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Full Length Research Paper

Effect of boron carbide on the microstructure and the mechanical properties of segments produced using hot pressing method

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In this study, effect of boron carbide (B_4C) addition on microstructure and mechanical properties of diamond cutting segments was investigated. For this purpose, the boron carbide addition quantity was changed as 2, 5 and 10 wt%. In all of the experiments, hot pressing process was carried out at 35 MPa, at 700°C and sintering time of 3 min. Microstructure and phase composition of segments were determined by Scanning Electron Microscopy, Energy Dispersive Spectroscopy (SEM/EDS) and X-ray diffraction (XRD) analysis. Hardness and bending strength values were measured by hardness and three-point bending test devices, respectively. Hardness and bending strength values of segments changed depending on boron carbide rate.

Key words: Segments, boron carbide, hot pressing.

INTRODUCTION

Diamond cutting tools are now accepted as the most effective means of sawing natural stone, concrete, reinforced concrete, asphalt, brickwork, glass and other ceramic materials. There are various types of diamond tools available in the industry; circular saws, drilling cores, diamond wires and drills (Xu, 1999). These tools are mostly produced by powder metallurgy. Generally, the diamond cutting tools have been produced by hot pressing method. Using this method reduces the amount of friction between the mould and metal powder; ultimately higher density is obtained at lower pressing pressures (Sun et al., 2009; Kim, 2008; Oliveira et al., 2007; German, 2005). During hot pressing, diamond particles are bonded to the metallic matrix by combination of physical and chemical interactions. Sintering parameters should be controlled carefully in order to avoid diamond dissolution, attack, and/or graphitisation, which negatively affects the final cutting performance of diamond cutting tool (Zeren and Karagöz, 2006).

Various factors affect the cutting performance and life cycle of diamond cutting tools. These basic factors are the diamond and matrix properties, the segment manufacturing method, the cutting conditions (cutting speed, peripheral speed and cutting depth), the cutting mode (down-cutting and up-cutting), the mineralogical and mechanical properties of natural stone, cooling effect, the properties of the cutting machine and the skills of the operator (Büyüksağış, 2007). The metallic matrix has two basic functions. One of them is to hold the diamond firmly and the other one is to wear in an optimum amount in line with the diamond loss (Konstanty, 2003a, b). The wear resistance of the matrix has to correspond with the abrasiveness of the workpiece material, so that neither the diamond grits protrude insufficiently nor they are lost prematurely. A matrix which is too soft wears faster than the diamond, which results in the possibility of diamond pullout. On the other hand, a matrix which is extremely

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Table 1. Compositions and the sintering conditions of segments.

No	Composition (%)		Sintering conditions		
	CuSn	B_4C	Temperature (°C)	Time (min)	Pressure (MPa)
S_1	100	-	700	3	35
S_2	98	2			
S_3	95	5			
S_4	90	10			

resistant to wear could wear more slowly than the break down of the diamond, causing the segment surface to polish. Therefore, the wear resistance of the matrix should be compatible with the wearability property of the material to be cut (Karagöz and Zeren, 2001; Konstanty, 2005).

In most previous studies, the iron, cobalt, nickel, titanium, tungsten, copper and bronze, or a combination of these metals were used as matrix materials. Nitkiewicz and Swierzy (2005), studied the effect of tin in diamond segments had on the cutting performance; they observed that adding a certain amount had a positive effect on the cutting performance and investigated whether it could be used together with iron matrixes in different tools. Barbosa et al. (2010) produced Fe-Cu-Co matrix diamond tools. They proved that the most suitable matrix compound was Fe- 60% Cu-20% Co in conclusion of three-point bending and wear tests. The intensity of segments increased with the increase in the Cu amount and their hardness improved.

Carbides were added to the matrix in order to increase the wear resistance of the metallic matrix. The number of subject-related studies in literature is limited. Meszaros and Vadasdi (1996), produced Co-2% WC matrix diamond cutting tools. The study reported that WC controlled the weight loss of the matrix with abrasion and ultimately increased the wear resistance. Oliveira et al. (2004), used Fe-Cu-SiC powders as a matrix for diamond cutting tools. There was a 14% rate of increase at the hardness level that has a controlling effect on the rate of wear with the addition of silicon carbide (SiC). Additionally, the wear resistance of the matrix increased as the grain size of silicon carbide (SiC) added increased.

In recent years, boron carbide (B_4C) has become an important material for advanced technology because of its high melting point, high hardness, low density, high chemical stability and excellent mechanical properties. Boron carbide is the hardest material known after diamond and cubic boron nitride (cBN). It is used to improve wear resistance because of its high level of hardness. Its high resistance/density rate makes it an ideal material in the industry (Pierson, 1996; Spohn, 1994; Jiang et al., 2009; Ma et al., 2010).

The purpose of this study was to investigate the effect of boron carbide (B_4C) on diamond segments, used in cutting natural stones, the effect it has on their microstructure and mechanical properties. 2, 5 and 10 wt.% B_4C was added in weight during experiments to achieve this purpose. Hot pressing technique was used in all the experiments. A Scanning Electron Microscope (SEM), an X-ray Diffractometer (XRD) and Energy Dispersive Spectroscopy (EDS) were used to determine the microstructure and phase compounds of the segments. Hardness tests were conducted to measure their microhardness and three-point bending tests were conducted to measure bending strength.

MATERIALS AND METHODS

Bronze (CuSn) and boron carbide (B_4C) powders were used as the matrix in the experimental studies. Boron carbide particles were added to the matrix at different percentage weights. Table 1 illustrates compositions and the sintering conditions of segments. A 99.9% pure bronze (85 wt.% Cu + 15 wt.% Sn) alloy, with a grain size of 45-50 µm, was used as the matrix material in all experiments. The average grain size of boron carbide was selected as 20 µm. Figure 1 illustrates the SEM images of CuSn and B_4C used to produce the segments. Bronze powder is sphere shaped, and boron carbide powder is sharp-edged shaped.

Powders were mixed with the addition of a 1 wt.% of paraffin wax, at a speed of 20 rpm, for 30 min. All samples were prepared via cold press with a pressure of 15 MPa. The cold-pressed segments were hot-pressed in graphite moulds for 3 min at 700°C with an applied pressure of 35 MPa on an automatic hot pressing machine. Figure 2 illustrates the cold pressing of the segments, the layout of the segments in the graphite mould and sintering graphs.

The relative density, hardness and bending strength of the segments were determined. The relative densities of the segments were measured by Archimedes' principle. Hardness measurements were performed in Brinell scale with a ball diameter of 2.5 mm and a load of 62.5 kg. A three-point bending test was used to measure the bending strength of segments with 40 x 7 x 3.2 mm sized samples.

Samples for metallographic examination were prepared using standard polishing techniques. A scanning electron microscope (SEM) fitted with energy dispersion X-ray spectroscopy (EDS), an X-ray diffractometer (XRD) were used to investigate the fractured surfaces, and identify the phase structures, and how the microstructure of segments changed based on their production conditions.

RESULTS AND DISCUSSION

CuSn and CuSn/B_4C samples were successfully produced using a hot pressing method together with a

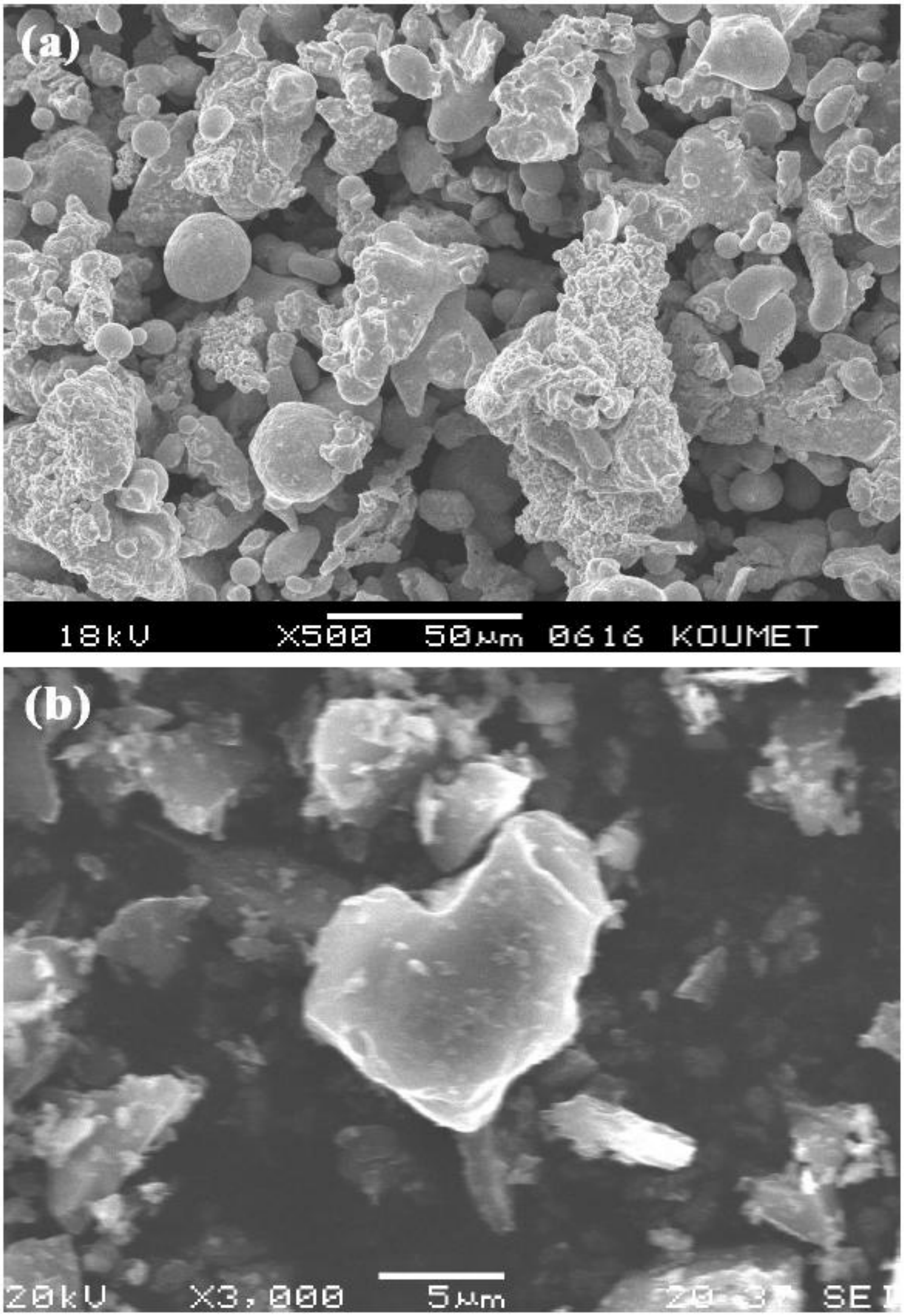

Figure 1. The SEM images of powders; (a) CuSn and (b) B_4C.

three minutes sintering at 700°C, under a pressure of 35 MPa. α-Cu and ε-bronze (Cu_3Sn) phases formed in the microstructure of the CuSn sample. This is supported with the Cu-Sn binary phase diagram (Figure 3) and the XRD graph (Figure 4).

The CuSn/B4C segment was produced by adding

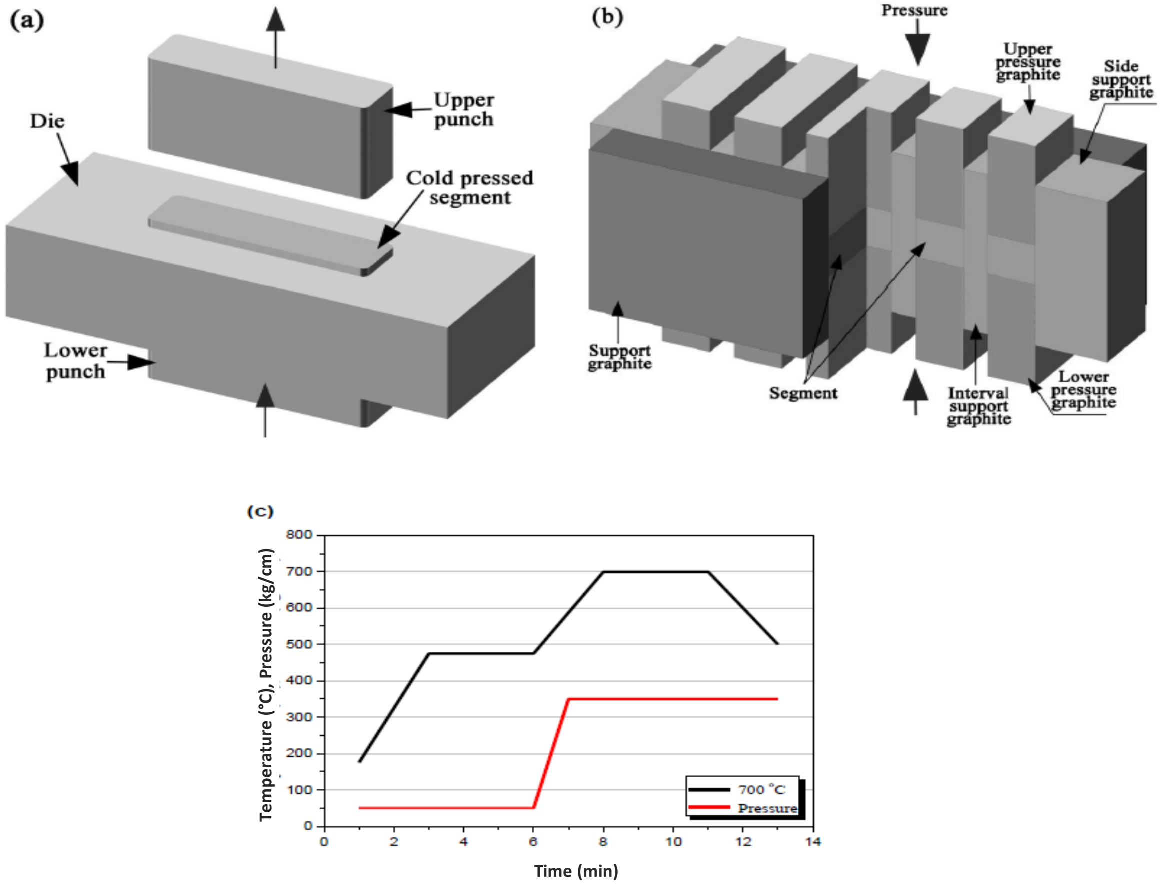

Figure 2. (a) the cold pressing of the segments, (b) the layout of the segments in the graphite mould and (c) sintering graph.

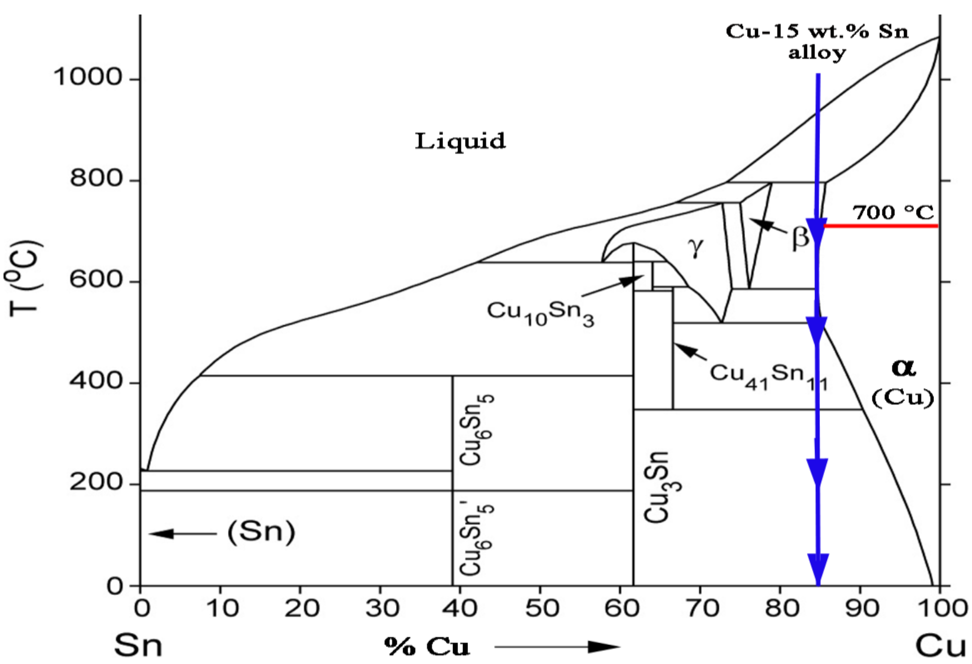

Figure 3. Cu-Sn binary phase diagram (Saunders and Miodownik, 1990).

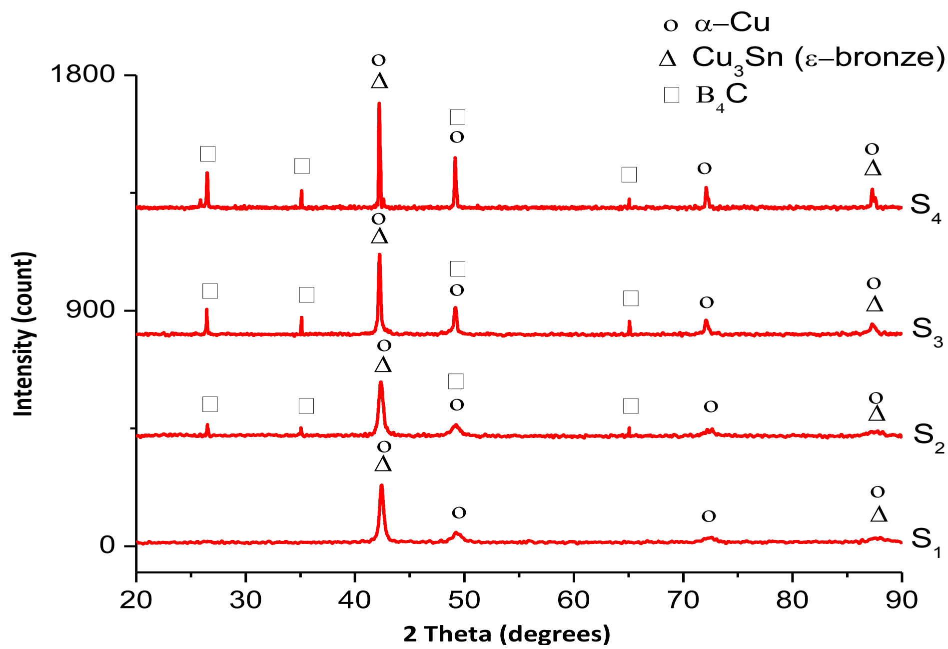

Figure 4. The XRD graphs of segments.

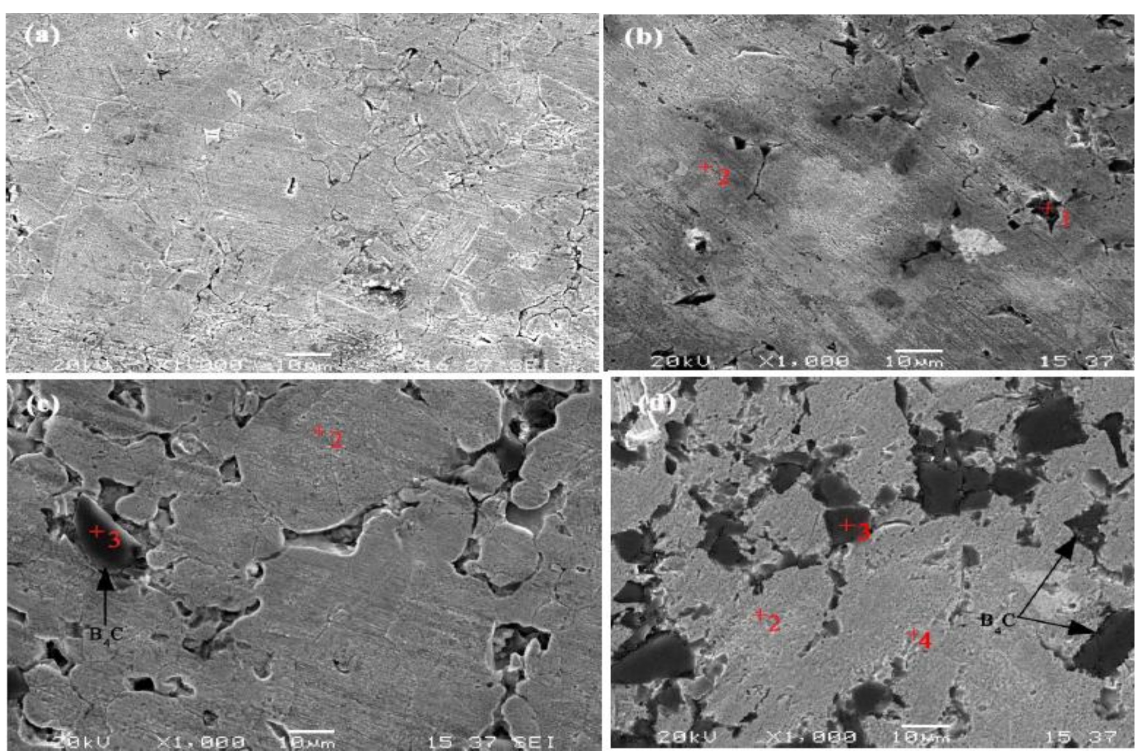

Figure 5. The SEM images of segment matrixes: (a) CuSn, (b) CuSn-2% B_4C, (c) CuSn-5% B_4C, and (d) CuSn-10% B_4C.

2, 5 and 10 wt.% B4C in weight to CuSn powder. The B4C particles were relatively homogeneously distributed throughout the microstructure and surrounded by CuSn (Figure 5). Under circumstances in which reinforcement particles in the composites do not disperse uniformly, the mechanical and physical properties of the composite are

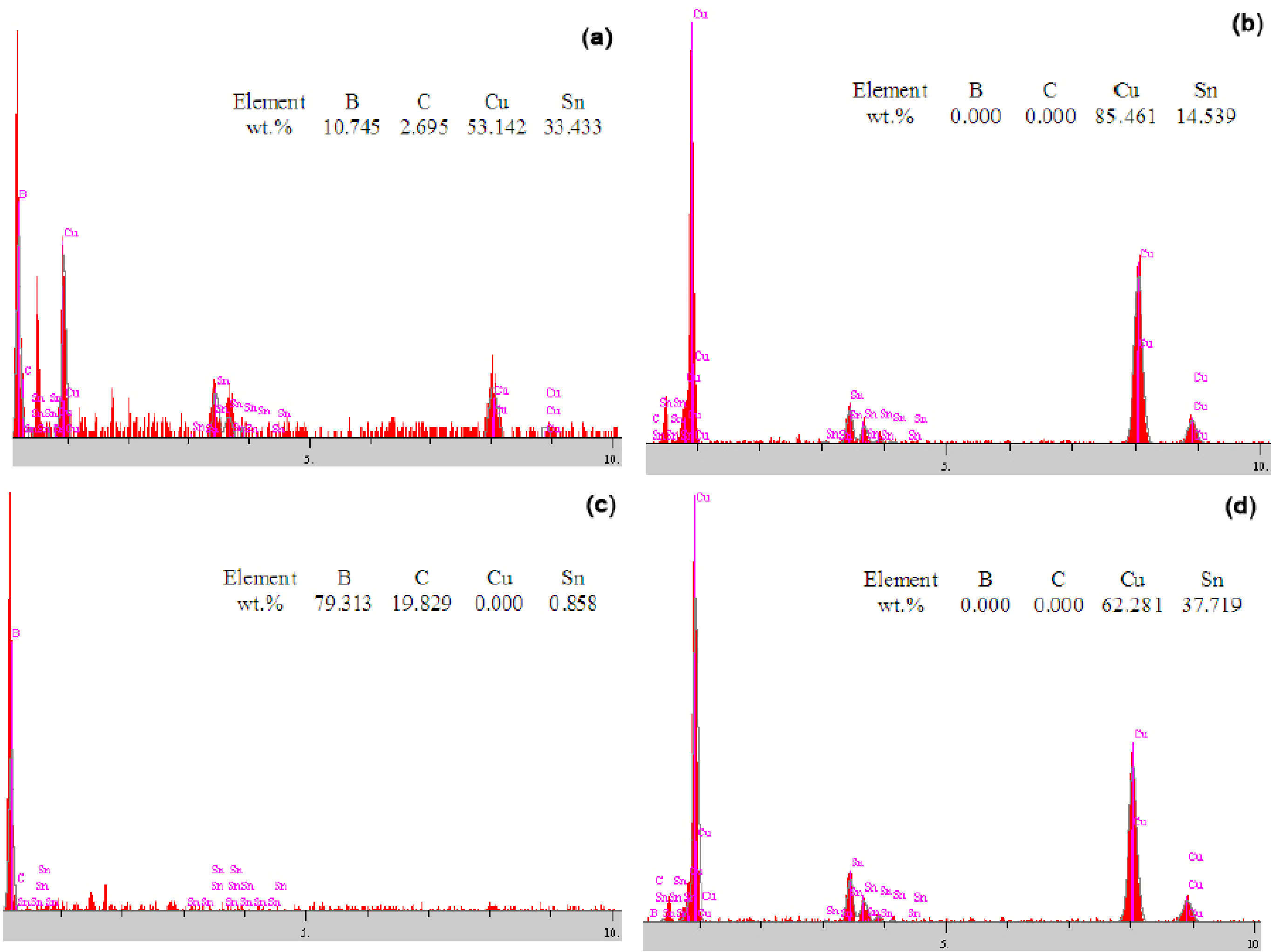

Figure 6. The EDS analysis of regions in the segments: (a) 1 region, (b) 2 region, (c) 3 region, and (d) 4 region.

adversely affected (Lee et al., 2001). In micrographs, light grey areas indicate CuSn matrix and dark grey and cornered shapes indicate the reinforcement component B_4C. As the rate of boron carbide increases, B_4C particles spread towards the grain borders of CuSn to form a network (Figures 5b, c and d). As illustrated in the XRD graphs, B_4C peaks become clear with increasing weight percentage of B_4C. The XRD graphs illustrate that there is no chemical reaction between CuSn and B_4C. Pores were formed at the grain borders in the microstructure of CuSn/B_4C segments. The level of porosity increased together with the increase of boron carbide rate. The highest pore rate was achieved at 10 wt.% B_4C. This may be due to reduction in compressibility of the B_4C powder.

Figure 6 illustrates the EDS analysis of regions identified in the SEM images illustrated in Figure 5. EDS analysis of region 1 is 10.745% B, 2.695% C, 53.142% Cu and 33.433% Sn. The region 1 illustrates the Cu_3Sn and B_4C phases formed at the grain border. EDS analysis of region 2 is 85.461% Cu and 14.539% Sn. Region 2 illustrates the CuSn. The analysis of region 3 was 79.313% B, 19.829% C and 0.858% Sn. This is the analysis taken from the boron carbide grain. EDS analysis of region 4 is 62.281% Cu and 37.719% Sn. Region 4 may be the Cu_3Sn phase formed at the grain boundary.

The effect of boron carbide on densities of segments is depicted in Figure 7 and Table 2. The sintered and theoretical densities of segments were used to determine their relative density. When boron carbide is introduced to the CuSn, it decreases the sintered density. This is due to the fact that the density of boron carbide is lower than that of bronze. The density of B_4C is 2.52 g/cm^3, while the density of bronze is 8.68 g/cm^3. Relative density also decreased as the amount of added boron carbide increases. This is due to the fact that the increased rate of added boron carbide has an adverse effect on sinterability. Another reason is the fact that a great difference in the melting points of the bronze and the boron carbide. The boron carbide may have a inhibiting

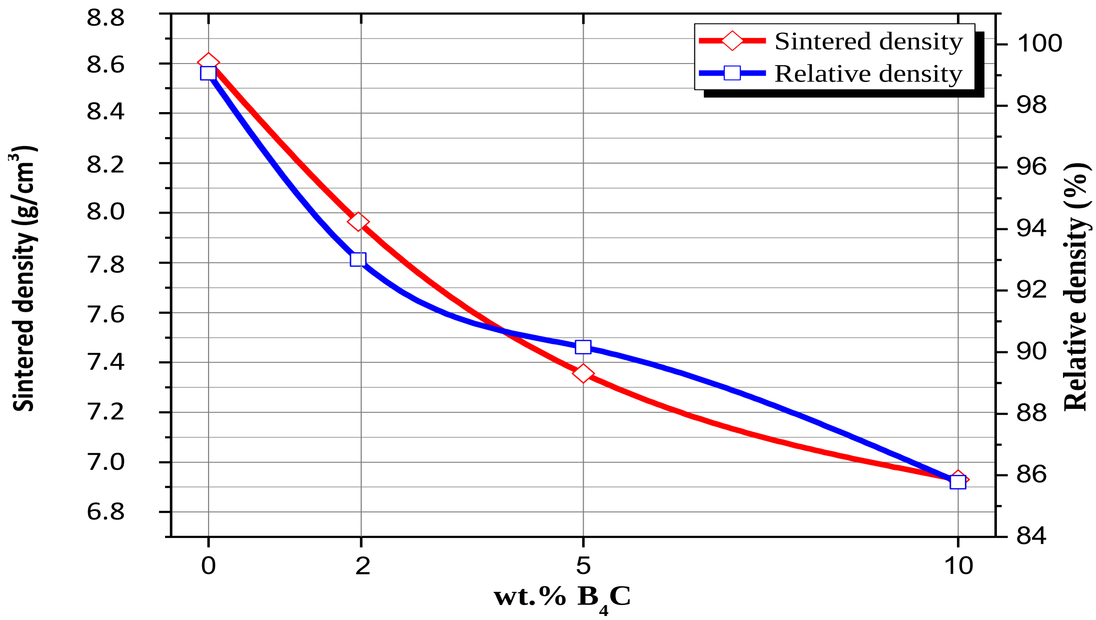

Figure 7. The effect ofboron carbide on the densities of the segments.

Table 2. The effect of B_4C particle content on the relative density of the segments.

Samples	Theoretical density (g/cm^3)	Sintered density (g/cm^3)	Relative density (%)
CuSn	8.68	8.60	99.05
2 wt.% B_4C	8.56	7.96	93.02
5 wt.% B_4C	8.37	7.55	90.16
10 wt.% B_4C	8.07	6.93	85.77

effect in the rearrangement of the particles during sintering (Rahimian et al., 2009). The highest compression for boron carbide added segments was obtained in the CuSn-2% B_4C segment, with a relative density of approximately 93.02% (Table 2).

Figure 8 shows hardness and bending strength as a function of the B_4C content in the segments. Hardness values were determined by taking the average of six different measurements on each segment. Hardness of the segments increased with increasing B_4C content. This may be explained by rule of mixture, applied to composite materials (Kim, 2000; Kumar et al., 2011). The hardness measurement values were 78 HB for CuSn, 87 HB for CuSn-2% B_4C, 109 HB for CuSn-5% B_4C, and 118 HB for CuSn-10% B_4C. The increase in the hardness of segments by addition of B_4C can be attributed to the dispersion strengthening effect (Min et al., 2005, 2007).

The bending strength for each segment was determined by using a three-point bending test. The three-point bending test was repeated five times for every segment. Figure 8 illustrates the effect of boron carbide on the bending strength. The bending strength of the segments decreased together with the increase in the amount of boron carbide. The bending strengths were 325 MPa for CuSn, 289 MPa for 2% B_4C, 265 MPa for 5% B_4C and 234 MPa for 10% B_4C. This situation can be explained that the increase of boron carbide particles lead to the increase of the total area of the weakly bonded interface, which results in the decrease of the bending strength (Jin et al., 2009). In addition, the difference in thermal expansion coefficient between B_4C and CuSn contributes to the interfacial stress. This stress may cause the bending strength to decrease (Samuel et al., 1995). Furthermore, the level of porosity affects the bending strength (Dwan, 2007).

In general, the failure of composite materials corresponds to three possible processes, e.g., particles fracture, weak bonding at the interface and matrix material exhaustion (Park and Mohamed, 1995). Many dimples were observed in the fractured surface of the segment without boron carbide (Figure 9a). The failure behavior of the CuSn matrix is ductile fracture. Weak bonds was formed among bronze grain boundary as a result of insufficient sintering. Therefore, the pores appeared in the structure. According to Figure 9a, necking is also more intense in this sample in comparison

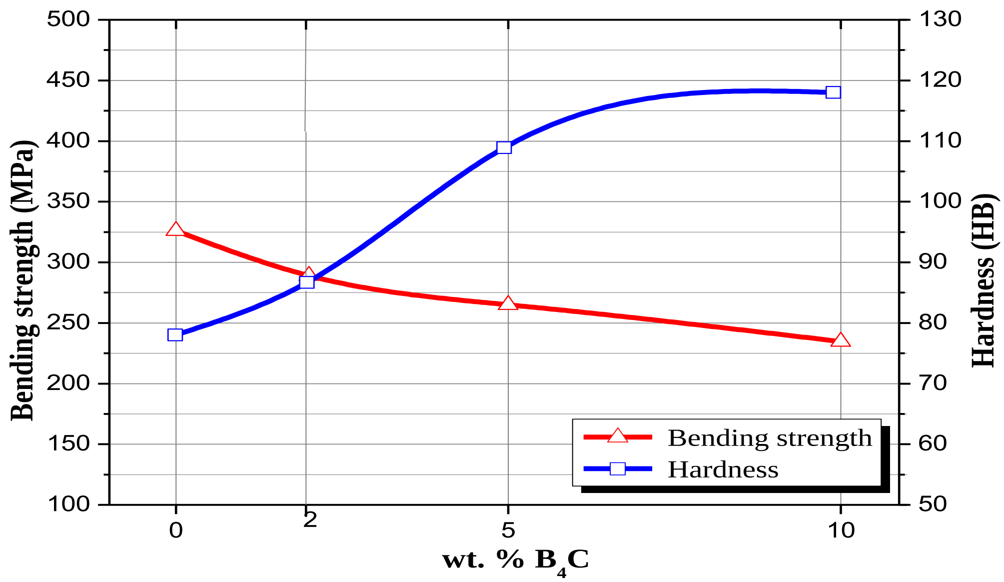

Figure 8. The effect of B_4C on the bending strength and hardness of segments.

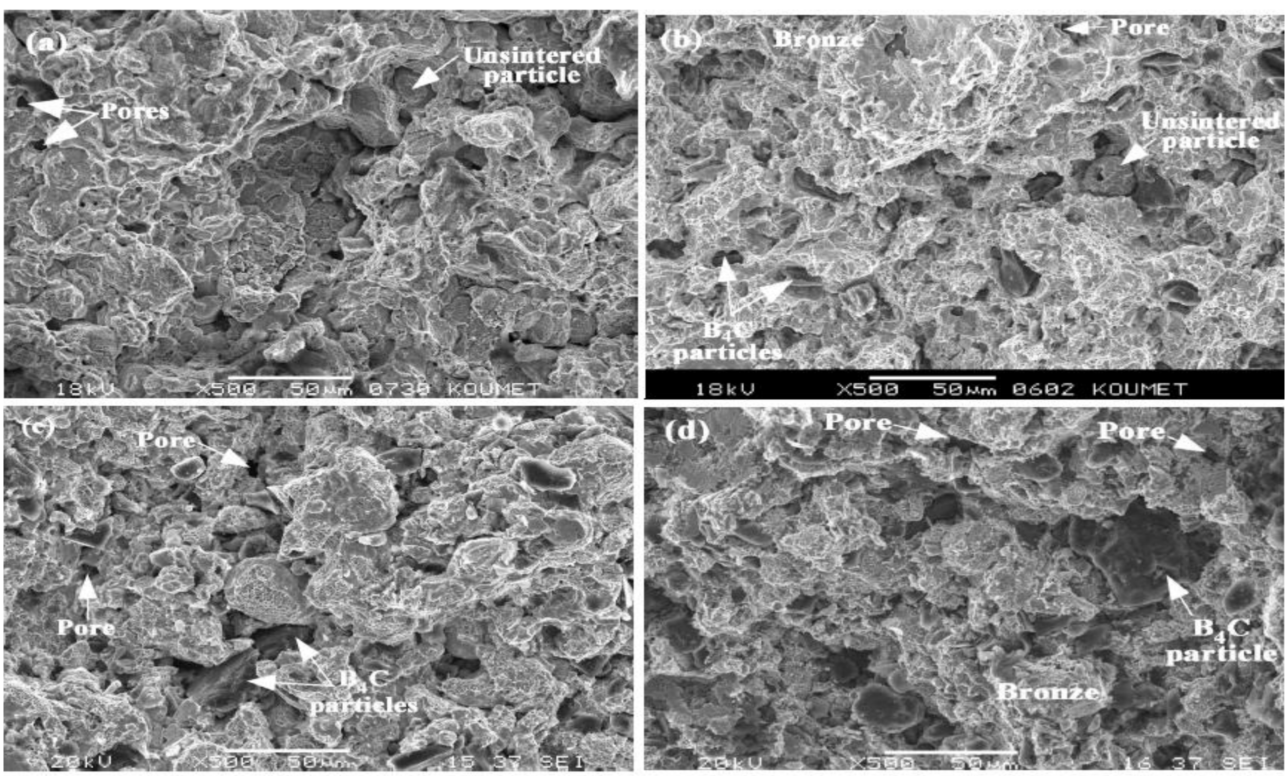

Figure 9. The SEM images of the fracture surfaces of the segments: (a) CuSn, (b) 2% B_4C, (c) 5% B_4C, and (d) 10% B_4C.

to other samples. The fracture surfaces of the bronze-B_4C segments are shown in Figures 9b,c and d. It can be seen that there is a weak bonding between B_4C and bronze. This weak bonding was due to insufficient sintering conditions. Generally, insufficient sintered P/M materials have low mechanical properties (Brunski, 1996). The bending strength can be increased by overcoming the weak bonding at the interface between

B_4C and bronze, by increasing the pressing pressure and sintering temperature.

Conclusions

The effects of boron carbide on the microstructure and mechanical properties of diamond cutting segments fabricated by hot pressing were investigated. The following conclusions are made:

1. Microstructure observation demonstrates a relative homogenous distribution in bronze of B_4C particulates.
2. Boron carbide particles formed at the grain boundary of bronze, and were surrounded by bronze. The increase in the amount of boron carbide added increased the amount of pores.
3. Relative density of segments decreased as the amount of added boron carbide increased. The highest densification for CuSn/B_4C segments was obtained in the CuSn-2% B_4C segment, with a relative density of approximately 93.01%.
4. Hardness of segments was increased as the amount of boron carbide particle increased. The highest hardness value was 118 HB, obtained by adding 10% B_4C.
5. The bending strength of the segments decreased together with the increase in the amount of boron carbide. The bending strengths were 325 MPa for CuSn, 289 MPa for 2% B_4C, 265 MPa for 5% B_4C and 234 MPa for 10% B_4C. This decrease is related to weak bonding between the B_4C and the bronze due to insufficient sintering conditions.

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