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High toughness and electrical discharge machinable B_4C-TiB_2-SiC composites fabricated at low sintering temperature

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ABSTRACT

Dense and electrical discharge machinable B_4C-TiB_2-SiC triple-phase ceramic composites with high fracture toughness and high hardness were successfully fabricated via reactive hot-pressing sintering using B_4C and nano-layered Ti_3SiC_2 with different ratios as raw materials at a relatively low temperature of 1850 °C. The results showed that the mechanical properties of B_4C-TiB_2-SiC composite were remarkably enhanced than that of monolithic B_4C ceramic. The micro-hardness, flexural strength, fracture toughness and compressive strength of B_4C-TiB_2-SiC composite prepared with B_4C-30 vol% Ti_3SiC_2 starting powder were 31.6 GPa, 492.3 MPa, 8.0 MPa·$m^{1/2}$ and 2727 MPa, respectively. High hardness was attributed to the low open-porosity and grain refinement, while the high toughness was mainly ascribed to the crack deflection due to the dispersed TiB_2 and SiC particles in the B_4C matrix. Moreover, the composites exhibited significantly improved machinability than monolithic B_4C, as evidenced by electrical discharge machining.

1. Introduction

Boron carbide (B_4C) is an extremely attractive engineering material with extremely high hardness, excellent chemical stability, good abrasion resistance and satisfactory radiation resistance [1–3]. Therefore, B_4C ceramics have great potential applications in military, aerospace and industrial as light-weight ballistic armors, body armors, blasting nozzles, cutting tools as well as wear resistant components. Additionally, owing to the neutron absorption capacity of isotope ^{10}B, B_4C ceramics are widely applied in the nuclear industry as controlling rods, neutron detectors and shielding materials [4–6]. Nevertheless, B_4C exhibits several shortcomings such as poor sinterability and relatively low fracture toughness [7]. In addition, considering the high hardness and low fracture toughness of B_4C, the machining of B_4C ceramics is costly and time consuming. These disadvantages seriously restrict the wide applications of B_4C-based ceramics. Therefore, it is of great importance to lower the sintering temperature of B_4C ceramics and to improve their mechanical properties and machinability.

Many efforts have been made to improve strength and toughness of monolithic B_4C ceramics, and addition of silicon carbide (SiC) and titanium diboride (TiB_2) as sintering additive were found to be effectively for it [8–12]. Both SiC and TiB_2 materials possess many excellent chemical and physical properties, such as high hardness, good chemical stability and good oxidation resistance [13–15]. Therefore, the addition of SiC or TiB_2 could maximize the retention of unique properties of B_4C. The B_4C-TiB_2 and B_4C-SiC composites usually fabricated by reactive hot pressing with different strating materials [16,17]. For example, Skorokhod et al. [18] prepared a B_4C-15 vol% TiB_2 composite with a fracture toughness of 6.1 MPa·$m^{1/2}$ by in situ reactions of B_4C, TiO_2 and C using hot pressing at 2000 °C. Zhang et al. [19] fabricated B_4C-SiC composites from B_4C, Si, and C powders (sintering temperature: 1700–1900 °C) and the fracture toughness of 6.0 MPa·$m^{1/2}$ was obtained with 1900 °C. In order to further improve the fracture toughness of B_4C ceramics, Zhang et al. [20] prepared B_4C-20 wt% (TiB_2-SiC) triple-phase composites by in-situ reactions of B_4C, TiC and Si using hot pressing at 1950 °C and the fracture toughness of which reached 6.38 MPa $m^{1/2}$. However, TiB_2-SiC agglomerates are randomly dispersed in the B_4C matrix, and hence the controlling of second phase distribution in matrix is important for improving the overall mechanical performance of composites. Up to date, most of B_4C composites were sintered at high temperatures and have a microstructure of inhomogeneous and coarse grain size. In order to obtain high-performance B_4C-base composites at relatively lower sintering temperature, nano-layered Ti_3AlC_2 was chosen as a novel sintering aid in our previous study and composites with significantly improved mechanical properties were obtained at a relatively low sintering temperature [5,8]. However, the existence of Al-rich phase had a detrimental influence on the hardness and strength of the composites.

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Table 1
Density of B_4C-base composites sintered with different amount of Ti_3SiC_2.

Ti_3SiC_2 content (vol%)	0	20	25	30
Density (g/cm^3)	2.04	2.67	2.79	3.06
Open-porosity	17.66%	8.92%	6.12%	1.28%

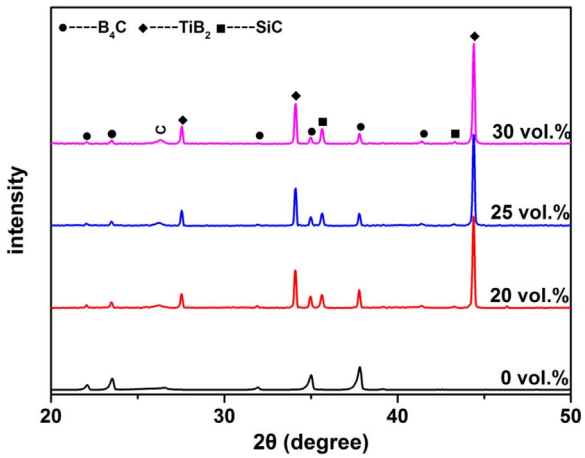

Fig. 1. XRD profiles of B_4C-base composites sintered with different amount of Ti_3SiC_2.

In order to obtain uniformly dispersed TiB_2 and SiC phases in B_4C matrix, in this study, we explored the feasibility of preparation of B_4C-TiB_2-SiC composites via reactive hot pressing using B_4C and nano-layered Ti_3SiC_2 powders as raw materials. The microstructure, mechanical properties and machinability of sintered B_4C-TiB_2-SiC composites were analyzed.

2. Experimental

B_4C-TiB_2-SiC composites were prepared from B_4C powders (Grade HS, H.C. Starck GmbH, Germany, purity ≥ 96.7%, ~0.5 μm) and Ti_3SiC_2 powders (Forsman, China, purity ≥ 98.0%, 0.5–10 μm), which were mixed according to the formula of B_4C-x vol% Ti_3SiC_2 with x = 0, 20, 25 and 30. The powders were ball-milled for 8 h using ethanol as a ball-milling media. After ball-milling, the slurries were dried and sieved. Then, the mixed powders were put into a graphite die with an inner diameter of 50 mm and sintered in vacuum atmosphere using a hot-pressing furnace at 1850 °C with a heating rate of 10 °C/min and a dwell time of 30 min. A unidirectional pressure of 30 MPa was applied during sintering.

The bulk density and open-porosity of the sintered samples was measured according to the Archimedes's method. Microstructural investigations of the specimens were studied by scanning electron microscopy (SEM) with an energy dispersive spectrometer (EDS) system. The phases of specimens were characterized by X-ray diffraction (XRD). Vickers hardness (H_V) was measured by a Vickers indenter with a load was 9.8 N for 15 s dwell. Specimens with a dimension of 2 mm × 2 mm × 4 mm were prepared for compression test at room temperature. The strain rate was 0.5 mm/min. The rectangular bars for the flexural strength measurement with a dimension of 3 mm × 4 mm × 35 mm was prepared by electrical discharge machining (EDM). The fracture toughness was determined using the single-edge notched samples with the rectangular bars of 2 mm × 4 mm × 35 mm with a 2 mm deep and 0.2 mm wide notch. The span of 30 mm was applied to the three-point bending test. The crosshead speed was 0.05 mm/min. The machinability of specimens was evaluated by EDM machine (NOVICK, AR1300, China).

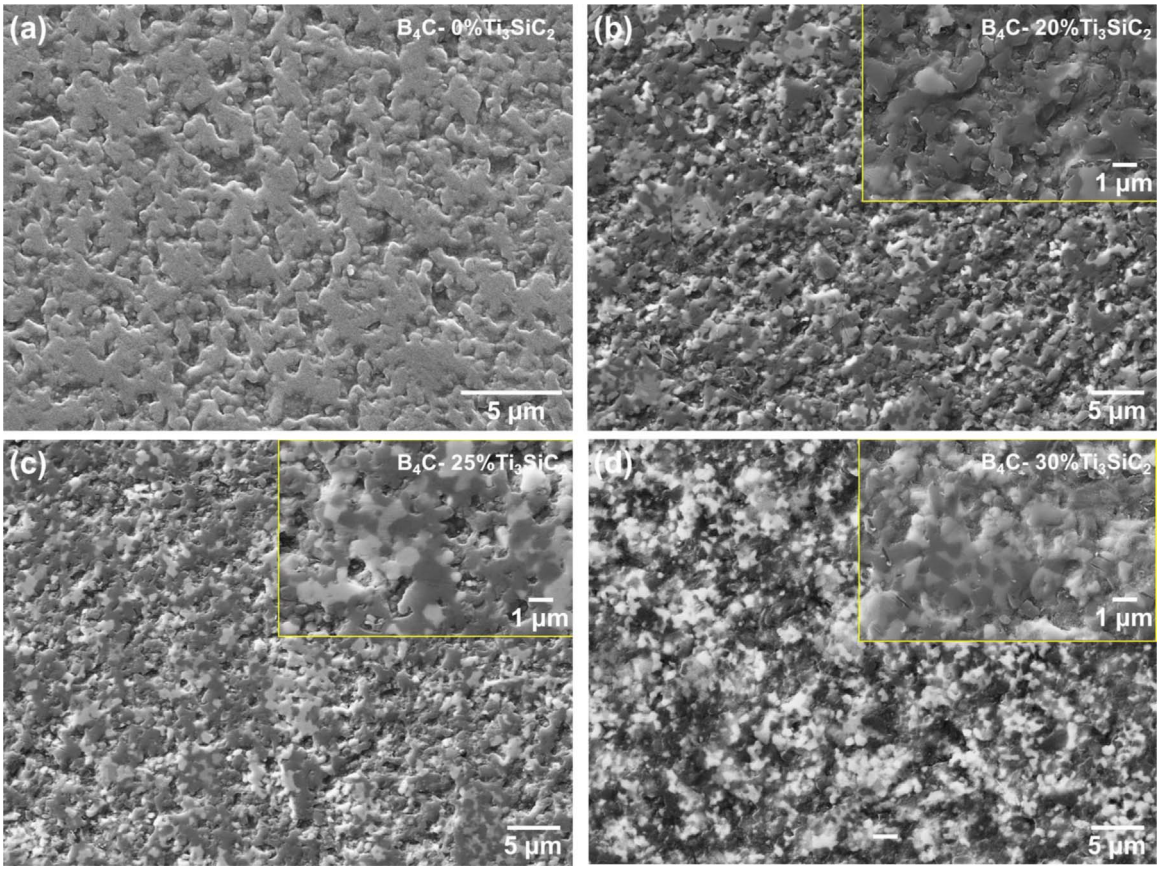

Fig. 2. Polished surfaces of B_4C-base composites sintered with different amount of Ti_3SiC_2. (a) 0 vol%, (b) 20 vol%, (c) 25 vol% and (d) 30 vol%.