disc wear test was adopted to reveal the friction and wear properties, and a variety of test and analysis methods were adopted to analyze the microstructure, wear surface, tribochemical product. Then, the wear mechanism was also discussed.
2 Experimental

2.1 Materials

B₄C powder (Shanghai Yao Tian Nano Material Co., Ltd., China, average particle size: 0.8 μm, the purity: 99.9%) and SiC powder (Weifang Hua Rong Ceramic Material Co. Ltd., China, average particle size: 0.45μm, the purity: 98.5%) were utilized as raw materials to prepare B₄C-SiC ceramic composites. Monolithic B₄C ceramic was also prepared as references for comparison with the mechanical and tribological properties of composites. Additional Al₂O₃ powder (Aijia NewMaterial Science & Technology Ltd., China, average particle size: 1.17μm, purity: 99.9%) and Y₂O₃ powder (Aijia NewMaterial Science & Technology Ltd., China, average particle size 0.37μm, purity 99.9%) were added in all samples as sintering additives. The composition of the B₄C-SiC ceramics and their numbers are shown in Table 1.

Table 1 Composition of the B₄C-SiC ceramic composites and their numbers.

| NO. | Ingredient (wt%) |
|-----|-----------------|
|     | B₄C | SiC | Al₂O₃ | Y₂O₃ |
| BS0  | 90   | 0   | 6    | 4    |
| BS10 | 80   | 10  | 6    | 4    |
| BS20 | 70   | 20  | 6    | 4    |

The mixed powders were milled in ethanol for 12 h by using ZrO₂ balls at a speed of 90r/min, and later dried. The weight ratio of ZrO₂ ball to mixed powder was 2:1. SEM images and XRD results of starting powders were shown in Fig.1. After slurry was dried, the powders were hot-press sintered in flowing N₂ at a temperature of 1900 °C and pressure of 40MPa for
dwell time of 30 min using an inductive hot-pressing vacuum furnace (ZT-40-21Y, Shanghai Chenhua Electric Furnace Co., Ltd., China), and a disc with a size of Φ45×6mm was prepared. The sintering process is schematically shown in Fig.2. The test piece with a size of 5 mm×5 mm×20 mm was cut from disc for testing bending strength and Vickers hardness; the test piece in a size of 2.5 mm×5 mm×20 mm with a 2.5 mm notch was also cut from disc for fracture toughness; the pin sample in a size of 5 mm×5 mm×10 mm was fabricated from disc for wear test.

Fig.1 Characterization of mixed sintered powder after ball milling: (a) BS0; (b) BS10; (c) BS20.

Fig.2 Schematic diagram of hot-press sintering process for preparing the B₄C-SiC ceramic composites.

2.2 Test procedure

The ceramic samples were deeply etched in a solution of NaOH for 2 min, and the microstructure of ceramic composite was observed by scanning electron microscope (SEM). And, the phase composition of composite was analyzed by X-ray diffract meter (XRD). The density and porosity of the composite was measured by using the Archimedes method. Three-point-bending method was used to measure the bending strength over a 16 mm span at a crosshead speed of 0.5 mm/min. The Vickers hardness was measured on polished surface with a load of 98 N for 10 s. Single edge notched bending (SENB) test was performed to reveal the fracture toughness of ceramic composite at a crosshead speed of 0.05 mm/min.

Wear testing was carried out with a MMW-1 type pin-on-disc wear test rig (which was produced by Jinan Hengxu Testing Machine Group Co., Ltd., China). In this test rig, an upper pin contacts a stationary disc in artificial seawater as shown in Fig.3, and the artificial seawater was prepared according to the standard of ASTM 1141-98. The pin specimen
(BS0-BS20 in Table1) with a filleted square end was used to form flat contacts, so the contact surface area is about 20 mm$^2$; the disc, as the friction pairs, was machined from PEEK, in a size of 44 mm in diameter and 5 mm in thickness. The chemical structure and main performance parameters of PEEK have been given in the other paper [23]. The PEEK disc was finished by grinding to achieve a surface roughness (Ra) of about 0.05 μm, and the surface roughness (Ra) of the B$_4$C-SiC composite ceramic pins were around 0.1 μm.

Fig.3 The schematic diagram of the MMW-1 type pin-on-disc wear test rig.

Both pin and disc were ultrasonically cleaned in fresh alcohol. The disc was fixed, and the ceramic pin was rotated at a speed of 500r/min (0.836 m/s) and a normal load of 20N. Total sliding distance was 1500m. The initial running-in period was not accounted for the calculation of friction coefficient (f) and wear rate (w). The friction coefficient is directly determined by the tester. The wear rate is defined by \( w = \frac{\Delta m}{\rho PL} \), where \( \Delta m \) represents the mass wear volume assessed by weight loss using a microbalance (accuracy = 0.1 mg), \( P \) is the normal load, \( L \) is the sliding distance, and \( \rho \) is the density. Friction coefficients and wear rates were obtained from the average of the values taken from three runs. The morphological analysis and chemical characterization of the wear surfaces were made by SEM/EDS, XPS and Raman spectrum.

3. Results and discussion

3.1. Phase composition and Microstructure

The XRD diffraction patterns of B$_4$C-SiC composite ceramics were presented in Fig.4. As shown, the ceramic composites were mainly composed of B$_4$C and SiC, while some weak peaks of ZrB$_2$ were also identified. Obviously, there was no new phase in the composite
samples, and there were no reactive products between B4C and SiC forming in the sintering process. Meanwhile, the formation of trace amounts for ZrB2 might be attributed to the reaction of B4C with ZrO2 [24-25]. Certainly, the influence of trace amounts for ZrB2 on the microstructure and mechanical properties of B4C-SiC composite was almost negligible. Meanwhile, the microstructures of B4C-SiC composites were shown in Fig. 5. It can be clearly observed that the grain is significantly refined with the increase of SiC content, and the denser microstructure is also observed.

Fig. 4 XRD patterns of B4C-SiC composite ceramics: (a) BS0, (b) BS10 and (c) BS20.

Fig. 5 SEM images of microstructures for B4C-SiC composite ceramics: (a) BS0, (b) BS10 and (c) BS20.

3.2 Physical and mechanical properties

The results of the density and porosity of the B4C-SiC composites are shown in Fig. 6. As shown, it can be seen that the density increases with the increase of SiC content, and the porosity decreases from 1.79% of BS0 to 1.02% for BS20. The incorporation of SiC increases the density of the ceramics, which is attributed to the higher density of 3.21 g/cm³ for SiC (which is higher than that of 2.49 g/cm³ for B4C). And, the lower porosity of 1.02% for BS20 is consistent with the dense microstructure (as shown in Fig. 5c).

Fig. 6 Density and porosity of the B4C-SiC composite ceramic.

Table 2 shows the Vickers hardness of the B4C-SiC composite, and it can be seen that the hardness of boron carbide ceramic was not significantly influenced by the incorporation of SiC, and the Vickers hardness was all at a range from 38.7GPa to 32.6GPa. As is well known, the hardness of SiC is lower than that of B4C ceramic. However, in this study, B4C-SiC ceramic composite didn’t showed obvious low hardness, which may be related to the denser
microstructure.

Table 2 Vickers hardness of $B_4C$-SiC ceramic composite

| NO. | BS0  | BS10 | BS20 |
|-----|------|------|------|
| $H_v$(GPa) | 38.7 | 34.9 | 32.6 |

Fig.7 shows the bending strength and the fracture toughness of the $B_4C$-SiC ceramic composite. With the increase of SiC content, the bending strength of $B_4C$-SiC ceramics increases from 393.6MPa to 447.6MPa, and the fracture toughness also increases from 6.44MPa·m$^{1/2}$ to 7.21MPa·m$^{1/2}$. As a whole, $B_4C$-SiC ceramics presents better strength and toughness.

Fig.7 Bending strength and fracture toughness of $B_4C$-SiC composite ceramics.

Fig.8 shows the side morphologies of bending fractures for BS0 and BS20. And, it can be obviously seen that the crack deflection of BS20 is more significant than that of BS0. A part of deflection angle for BS20 is higher than right angle (Fig.8b), while the fracture of BS0 is relatively straight (Fig.8a). Fig. 9 shows the SEM image and EDS analysis results of fracture for BS20, and it can be found that the crack deflects when it expands to the SiC grains (as indicated by the arrows in Fig.9).

Fig.8 Fracture morphology of different samples: (a)BS0 and (b)BS20.

Fig.9 EDS analysis results of the fracture for BS20 sample.

It is well known that, the thermal coefficients of $B_4C$ and SiC ceramics are $4.4 \times 10^{-6}$ K$^{-1}$ and $4.8 \times 10^{-6}$ K$^{-1}$, and their Young modulus are 447GPa and 440GPa, respectively. So, when SiC as incorporation phase was added into $B_4C$ ceramic, in the case of no new reaction transition layer, the residual stress appeared at the interface of the two phases. And, the
residual stress caused the crack to deflect. In general, the B\_4C-SiC composites in this study presented good strength and toughness due to the reasonable control of the process and the strengthening and toughening of SiC phase.

3.3. Tribological characteristics

Fig.10 gives the friction coefficients of BS0/PEEK, BS10/PEEK and BS20/PEEK pairs in artificial seawater as a function of sliding distance. It can be seen that BS0/PEEK pair shows an upward fluctuating function from 0.14 to 0.2, BS10/PEEK sliding pair presents a stable friction station at arrange of 0.10-0.14, and the friction coefficient of BS20/PEEK sliding pair fluctuates slightly around 0.05.

Fig.10 Friction coefficients of B\_4C-SiC composite against PEEK as a function of the sliding distance.

Fig.12 presents the average friction coefficient and wear rates of the sliding pairs. From Fig.12(a), it could be easily found that, the addition of SiC to the B\_4C matrix reduces the friction coefficient from 0.192 to 0.052. From Fig.12(b), all the wear rates of composite pin and PEEK disc were no more than the order of 10^-6 mm^3/Nm. It is obvious that the friction pair of BS20/PEEK pair shows better comprehensive friction and wear properties.

Fig.12 Average friction coefficients and wear rates of the B\_4C-SiC/PEEK sliding pairs in artificial seawater.

The worn surface morphologies of BS0, BS10 and BS20 pins were shown in Fig.13. The marks of fracture, debris and spalling can be clearly observed on the worn surface of SN0 pin (as shown in Fig.13a). While, the worn surface of SN10 pin is obviously smoother than that of SN0 pin, and a small amounts of fracture and debris appears on the worn surface composed of smooth area and rough area(as shown in Fig.13b). And, SN20 pin presents the smoothest worn surface, and only a little debris was observed on the surface (as shown in Fig.13c).
Fig.13 SEM micrographs of the worn surfaces of the $B_4C$ composite ceramics pin in seawater.

Fig.14 shows the EDS map analysis results of the worn surface for BS20 pin against PEEK disc in seawater, and the results shows that O, Si, Ca, Mg and Na elements are detected on the worn surface of SN20 pin. Fig.15 shows the Raman spectrum analysis results of the worn surfaces for BS20 pin and PEEK disc. The analysis results indicated that some new products such as SiO$_2$, B$_2$O$_3$, H$_3$BO$_3$, Si(OH)$_4$, Mg(OH)$_2$ and CaCO$_3$ forming on the worn surfaces of BS20/PEEK pair.

Some relevant papers [28-29] reported that SiC and $B_4C$ could react with water molecule, as the following reactions.

$$B_4C + 6H_2O = 2B_2O_3 + CH_4 + 4H_2 \quad (3)$$

$$SiC + O_2 + H_2O = SiO_2 + CO + H_2 \quad (4)$$

$$SiO_2 + 2H_2O = Si(OH)_4 \quad (5)$$

$$B_2O_3 + 3H_2O = 2H_3BO_3 \quad (6)$$

As discussed above, when $B_4C$-SiC composites slid against PEEK under seawater environment in this study, $B_4C$-SiC composites would react with water molecule to form new products (B$_2$O$_3$ and SiO$_2$). Subsequently, B$_2$O$_3$ and SiO$_2$ could react with water molecule to form H$_3$BO$_3$ and Si(OH)$_4$. Especially, H$_3$BO$_3$ possess the lamellar triclinic crystal structure, and has good lubrication performance.

Previously, our research team [30-31] found that Si$_3$N$_4$-hBN could react with water molecule during the friction process, and the tribochemical products (B$_2$O$_3$, H$_3$BO$_3$ and SiO$_2$)
smoothed the wearing surface under liquid environment. With the bearing effect of liquid in the wear interface, the direct contact area decreased. According to friction binomial, the friction coefficient is positively correlated with the direct contact area, as the following equations.

\[ F = \alpha A + \beta W \]  
\[ f = \frac{\alpha A}{W} + \beta \]

Where, \( F \) is friction force; \( f \) is friction coefficient; \( A \) is real contact area; \( W \) is normal load; \( \alpha \) and \( \beta \) are the coefficients determined by the physical and mechanical properties of the friction surface, respectively. From the equations above, with the decrease of real direct contact area, the friction force and friction coefficient would present a downward tendency.

In this study, when \( \text{B}_4\text{C}-20\%\text{SiC} \) composites slid against PEEK under seawater environment, the hard micro-bulges on the ceramic surface would plough the soft polymer material (PEEK) at the beginning stage. Due to the denser microstructure and better mechanical properties, the abrasive wear was weakened in seawater. And then, with the increase of friction process, the wear surface of ceramic pin gradually became smooth due to tribochemical reaction. Correspondingly, the wear surface of PEEK disc also became smooth, as shown in Fig.16. Under the bearing of seawater, the real contact area decreased, so the friction force and friction coefficient decreased (as shown in Fig.10).

![SEM image of worn surface of PEEK disc against BS20 in seawater.](image)

When \( \text{B}_4\text{C} \) slid against PEEK, the polymer disc surface was also ploughed by the micro-bulges on the pin surface at the beginning stage, but the wear surfaces of ceramic did not become smooth with the friction process. Bigger spalling pits, cracks and some wear particles
appeared on the worn surface of BS0 pin, and apparent plastic deformation was observed on
the surface of the polymer disc, as shown in Fig.17. Maybe, the relatively poor mechanical
property of BS0 pin leaded to more severe abrasive wear during the friction process. Even
with the lubrication, cooling and tribochemical removal of seawater, the continuous abrasive
wear cannot be inhibited. So, the higher friction coefficient and slightly higher wear rates
were obtained.

Fig.17 Magnified morphologies of worn surfaces for BS0/PEEK sliding pair in seawater: (a) PEEK disc
and (b) BS0 pin.

In this study, with the addition of SiC, B₄C ceramic presented denser microstructure and
better mechanical properties. When the ceramic composite slid against PEEK in seawater, the
ceramic surface gradually became smooth under the combined effects of lubrication, cooling
and tribochemical removal of seawater. When two smooth surfaces slide against each other
under liquid lubrication, the sliding pair presented the lower friction and wear behaviors [32].
Fig.18 shows the schematic diagram of the friction process of BS20/PEEK pair in seawater.

Fig.18 Schematic diagram of the friction process for BS20/PEEK pair.

4 Conclusions

B₄C-SiC ceramics with different content of SiC were fabricated by hot-pressed sintering.
The microstructures, density, mechanical properties, and tribological properties of the
B₄C-SiC ceramics have been studied in this study, and get the following conclusions.

(1) B₄C-SiC ceramics were mainly composed of B₄C and SiC, and no new phase formed
in the ceramic composite. When the SiC content reached 20wt.%, the microstructure
significantly became denser.
(2) With the increase of SiC content, the density of ceramic composite obviously increased, and the porosity presented the downward trend. Meanwhile, the hardness of ceramic was not significantly affected by the addition of SiC phase, while the bending strength and fracture toughness were obviously improved due to the incorporation of SiC phase.

(3) When B₄C-SiC ceramics (with better mechanical properties) slid against PEEK in seawater, the incorporation of SiC significantly enhanced the tribological characteristics of ceramic composite. Under the combined effects of lubricating, cooling, and tribochemical removal of seawater, the wear surfaces became smooth, and the real contact area decreased. So, the sliding pair presented lower friction and wear behaviors.

(4) When B₄C ceramic slid against PEEK in seawater, the wear surfaces show typical abrasive wear morphology, and higher friction coefficient and wear rate of sliding pair were obtained. This result may be related to the relatively poor mechanical properties of the single-phase boron carbide ceramic.

Acknowledgement

The authors are thankful for the funding provided by the Open Fund of National Joint Engineering Research Center for abrasion control and molding of metal materials (grant number No. HKDNM2019012). Meanwhile, the authors are also grateful to the Natural Science Foundation of China (51905325) and China Postdoctoral Science Foundation (2019M653525).
**References**

[1] Huttunen-Saarivirta E, Isotahdon E, Metsäjoki J, et al. Behaviour of leaded tin bronze in simulated seawater in the absence and presence of tribological contact with alumina counterbody: Corrosion, wear and tribocorrosion. Tribo Int. 2019, 129: 257-271.

[2] Song YW, Liu D, Tang WN, et al. Comparison of the corrosion behavior of AM60 Mg alloy with and without self-healing coating in atmospheric environment. J Magnes Alloy. 2020, online.

[3] Xu CG, Liu Y, Liu YP, et al. New inorganic coating-based triboelectric nanogenerators with anti-wear and self-healing properties for efficient wave energy harvesting. Appl Mater Today 2020, 20: 2352-9407.

[4] Ko PL, Wozniewski A, Zhou PA. Wear-corrosion-resistant materials for mechanical components in harsh environments. Wear 1993, 162-164:721-732.

[5] Mungiguerra S, Martino G D D, Savino R, et al. Characterization of novel ceramic composites for rocket nozzles in high-temperature harsh environments. Int J Heat Mass Tran. 2020, 163:120492.

[6] Yakaboylu GA, Pillai RC, Sabolsky K, Sabolsky EM. MoSi$_2$- and WSi$_2$-based embedded ceramic composite thermocouples for high-temperature and harsh-environment sensing. Sensor Actuat A: Phys. 2018, 272:139-152.

[7] Yu Y, Liu XY, Duan HT, et al. Outstanding self-lubrication of SiC ceramic with porous surface/AlCoCrFeNiTi$_{60.5}$ high-entropy alloy tribol-pair under 90 wt% H$_2$O$_2$ harsh environment. Mater Lett. 2020, 276: 128025.

[8] Domnich V, Reynaud S, Haber R A, Chhowalla M. Boron carbide: structure, properties, and stability under stress. J Am Ceram Soc. 2011, 94: 3605-3628.

[9] Suri AK, Subramanian C, Sonber JK. Synthesis and consolidation of boron carbide: a review. Int Mater
[10] Zhang W. A review of tribological properties for boron carbide ceramics. Prog Mater Sci. 2021, 116: 100718.

[11] Yue XY, Zhao SM, Lü P. Synthesis and properties of hot pressed B$_4$C-TiB$_2$ ceramic composite. Mater Sci Eng: A. 2010, 527: 7215-7219.

[12] Ojalvo C, Zamora V, Moreno R, et al. Transient liquid-phase assisted spark-plasma sintering and dry sliding wear of B$_4$C ceramics fabricated from B$_4$C nanopowders. J Eur Ceram Soc. 2021, 41:1869-1877.

[13] Li XQ, Gao YM, Wei SZ, Yang QX. Tribological behaviors of B$_4$C-hBN ceramic composites used as pins or discs coupled with B$_4$C ceramic under dry sliding condition. Ceram Int. 2017, 43: 1578-1583.

[14] Li XQ, Gao YM, Wei SZ, Yang QX. Sliding tribological performance of B$_4$C-hBN composite ceramics against AISI 321 steel under distilled water condition. Ceram Int. 2017, 43:14932-14937.

[15] Sedlá k R, Kovalčíková A, Balko J, et al. Effect of graphene platelets on tribological properties of boron carbide ceramic composites. Metals & Hard Materials. 2017, 65: 57-63.

[16] Yan SR, Lyu ZJ, L Foong K. Effects of SiC amount and morphology on the properties of TiB$_2$-based composites sintered by hot-pressing. Ceram Int. 2020, 46: 18813-18825.

[17] Wang P, Li S, Geng X, et al. Microstructure, surface stress and surface temperature response of ZrB$_2$-SiC based coatings. J Alloy Compo. 2020, 843: 156084.

[18] Nguyen VH, Asl MS, Mahaseni ZH, Germi MD, Mohammadi M. Role of co-addition of BN and SiC on microstructure of TiB$_2$-based composites densified by SPS method. Ceram Int. 2020, 46: 25341-25350.

[19] Hwang C, Yang Q, Xiang SS, Domnich V, et al. Fabrication of dense B$_4$C-preceramic polymer derived SiC composite. J Eur Ceram Soc. 2019, 39: 718-725.

[20] So SM, Choi WH, Kim KH, et al. Mechanical properties of B$_4$C-SiC composites fabricated by
hot-press sintering. Ceram Int. 2020, 46: 9575-9581.

[21] Du XW, Wang Y, Zhang ZX, et al. Effects of silicon addition on the microstructure and properties of B$_4$C-SiC composite prepared with polycarbosilane-coated B$_4$C powder. Mater Sci Eng: A. 2015, 636:133-137.

[22] Chen BB, Wang JZ, Yan FY. Comparative investigation on the tribological behaviors of CF/PEEK composites under sea water lubrication. Tribo Int. 2012, 52:170-177.

[23] Chen W, Wang ZX, Jia JH, Hua Y. Effect of load on the friction and wear characteristics of Si$_3$N$_4$-hBN ceramic composites sliding against PEEK in artificial seawater. Tribo Int. 2020, 141: 105902.

[24] Lin X, Ai SH, Feng Y, Gao DZ, et al. Fabrication and properties of in-situ pressureless-sintered ZrB$_2$/B$_4$C composites. Ceram Int. 2017, 43: 15593-15596.

[25] Asl MS, Kakroudi MG, Nayebi B. A fractographical approach to the sintering process in porous ZrB$_2$-B$_4$C binary composites. Ceram Int. 2015, 41:379-387.

[26] Zhang W, Yamashita S, Kita H. Tribological properties of SiC-B$_4$C ceramics under dry sliding condition. J Eur Ceram Soc. 2020, 40: 2855-2861.

[27] Cheng L, Xie Z, Liu G. Spark plasma sintering of TiC-based composites toughened by submicron SiC particles. Ceram Int. 2013, 39: 5077-5082.

[28] Zhang W, Yamashita S, Kita H. Progress in tribological research of SiC ceramics in unlubricated sliding-A review. Mater Design 2020, 190: 108528.

[29] Cao XQ, Shang LL, Liang YM, Lu ZB. The effect of tribo-chemical reactions of mating materials on tribological behaviors of the B$_4$C film in various relative humidity environments. Ceram Int. 2019, 45: 4581-4589.

[30] Chen W, Wang K, Gao YM, et al. Investigation of tribological properties of silicon nitride ceramic
composites sliding against titanium alloy under artificial seawater lubricating condition. Int J Refract Met. 2018, 76:204-213.

[31] Chen W, Shi HX, Xin H, He NR, Yang WL, Gao HZ. Friction and wear properties of Si$_3$N$_4$-hBN ceramic composites using different synthetic lubricants. Ceram Int. 2018, 44: 16799-16808.

[32] Zhang W, Yamashita S, Kita H. Effect of counterbody on tribological properties of B$_4$C-SiC composite ceramics. Wear. 2020, 458-459: 203418.
Table 1 Composition of the B₄C-SiC ceramic composites and their numbers.

| NO  | Content (wt%) |        |        |        |        |
|-----|---------------|--------|--------|--------|--------|
|     | B₄C           | SiC    | Al₂O₃  | Y₂O₃   |        |
| BS0 | 90            | 0      | 6      | 4      |        |
| BS10| 80            | 10     | 6      | 4      |        |
| BS20| 70            | 20     | 6      | 4      |        |

Table 2 Vickers hardness of the B₄C-SiC ceramics.

| NO  | BS0 (GPa) | BS10 (GPa) | BS20 (GPa) |
|-----|-----------|------------|------------|
| Hᵥ   | 38.7      | 34.9       | 32.6       |