

Microstructure and mechanical properties of cBN-WC-Co composites used for cutting tools

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Abstract Composites containing ultrafine tungsten carbide/cobalt (WC-Co) cemented carbides and 30 vol% cubic boron nitride (cBN) were fabricated by spark plasma sintering technique. The effect of cBN particles on the densification behavior, microstructure, and mechanical properties of the composites were investigated. According to SEM observation of microstructure, cBN particles are uniformly distributed and have excellent bonding with the cemented carbide matrix. X-ray diffraction analysis shows that there is no indication of phase transformation from cBN to hBN. The addition of very hard dispersed cBN to the WC-Co promotes an increase of hardness, but a decrease of flexural strength. The density and the hardness of cBN-WC-Co composites increase with the increase of the sintering temperature. However, it has the highest hardness of 2,170 HV at 1,370 °C and then the hardness decreases with the further increase of the sintering temperature.

Keywords Cubic boron nitride · Tungsten carbide · Cutting tools · Microstructure · Mechanical properties

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1 Introduction

Cubic boron nitride (cBN) is a synthetic material exhibiting both high hardness and excellent thermal conductivity which are nearly comparable to diamond [1]. Particularly, diamond burns at 600 °C and dissolves in iron at elevated temperature, but cBN is chemically stable and does not react with ferrous materials at temperature up to 1,200 °C [2]. Therefore, cBN is always used for cutting tools in the various industrial machining fields of difficult-to-cut materials, such as high-speed tool steels, die steels, bearing steels, titanium alloy, and nickel based superalloy [3, 4]. Polycrystalline cubic boron nitride used today for cutting tools is manufactured by sintering micrometer cBN particles on a cemented carbide substrate at temperature between 1,300 °C and 1,400 °C and pressure of 5–6 GPa using a metal or ceramic material as the binder [5]. Polycrystalline single-phase cBN is directly converted and simultaneously sintered from hexagonal boron nitride (hBN) or CVD-based pyrolytic hBN (pBN) into cBN under ultra-high temperature and pressure without using a binder. Polycrystalline single-phase cBN sintered tools have a good wear resistance and a long service life [6], but it is brittle and is difficult to make cutting inserts with high toughness and large size.

Another material widely used for cutting tools is tungsten carbide, which is commonly sintered with cobalt as the binding phase. Most of cutting tools are made of tungsten carbide/cobalt (WC-Co) cemented carbides owing to their excellent toughness and strength, and wear resistance as well as their high resistance to cracking [7]. Morphologically, WC-Co is consisted of a high volume fraction of hard WC phase embedded within a soft and tough Co binder phase. Co provides the ductility, and thus, contributes to the fracture toughness, while the wear resistance benefits from the high concentration of WC [8]. Increasing the volume fraction of WC improves the hardness and wear resistance at the expense of the fracture toughness.

It is well known that WC-Co has a better fracture toughness in comparison with cBN, but its hardness and wear resistance are inferior to those of the latter. Therefore, some researchers [9, 10] proposed that the hardness maybe significantly increased by replacing the part of WC alloy with CBN particles, and superior mechanical properties can be obtained for the consolidation of cBN-WC-Co composites. Yaman and Mandal [11, 12] sintered 25(vol%) cBN/6(wt%) Co/WC by spark plasma sintering (SPS) technique, and wear resistance and mechanical properties tests were carried out. The experimental results showed that the addition of cBN significantly increased the wear resistance, the mechanical and thermal properties of the material. Rosinski and Michalski [13] fabricated cBN-WC-Co by pulse plasma sintering technique. They reported that the composites sintered at temperature of 1,200 °C under pressure of 100 MPa for 5 min had density near the theoretical value, and no phase transformation from cBN to hBN took place during the sintering process. Shi et al. [14] sintered cBN-WC-Co composites using nanocrystalline WC powder and cBN particles plated with titanium. They found that the coated titanium layer cannot only improve the thermal stability of cBN, but also increase the mechanical properties of cBN-WC-Co composites.

In this study, ultrafine WC-Co cemented carbides with cBN were fabricated by SPS technique. The effect of cBN addition on the densification behavior, microstructure, and mechanical properties of the composites was investigated. The influence of sintering condition on the phase composition of the composites was discussed.

2 Experimental procedure

Commercial WC powder containing 6 wt% Co and cBN particle were used as starting materials. The average particle sizes of WC, Co, and cBN particle are 0.8, 3, and 40 μm , respectively, and they are all of industrial reagent grade. The composite powders with a WC-6Co to cBN volume ratio of 70:30 were mixed by planetary ball-mixer at rotational speed of 70 rpm in isopropyl alcohol for 2 h. The balls for mixing were made from cemented carbide, and the ball-to-powder mass ratio was 10:1. The mixed powder slurries were dried in a vacuum oven at 35 °C and then sieved to break up the soft agglomerates. The powders were poured into a 30 mm inner diameter graphite die directly and uniaxially pre-pressed under pressure of 2 MPa. The SPS was carried out in FCT HP D 25/3 under vacuum at different temperatures in the range of 1,330 °C to 1,390 °C for 5 min under a pressure of 30 MPa. The heating rate was 100 °C/min, and the cooling rate after sintering was the same as that of heating.

The densities of the SPSed composites were determined by immersing the samples in water according to Archimedes method. The hardness was measured by indentation test

through Vickers method with a 49 N load for 15 s. The SPSed samples were cut using wire-electro-discharge machine, and then ground at a rigid super precision surface grinding machine with diamond grinding wheel into 20 mm \times 6.5 mm \times 5.25 mm rectangular bars. The ground bars were used to measure flexural strength with three-point bending experiment. The microstructure and chemical composition of fracture surface were observed using scanning electron microscopy (SEM, JSM-5610LV) equipped with a energy dispersive spectroscopy (EDS) system designed for chemical analyses. The phase composition of the SPSed composites was measured using X-ray diffractometer (XRD) to determine cBN to hBN transformation.

3 Results and discussion

3.1 Microstructure and composition

Figure 1 shows the typical SEM photographs on the fracture surface of the as-prepared cBN-WC-Co composites SPSed at 1,370 °C. It is obvious that the sharply cornered cBN particles are uniformly distributed in the cemented carbide matrix. Fracture through the sample shows that only a small amount of cBN particles is torn out from the cemented carbide matrix, and most of them are cleaved along the fracture plane.

Microstructure of composites SPSed at 1,370 °C is given in Fig. 2. The SPSed material is observed to be dense, the cBN particles are firmly bound with the cemented carbide matrix, and only a few micro-pores are visible. As seen clearly from Fig. 2(a), the characteristics of cleavage and dimple occur on the fracture surface. Both intergranular fracture and

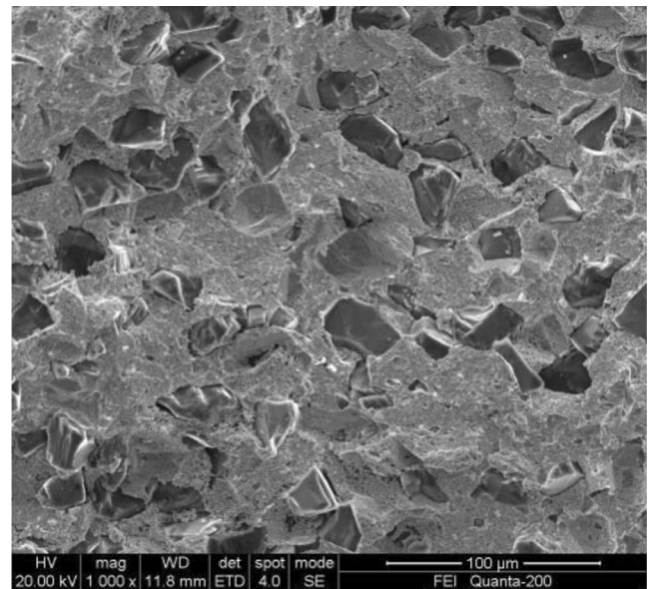
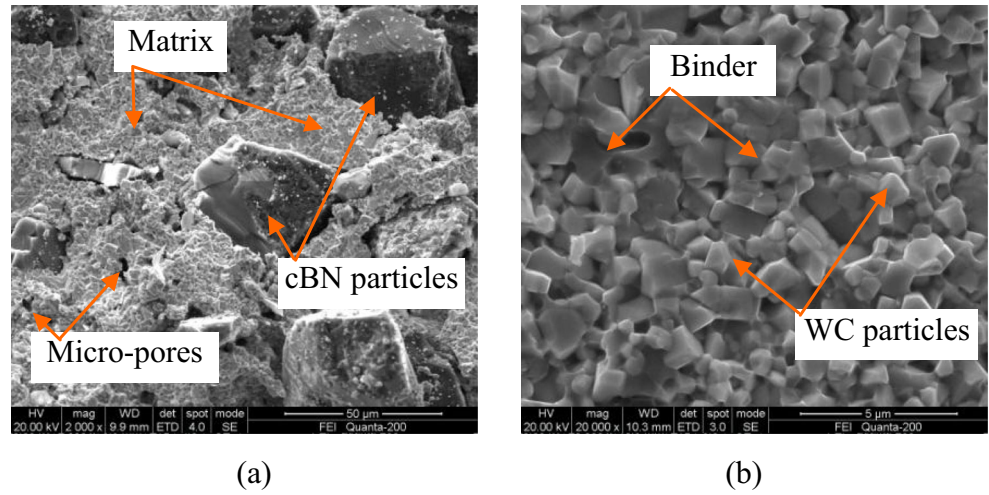


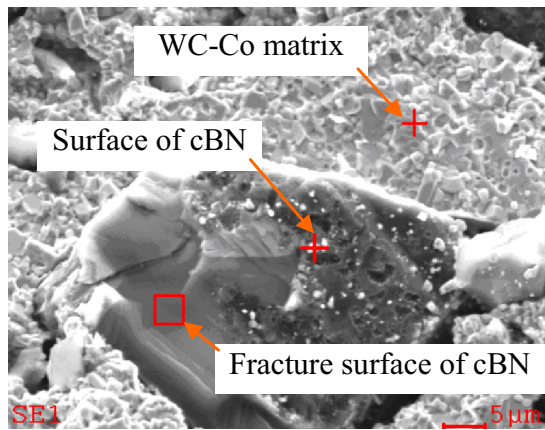
Fig. 1 The typical SEM photograph on the fracture surface of cBN-WC-Co composites SPSed at 1,370 °C

Fig. 2 The microstructure on the fracture surface of cBN-WC-Co composites SPSeD at 1,370 °C: **a** bonding conditions between cBN and matrix and **b** WC-Co matrix

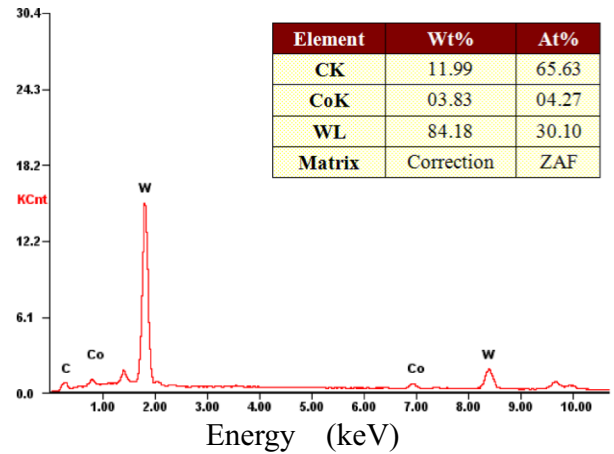


transgranular fracture of WC and cBN particles can be found in the sample. This indicates that the fracture resistance of the

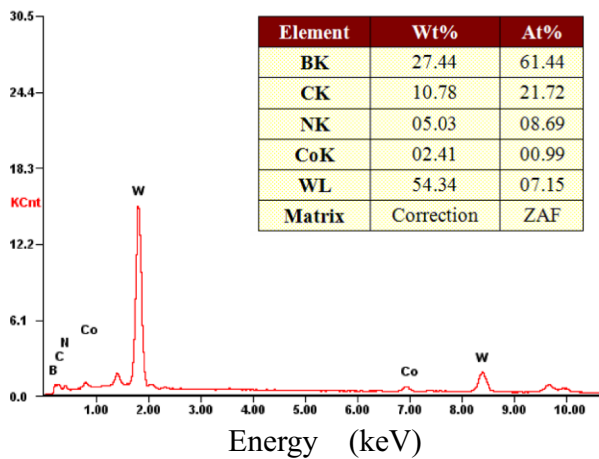
sintered material during flexural test stemmed from the intrinsic strengths of the binder, WC and cBN particles. Rong et al.



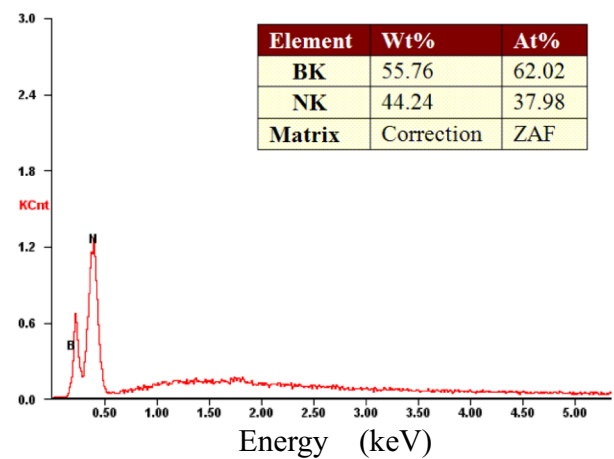
(a)



(b)



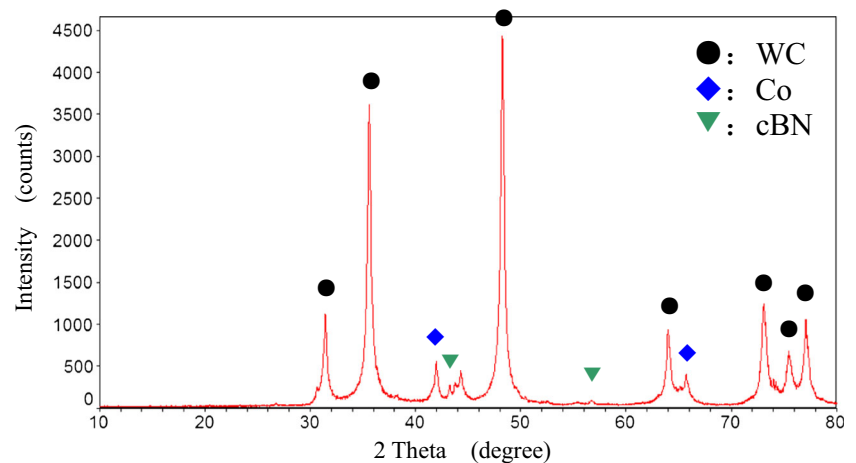
(c)



(d)

Fig. 3 EDS analysis of cBN-WC-Co SPSeD at 1,370 °C: **a** measurement zone, **b** WC-Co matrix, **c** surface of cBN, and **d** fracture surface of cBN

Fig. 4 XRD patterns of cBN-WC-Co SPSed at 1,370 °C



[15] explained the formation of the micro-pores. Although Co was mixed with WC powder and cBN particles at a lower rotational speed for 2 h, particle deformation and agglomeration will inevitably occur, which promoted the appearance of micro-pores during sintering. Furthermore, the as-prepared cBN-WC-Co composites were fabricated by powder metallurgy, liquid phase occurred during heating and the bond of particles depended on the formation of liquid phase. Therefore, the appearance and flow of the liquid phase are very important for the microstructure of the composites. However, the formation and flow of liquid phase were not sufficient during the rapid sintering by SPS, and then micro-pores would be also occurred.

From the photograph of WC-Co matrix as shown in Fig. 2(b), WC crystal grain size and distribution in the cemented carbide matrix are homogeneous, and discontinuous growth phenomenon for WC crystal grain does not occur. Cobalt phase is uniformly distributed, and there is no indication of obvious cobalt pools. Chen et al. [16] found that cobalt pool is a primary fracture source in the cemented carbide, and it can greatly affect the transverse fracture strength. Yaman and Mandal [12] also proposed that the cobalt-rich liquid phase enhances the tendency of cBN to transform into hBN during sintering. Therefore, the uniform distribution of Co phase is help not only to increase the flexural strength of composites, but also to prevent the transformation of cBN into hBN.

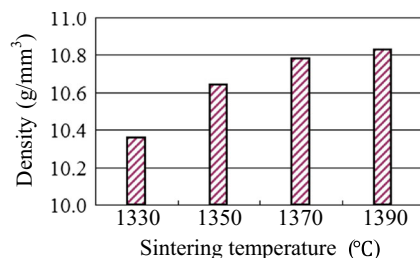


Fig. 5 Density of the cBN-WC-Co composite at different sintering temperatures

The EDS analysis of the fracture surface for composites SPSed at 1,370 °C was carried out and representative results are shown in Fig. 3. It is found that there are no boron and nitrogen on the WC-Co matrix. The contents of carbon, cobalt, and tungsten on the fracture surface of cBN are zero, which is expected. Figure 3(c) shows the contents of boron, carbon, nitrogen, cobalt and tungsten for the surface of cBN are 27.44 wt%, 10.78 wt%, 5.03 wt%, 2.41 wt%, and 54.34 wt%, respectively. This reveals that there are some WC-Co is bonded on the surface of cBN even if the composite is fractured. This indicates that the bond between the WC-Co and cBN is mechanically strong.

The phase compositions of the SPSed composite were measured by XRD. Typical XRD patterns of cBN-WC-Co composites SPSed at 1,370 °C are shown in Fig. 4. WC, Co, and cBN phases are observed in cBN-WC-Co composite. However, the intensity of the cBN peak is much lower than that expected according to its volume fraction (30 vol%). It can be explained by the very strong mass-absorption coefficients of WC and Co in comparison to cBN phase. Therefore, it is not completely sure that there is no phase transformation from cBN to hBN even if hBN is not detected in cBN-WC-Co composite. However, the thermal stability of cBN under

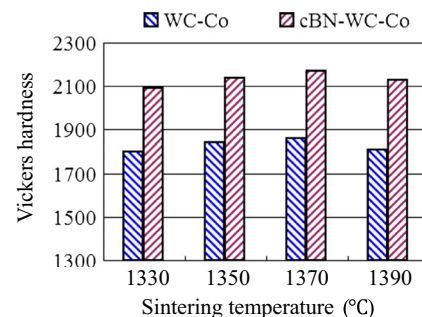
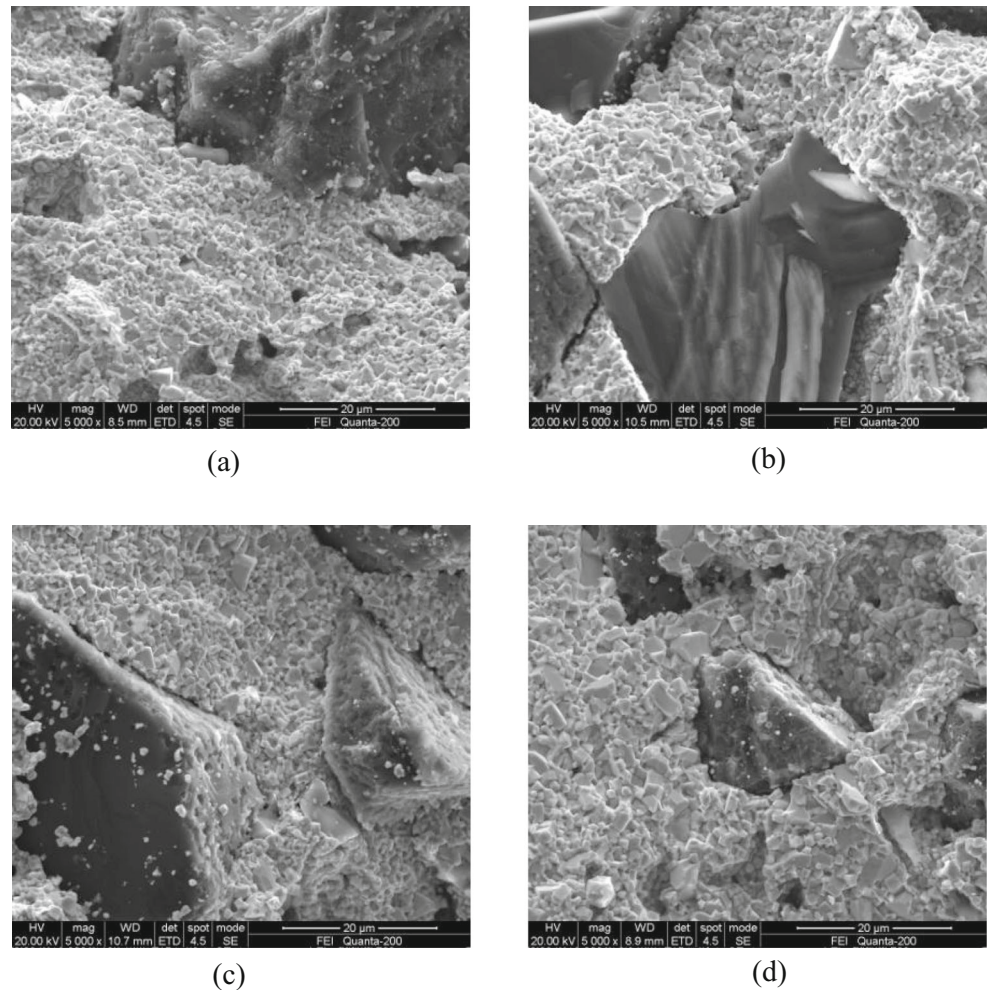


Fig. 6 Vickers hardness of the composites at different sintering temperatures

Fig. 7 SEM micrographs of fractured surface of cBN-WC-Co SPSeD at: **a** 1,330 °C, **b** 1,350 °C, **c** 1,370 °C, and **d** 1,390 °C



the sintering process applied in this study is also confirmed by SEM images. Observation of cBN on the fracture surface, as shown in Fig. 3(a), does not show hBN phase, which could be visible as flakes [13]. Consequently, it can be concluded that there are no cBN phase transformation happened during sintering. These phenomenon means that the excellent properties of cBN can be potentially kept.

It is well known that the stability of cBN at high temperature is poor, which will reduce the sintering properties of the tungsten carbide. The thermal stability is sharply deteriorated when cobalt is appeared especially liquid phase cobalt is generated. The maximum sintering temperature in this study is 1,390 °C, which is higher than eutectic temperature 1,320 °C of WC-Co alloy [17]. However, Hotta and Goto [18] researched the effect of sintering time on the phase transformation from cBN to hBN and found that the short sintering time helped to prevent the hBN formation during SPS. Furthermore, the formation of liquid phase cobalt is not sufficient during the rapid sintering by SPS, and then the tendency for cBN to hBN phase transformation is decreased.

3.2 Mechanical properties

Figure 5 shows the variation of the density for cBN-WC-Co composite with the sintering temperature. It is found that the density increases with the increase of sintering temperature. The reason for this phenomenon is possibly that more liquid phase Co appears and flows to fill the micro-pores of the composites SPSeD at a higher sintering temperature. Heng et al. [19] found that the increase of sintering temperature

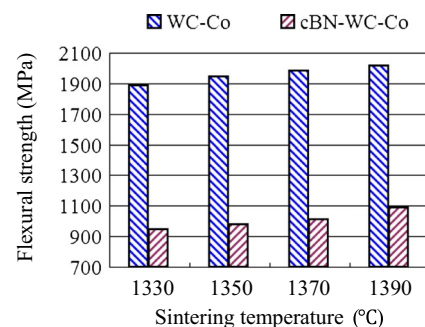


Fig. 8 Flexural strength of the composites

causes the increase of cobalt melt fluidity during liquid phase sintering, which leads to the improvement of the capillary pressure as well as the filling of porosities of samples more completely. This redounds to the increase of the bulk density.

It can be found from Fig. 6 that the Vickers hardness of the as-prepared cBN-WC-Co is comparably higher than their counterparts of WC-Co matrix. This phenomenon can be explained by two reasons. One factor is the replacing part of the carbide phase with much harder material of cBN is helpful to improve the hardness. Another factor for the hardness increase is attributed to the strong binding force on the interface between the cBN particle and cemented carbide matrix, as can be seen from Fig. 3.

Figure 6 also shows that the hardness of cBN-WC-Co composite increases with the increase of the sintering temperature. However, it has the highest hardness of 2,170 HV SPSed at 1,370 °C, and then the hardness decreases with the further increase of the sintering temperature. Mahmoodan et al. [20] proposed that the hardness of the WC-Co composite is mainly affected by two phenomena occurred simultaneously during high temperature sintering. The first is the increase of bulk density as well as the decrease of porosity volume fraction cause the improvement of the hardness. The second is the occurrence of grain growth. For cBN-WC-Co composite, the change of hardness may be also due to the transformation of cBN to low-hardness hBN. However, according to XRD and SEM analysis as previously mentioned in this study (as shown in Figs. 3 and 4), there is no indication that cBN transformed to hBN. Therefore, the evolution of hardness for cBN-WC-Co composite can be due to both grain growth and the density increase.

Usually, the hardness of cemented tungsten carbide is significantly decreased due to grain growth. Figure 7 shows SEM micrographs of fractured surface for cBN-WC-Co composites SPSed at different temperature. It is found that the average grain size of WC slightly increased with the sintering temperature increasing. It is believed that the grain size of the WC is mainly influenced by the sintering temperature, originating from the temperature-dependent grain boundary migration. The mobility of grain boundary increases with the enhancing of the sintering temperature. The hardness profiles, as shown in Fig. 6, indicate that the predominant influence factor on the hardness of the composite is density when the sintering temperature is lower than 1,370 °C. On the contrary, grain growth is a dominant factor for the decrease of the hardness during 1,390 °C sintering. Thus the best hardness value can be balanced at 1,370 °C.

Figure 8 compares the flexural strength of WC-Co and cBN-WC-Co composites. It is obvious that there is a decrease of the flexural strength of the cemented carbide by the addition of cBN. This may be attributed to the transgranular fracture mode of cBN particles and the weak strength of cBN. Furthermore, although as mentioned before the adhesion

resistance or the bonding between the cBN particles and the WC-Co matrix is excellent, it is lower than the bonding strength of the WC-Co matrix itself. Consequently, the addition of cBN particles in WC-Co matrix causes the decrease of the flexural strength.

4 Conclusion

Composites containing ultrafine WC-Co cemented carbides and 30 vol% cBN are fabricated by SPS technique at temperature between 1,330 °C and 1,390 °C for 5 min under a pressure of 30 MPa, and the following conclusions may be drawn:

- (1) According to SEM observation of microstructure and XRD analysis, cBN particles are uniformly distributed and have excellent bonding with the cemented carbide matrix. And there is no indication of phase transformation from cBN to hBN.
- (2) The addition of very hard dispersed cBN to the WC-Co promotes an increase of hardness, but a decrease of flexural strength.
- (3) The density and the hardness of cBN-WC-Co composite increase with the increase of the sintering temperature. However, it has the highest hardness of 2,170 HV at 1,370 °C and then the hardness decreases with the further increase of the sintering temperature.

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