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An investigation of the mechanical property and thermal shock behavior of machinable B_4C/BN ceramic composites

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Machinable B_4C/BN ceramic composites were fabricated by a hot-pressing process at 1,850 °C for 1 h under a pressure of 30 MPa. In this article, the mechanical property, thermal shock behavior and machinability of the B_4C/BN ceramic composites were investigated. The fracture strength and fracture toughness of B_4C/BN nanocomposites were significantly improved in comparison with B_4C/BN microcomposites. The Vickers hardness of B_4C/BN nanocomposites and B_4C/BN microcomposites decreased gradually with an increase in the content of h-BN, while the machinability of B_4C/BN nanocomposites and B_4C/BN microcomposites decreased were significantly improved. The B_4C/BN ceramic composites with an h-BN content of more than 20 wt% exhibited excellent machinability. The thermal shock resistance of the B_4C/BN ceramic composites was much better than that of the B_4C monolith, and the thermal shock resistance of B_4C/BN nanocomposites was much better than that of B_4C/BN microcomposites. The thermal shock temperature difference (Δ Tc) of the B_4C monolith was about 300 °C, while the Δ Tc of B_4C/BN microcomposites was about 500 °C and the Δ Tc of B_4C/BN nanocomposites was about 600 °C.

Key words: Boron carbide, Boron nitride, Mechanical property, Thermal shock resistance, Machinability.

Introduction

Among the advanced ceramic materials, boron carbide (B_4C) ceramics are recognized as one of the most promising structural materials for application in various engineering fields due to its many excellent properties including high strength and toughness, high melting point (2,450 °C) and low density (2.52 g/cm^3) , and extremely high Vickers hardness (> 30 GPa) [1, 2]. However, the machinability and thermal shock resistance of B₄C ceramics are extremely poor [3]. On the other hand, hexagonal boron nitride (h-BN) materials have properties of low strength and toughness, but excellent machinability and thermal shock resistance [4, 5]. So in order to improve the machinability and thermal shock resistance of B_4C ceramics, machinable B_4C/BN ceramic composites were developed. The h-BN material can be incorporated into a B₄C matrix, and the combination of B₄C and h-BN would produce machinable B₄C/BN composites, which would significantly improve the machinability and thermal shock resistance of B₄C ceramics.

Recently, machinable nanocomposites with the high mechanical properties and good machinability have been the concern of many researchers [4-6]. Kusunose and co-workers reported that they have fabricated Si_3N_4/BN nanocomposites and Al_2O_3/BN nanocomposites by a chemical reaction and a hot-pressing process [4-6]. The machinable nanocomposites mainly included Si_3N_4/BN ,

SiC/BN, Al₂O₃/BN, ZrO₂/BN. These nanocomposites achieved significantly improved mechanical properties in comparison with the microcomposites and exhibited excellent machinability [4-6]. However, the thermal shock behavior of the machinable ceramic composites was not investigated in detail. Also the mechanical properties and thermal shock behavior of machinable B₄C/BN ceramics composites has not been reported. So in this research, B₄C/BN nanocomposites were fabricated by a chemical reaction and hot-pressing process. For comparison, B₄C/BN microcomposites were fabricated by a hot-pressing process. Therefore, in this article, the microstructure, mechanical properties, machinability and thermal shock behavior of B₄C/BN microcomposites and B₄C/BN nanocomposites are discussed and compared.

Experimental Procedure

For fabrication of B_4C/BN nanocomposites, the starting materials were B_4C powders with a mean particle size of 3.5 µm. Boric acid (H_3BO_3) and urea ($CO(NH_2)_2$) were selected to prepare the nanostructure BN powders. The relative BN contents of the B_4C/BN composite powders produced were adjusted to be from 0 wt% to 40 wt%. The mole ratio of H_3BO_3 and $CO(NH_2)_2$ was about 1 :4. The B_4C powders, H_3BO_3 and $CO(NH_2)_2$ were mixed by mechanically milling for 24 h and dried slowly. The dried powders mixture were reacted at 550 °C for 15 h in air, and then heat treated at 850 °C for 6 h in a N_2 atmosphere, so that the B_4C/BN composite powders were prepared by this chemical reaction process. The

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Fig. 1. SEM micrographs of the (a) B₄C/BN microcomposites (20 wt%h-BN) and the (b) B₄C/BN nanocomposites (20 wt%h-BN) samples.

B₄C/BN composite powders produced were mixed with 10 wt% sintering aids of a mixture of Al₂O₃ and Y₂O₃ powders, and mechanically milled and dried slowly. Then the B₄C/BN nanocomposites samples were fabricated by a hot-pressing process at a temperature of 1,850 °C, under a pressure of 30 MPa with a holding time of 1 h in a N₂ atmosphere. For comparison, micro-sized B₄C powders and h-BN powders with mean particle sizes of 4 µm together with 10 wt% sintering aids of a mixture of Al₂O₃ and Y₂O₃ powders were used to fabricate the B₄C/BN microcomposites samples by the same hot-pressing process.

The microstructures of the hot-pressed B_4C/BN ceramic composites were observed and analyzed by a S-2700 scanning electron microscope (SEM). The density of sintered samples was measured by Archimedes immersion methods. The fracture strength was measured by three-point bending tests using a sample size of 3 mm × 4mm × 30 mm. The fracture toughness was measured by a single edge notch beam (SENB) with the conditions the same as for the fracture strength. The values of Young's modulus were measured by three-point bending tests. The Vickers hardness was measured by a HV-5 Vickers hardness meter with a load of 49 N and a holding time of 15 s. The machinability of the B_4C/BN composites was measured by drilling experiments using WC cermets drills with a diameter of 2 mm. The drilling rates of the hot-pressed composites samples were evaluated. The thermal shock tests were carried out by a water quenching method. The thermal shock temperature difference (ΔT) was from 100 °C to 1,000 °C. The test specimens were the same as for the bending test specimens, the specimens were heated up to the expected temperature and held at this temperature for 20 minutes in an air furnace, and then quenched into water at 20 °C. The residual fracture strength of the specimens was determined by the three-point bending tests after the thermal shock test.

Results and Discussion

The microstructure of the hot-pressed B_4C/BN ceramic composites samples

Figure 1 shows SEM micrographs of the B₄C/BN ceramic composites with a h-BN content of 20 wt%. Fig. 1(a) shows a SEM micrograph of a B₄C/BN microcomposites sample. The microstructure of the B₄C/BN microcomposites confined the larger micro-sized h-BN grains to be dispersed at the grain boundaries of the B₄C matrix. Therefore, the B₄C/BN microcomposites sample exhibited a rougher microstructure than the B₄C/BN nanocomposites. Fig. 1(b) shows a SEM micrograph of a B₄C/BN nanocomposites

Table. 1. The mechanical properties and machinability of the B₄C/BN microcomposites and the B₄C/BN nanocomposites samples

| B ₄ C/BN microcomposites | ρ (g/cm ³) | σ_f (MPa) | $K_{IC} (MPa \cdot m^{1/2})$ | Hv (GPa) | E (GPa) | $V (mm \cdot min^{-1})$ |
|----------------------------------------|-----------------------------|------------------|------------------------------|----------|---------|-------------------------|
| B_4C | 2.503 | 409 | 5.369 | 20.26 | 430 | 0 |
| B ₄ C/BNm10 | 2.474 | 360 | 4.57 | 12.33 | 322 | 1.12 |
| B ₄ C/BNm20 | 2.456 | 327 | 4.35 | 7.52 | 253 | 5.12 |
| B ₄ C/BNm30 | 2.434 | 303 | 3.99 | 5.38 | 205 | 5.82 |
| B ₄ C/BNm40 | 2.425 | 245 | 3.52 | 4.64 | 171 | 6.29 |

Table. 1. The mechanical properties and machinability of the B₄C/BN microcomposites and the B₄C/BN nanocomposites samples

| B ₄ C/BN nanocomposites | ρ (g/cm ³) | $\sigma_f(MPa)$ | $K_{IC} (MPa \cdot m^{1/2})$ | Hv (GPa) | E (GPa) | $V (mm \cdot min^{-1})$ |
|------------------------------------|-----------------------------|-----------------|------------------------------|----------|---------|-------------------------|
| B ₄ C | 2.503 | 409 | 5.369 | 20.26 | 430 | 0 |
| B ₄ C/BNn10 | 2.492 | 424 | 6.08 | 15.35 | 342 | 0.36 |
| B ₄ C/BNn20 | 2.473 | 415 | 5.34 | 10.51 | 278 | 3.5 |
| B ₄ C/BNn30 | 2.463 | 359 | 5.05 | 7.79 | 225 | 4.28 |
| B ₄ C/BNn40 | 2.445 | 306 | 4.19 | 6.32 | 185 | 4.47 |

sample. It can be observed that the nano-sized h-BN particles were homogenously distributed in the B_4C ceramic matrix. The length of the nano-sized h-BN particles was less than 1 μ m and the thickness was about 100-200 nm. The grain size of B_4C matrix was about 1-2 μ m. The homogenous distribution of the nano-sized h-BN particles inhibited the grain growth of B_4C matrix remarkably. Therefore, the B_4C/BN nanocomposites exhibited a finer and more homogenous microstructure.

The mechanical properties and machinability of the B₄C/BN composites

The mechanical properties and machinability of the hot-pressed B₄C/BN nanocomposites and B₄C/BN microcomposites are shown in Table 1. The density of the B₄C/BN nanocomposites and the B₄C/BN microcomposites decreased gradually with an increase in the content of h-BN, the density of the B₄C/BN nanocomposites was slightly higher than that of the B₄C/BN microcomposites. With an increase in the content of h-BN, the fracture strength of the B₄C/BN microcomposites decreased gradually, while the fracture strength of the B₄C/BN nanocomposites slightly increased at first (10 wt%h-BN and 20 wt%h-BN), and then decreased gradually. The fracture strength of the B₄C/BN nanocomposites was significantly improved in comparison with the B₄C/BN microcomposites. The improved fracture strength of the B₄C/BN nanocomposites was chiefly attributed to the refined B₄C matrix grains as well as the reduction of flaw size caused by the dispersion of nano-sized h-BN particles. With an increase in the content of h-BN, the fracture toughness of the B₄C/BN microcomposites decreased gradually, while the fracture toughness of B₄C/BN nanocomposites increased initially (10 wt%h-BN), and then decreased gradually. The fracture toughness of the B₄C/BN nanocomposites was much improved in comparison with the B_4C/BN microcomposites. The Vickers hardness of the B₄C/BN nanocomposites and the B₄C/BN microcomposites decreased gradually with an increase in the content of h-BN. This decrease in the Vickers hardness would significantly improve the machinability of the B₄C/BN ceramic composites. Table 1 shows that the Young's modulus of the B₄C/BN ceramic composites decreased gradually with an increase in the content of h-BN. The decrease in Young's modulus would improve the thermal shock resistance of the B₄C/BN ceramic composites.

The machinability of the B_4C/BN ceramic composites was measured by the drilling experiments. Table 1 shows that the drilling rates (V) of the B_4C/BN microcomposites and the B_4C/BN nanocomposites increased with an increase in the content of h-BN. When the h-BN content was more than 20 wt%, the drilling rates (V) of the B_4C/BN ceramic composites significantly increased. The B_4C/BN ceramic composites samples with an h-BN content more than 20 wt% could be easily machined by the WC cermets drills, and this result indicated that the B_4C/BN nanocomposites and the B_4C/BN microcomposites with an h-BN content more than 20wt% exhibited excellent machinability.



Fig. 2. The residual fracture strength of the B_4C monolith, and the B_4C/BN microcomposites (20 wt%h-BN) and the B_4C/BN nanocomposites (20 wt%h-BN) samples after the thermal shock test with a thermal shock temperature difference (Δ T) from 100 °C to 1,000 °C.

Thermal shock resistance of the B₄C/BN composites

Fig. 2 shows the residual fracture strength of the B_4C monolith, and the B₄C/BN microcomposites (20 wt%h-BN) and the B₄C/BN nanocomposites (20 wt%h-BN) samples after the thermal shock test with a thermal shock temperature difference (ΔT) from 100 °C to 1,000 °C. The critical temperature difference of fracture (ΔTc) of the B₄C monolith was about 300 °C, while the ΔTc of the B₄C/BN microcomposites was about 500 °C and the Δ Tc of the B₄C/BN nanocomposites was about 600 °C. It can be observed from the figure that the thermal shock resistance of the B₄C/BN microcomposites and the B₄C/BN nanocomposites were much better than that of the B_4C monolith, and that the thermal shock resistance of the B₄C/BN nanocomposites was much better than that of the B_4C/BN microcomposites. To avoid fracture initiation by thermal shock, favorable materials characteristics include high values of fracture strength and thermal conductivity, and low values of Young's modulus and thermal expansion coefficient. In comparison with the B₄C monolith, because of the addition of the low Young's modulus h-BN material into the B₄C ceramic matrix, the Young's modulus of the B₄C/BN ceramic composites decreased sharply. Therefore, the thermal shock resistance of the B₄C/BN ceramic composites was improved significantly in comparison with the B₄C monolith.

On the other hand, because that there was a large difference of thermal expansion coefficients between B_4C and h-BN (B_4C : $4.5 \times 10^{-6}K^{-1}$; h-BN: $7.5 \times 10^{-6}K^{-1}$) [2-4, 6], the h-BN grains were easily separated from the matrix grains; therefore, there were some microcracks inside the B_4C/BN ceramic composites. Because these microcracks could relax the thermal stress due to the thermal expansion difference at high temperature, so the thermal shock resistance of the B_4C/BN composites was improved significantly. It can be observed from this figure that the thermal shock resistance of the B_4C/BN nanocomposites

was much higher than that of the B_4C monolith and the B_4C/BN microcomposites. This was because the nanosized h-BN particles were homogenously distributed in the B_4C ceramics matrix, when fracture was initiated and propagated, the resistance of the B_4C/BN nanocomposites was larger than that of the B_4C monolith and the B_4C/BN microcomposites. The fracture strength of the B_4C/BN nanocomposites also remained at a higher level. Therefore, the thermal shock resistance of the B_4C/BN nanocomposites was the largest.

Conclusions

 B_4C/BN microcomposites and B_4C/BN nanocomposites were fabricated by a hot-pressing process. With an increase in the content of h-BN, the density, fracture strength and fracture toughness of the B_4C/BN ceramic composites decreased gradually, the fracture strength and fracture toughness of the B_4C/BN nanocomposites were significantly improved in comparison with the B_4C/BN microcomposites. The Vickers hardness of the B_4C/BN ceramic composites decreased gradually with an increase in the content of h-BN, while the drilling rates and machinability were significantly improved, and the B_4C/BN ceramic composites with an h-BN content more than 20 wt% exhibited excellent machinability. The thermal shock resistance of the B₄C/BN ceramic composites was much better than that of the B₄C monolith, and the thermal shock resistance of the B₄C/BN nanocomposites was much better than that of the B₄C/BN microcomposites. The thermal shock temperature difference (Δ Tc) of the B₄C monolith was about 300 °C, while the Δ Tc of the B₄C/BN microcomposites was about 500 °C and the Δ Tc of the B₄C/BN nanocomposites was about 600°C.

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