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INVESTIGATION OF THE USABILITY OF CUBIC BORON NITRIDE CUTTING TOOLS AS AN ALTERNATIVE TO DIAMOND CUTTING TOOLS

BADANIE UŻYTECZNOŚCI NARZĘDZI TNĄCYCH Z REGULARNEGO AZOTKU BORU JAKO ALTERNATYWY DLA DIAMENTOWYCH NARZĘDZI TNĄCYCH

Diamond and cubic boron nitride (cBN) cutting segments were produced using hot pressing technique for this study to be used in cutting natural stone. cBN grains were added to bronze powder, the chosen matrix, at a rate of 0%, 20%, 40%, 60%, 80%, and 100% (according to percentage by weight). Segments were produced under a pressure of 35 MPa, at a sintering temperature of 600°C, over a sintering time of 3 minutes. The cutting properties of the produced segments were determined by cutting Ankara andesite. A Scanning Electron Microscope (SEM) and an X-Ray Diffractometer (XRD) were used to analyse the microstructure, phase compound, and wear surfaces of each segment type.

Keywords: cBN cutting tools, hot-pressing technique, wear

Diamentowe i wytworzone z regularnego azotku boru (cBN) techniką prasowania na gorąco segmenty tnące zostały zastosowane do cięcia kamienia naturalnego. Ziarna cBN dodano do proszku brązu (matrycy) w ilości 0%, 20%, 40%, 60%, 80% i 100% (wagowo). Segmenty wytworzono pod ciśnieniem 35 MPa, w temperaturze spiekania 600°C, w czasie 3 minut. Właściwości tnące wytworzonych segmentów zostały określone przez cięcie andezytu. Skaningowej mikroskopii elektronowej (SEM) i dyfrakcji rentgenowskiej (XRD) użyto do analizy mikrostruktury, składu fazowego, oraz zużycia powierzchni każdego typu segmentu.

1. Introduction

Boron nitride is a chemical compound that can exist in two forms; cubic and hexagonal. Cubic boron nitride (cBN) transforms into hexagonal boron nitride (hBN) at high temperatures. While hexagonal boron nitride is used in manufacturing refractory materials, cubic boron nitride is used in manufacturing composite materials. cBN is the second hardest material after diamond, and possesses numerous excellent physical and chemical properties, high resistance to chemical attack, and mechanical properties [1-3]. Diamond causes graphitisation during studies conducted at high temperatures; ultimately reducing its performance. However, graphitisation does not occur at high temperature when cBN is used, due to its properties such as high thermal and chemical stability [4-7]. The fundamental reason behind the bonding structure of cBN is that it has better thermal and chemical stability in comparison to diamond [8]. While diamond has covalent bonds, cBN has both covalent and ionic bonds [9].

cBN is a material with huge potential in the cutting tool industry [10,11]. cBN tools are produced using cBN and ceramic or metal binders under high pressure and high tempera-

ture. These tools can be used for cutting the following materials: alloy steel with a hardness of around HRC 70, forging steel with a hardness of around HRC 45-68, chill iron, nickel-base superalloy, and cobalt-base superalloy [12].

There are studies available in literature regarding the choice of suitable matrix for cutting tools of natural stone, the properties of synthetic diamond, the use of coated diamond, the manufacturing conditions of tools and the wear these tools are exposed to, and fracture mechanics [13-16]. There aren't studies available in literature that addresses the usage of another hard grain instead of synthetic diamond, which carries out cutting procedure in diamond cutting tools.

The aim of this study was to investigate the usability of cubic boron nitride as an alternative in natural stone cutting tools. Different amounts of cubic boron nitride were added to the segment matrix in order to achieve this purpose. The cutting properties of the segments were identified by cutting Ankara andesite stone. A Scanning Electron Microscope (SEM) and an X-Ray Diffractometer (XRD) were used to analyze the microstructure, chemical compound, and wear surfaces of each segment type.

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2. Experimental Studies

Bronze powder (Cu – 15 wt.% Sn) with a grain size of -325 mesh was used as matrix material to manufacture natural stone cutting tools. The diamond and cubic boron nitride (cBN), in size from 40/50 U.S. mesh, were in a sintered bronze matrix at concentrations of 30 (a concentration of 100 is conventionally defined as 0.88 g of diamond per cubic centimetre of impregnation: approximately 25% by volume). Table 1 illustrates the sample groups and production parameters used to manufacture diamond/cBN cutting segments. SEM micrographs of the diamond, cBN and the bronze powder are given in Fig. 1. As shown in the SEM micrographs, the bronze powder has a spherical structure, the cBN grains have a variable structure and are sharp-edged, and the diamond grains have a cubic octahedral structure.

TABLE 1

The matrix groups and production parameters used to manufacture segments

| No | Matrix | Cutting grain (wt.%) | | Sintering conditions | | |
|----|--------|----------------------|-----|----------------------|------------------|----------------|
| | | Diamond | cBN | Time (min) | Temperature (°C) | Pressure (MPa) |
| 1 | Bronze | 100 | - | 3 | 600 | 35 |
| 2 | Bronze | 80 | 20 | | | |
| 3 | Bronze | 60 | 40 | | | |
| 4 | Bronze | 40 | 60 | | | |
| 5 | Bronze | 20 | 80 | | | |
| 6 | Bronze | 0 | 100 | | | |

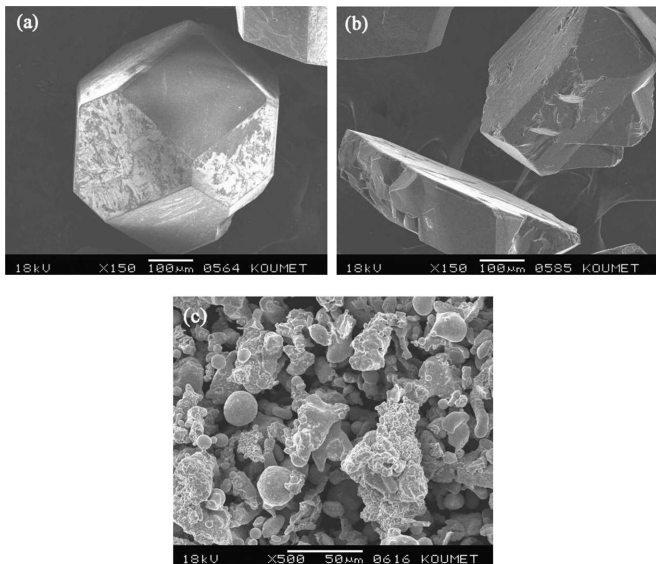


Fig. 1. SEM micrographs of (a) diamond grain, (b) cBN grain, and (c) bronze powder

Bronze powder, diamond, and cBN grains were mixed together with the addition of a 1 wt.% of paraffin wax, at a speed of 20 rpm, for 30 minutes. Firstly, the segments were prepared via cold press with a pressure of 15 MPa. Then, the cold-pressed segments were hot pressed in graphite moulds

for 3 min at 600°C, with an applied pressure of 35 MPa using an automatic hot pressing machine. Fig. 2 illustrates the cold pressing of the segments, and the layout of the segments in the graphite mould. The circular diamond saw blade used during the tests had a diameter of 300 mm, and a steel core of thickness 1.8 mm, 21 pieces of diamond impregnated segments (size 40×7×3.2 mm) were brazed to the periphery of circular steel core with a standard narrow radial slot.

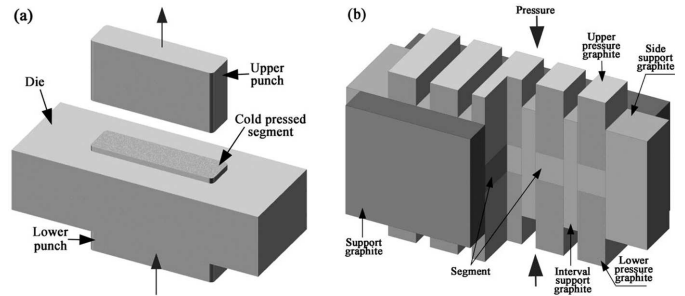


Fig. 2. (a) The cold pressing of the segments, and (b) the layout of the segments in the graphite mould

Three-point bending tests were performed using an Instron 4411 universal testing machine, at a loading rate of 1 mm/min, at room temperature, to determine the transverse rupture strength (TRS) of the segments. Five tests were repeated for each specimen, and the results were averaged. The size of the hot-pressed segment for the three-point bending test was 40×7×3.2 mm. Fig. 3a displays the three-point bending test setup. The cutting performance of cutting tools were tested by cutting a 500×150×30 mm andesite using a PLC-controlled marble cutting machine. The andesite stone cutting process is shown in Fig. 3b. The amount of andesite cut during the cutting process was calculated by multiplying the cut length with the cut depth. The sawing tests were completed with a total of approximately 60 m² sawn area. The diameters of the circular diamond saw blades were measured before and after the cutting procedure using a digital caliper with a resolution of 10⁻² mm. Ten measurements from each saw blade were taken. The wear rate (mm/m²) of each segment was calculated by dividing the radial wear (mm) of each segment with the amount of andesite cut (m²) [15,17]. The cutting parameters of the andesite stone are summarized in Table 2.

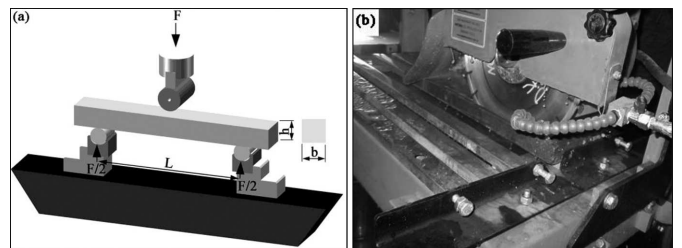


Fig. 3. (a) Three-point bending test setup and (b) cutting process

A scanning electron microscope (SEM) (JEM-2100F, JEOL, Japan) and an X-ray diffractometer (XRD) (Bruker AXS D8 Advanced System, Germany) were used to investigate the fractured and wear surfaces, identify the phase structures, and how the microstructure of segments changed based on the cBN content.

TABLE 2

| Cutting parameters | |
|-------------------------------------|-----------------------|
| Feed rate (m/min) | 0.8 |
| Depth of cut (mm) | 30 |
| Peripheral speed (m/s) | 45 |
| Cutting rate (cm ² /min) | 240 |
| Cooling medium and flow rate | City water, 20 l/min |
| Cutting mode | Down-cutting |
| Natural stone type | Ankara andesite stone |

3. Results and discussion

Figure 4 illustrates the XRD graphs of cubic boron nitride and diamond cutting segments. XRD analyses identified cBN, diamond, α -Cu, and Cu₃Sn phases in the segments. The fact that there was no phase between bronze, diamond, and cBN is due to the fact that the chosen sintering temperature was low. In other words, there was only a mechanical bonding between the cutting grains and the matrix (bronze). XRD graphs show that there was an increase in the intensity of cBN peaks together with the increase in the amount of cBN added to the matrix.

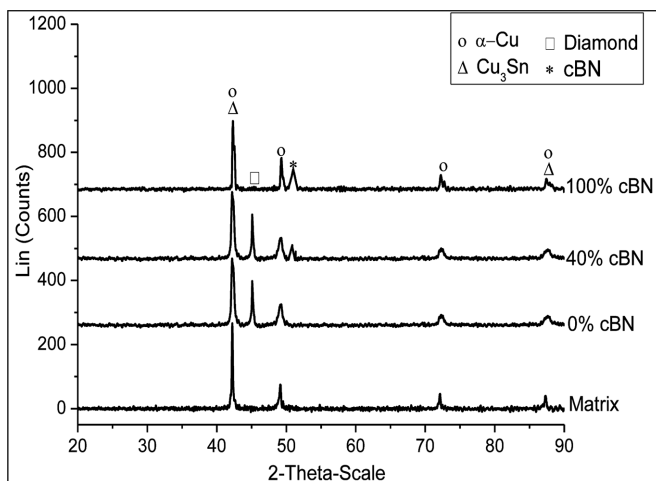


Fig. 4. XRD graphs of segments

Fig. 5 illustrates the transverse rupture strength (TRS) of segments versus cBN content. It can be seen that the TRS of cBN segments was higher in comparison to diamond segments. The TRS values for 0%, 20%, 40%, 60%, 80%, and 100% – cBN segments were 241 MPa, 274 MPa, 292 MPa, 299 MPa, 305 MPa, and 312 MPa, respectively. The TRS of the 100% cBN segment was approximately 30% more than the TRS of the 100% diamond segment; the possible reason behind this is that cubic boron nitride forms a better mechanical bonding with the matrix in comparison to diamond.

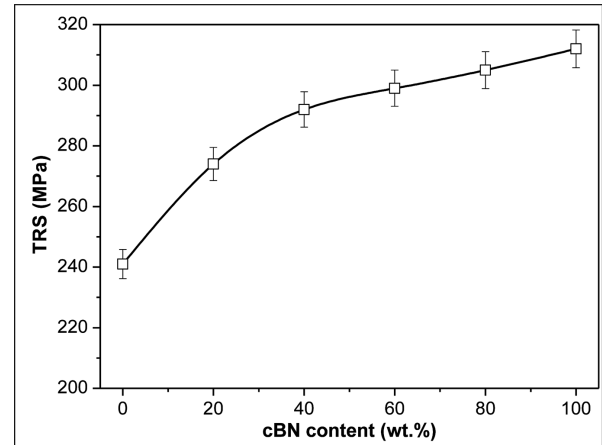


Fig. 5. The effect cBN content on the transverse rupture strength (TRS) of segments

Figure 6 shows the SEM images regarding the fractured surfaces of diamond and cBN cutting segments. The SEM images illustrate that the interface bonding between the matrix and cBN is stronger than the interface bonding between the matrix and the diamond grain. This is related to the fact that the cBN grains used in this study have a larger bonding surface in comparison to diamond grains. All fracture images prove that bonding between the matrix and cutting grains was weaker than the desired level. The excessive porosity in the matrix also raises attention in the SEM images of fracture surface; the reason being inadequate sintering conditions.

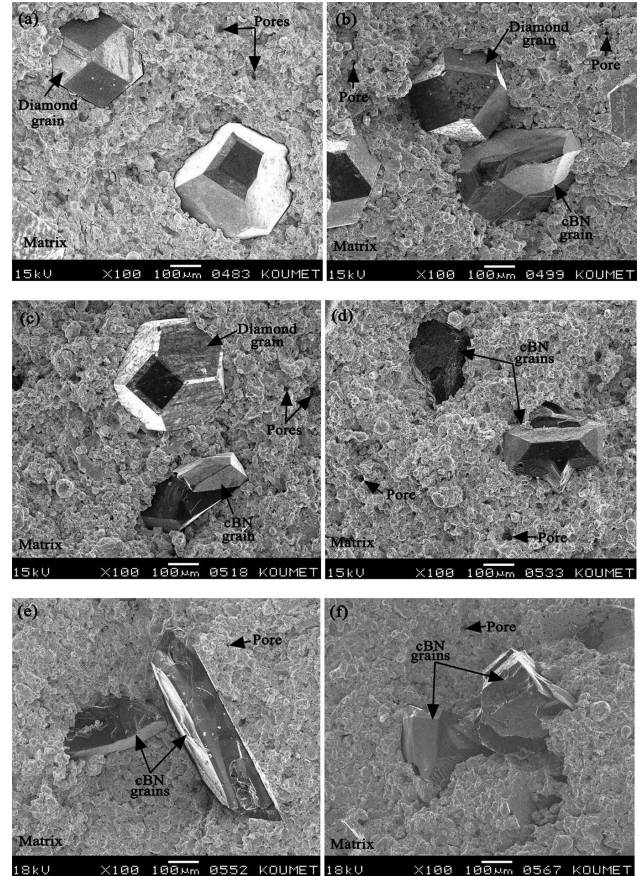


Fig. 6. The SEM images of the fracture surfaces of the segments: (a) 0% cBN, (b) 20% cBN, (c) 40% cBN, (d) 60% cBN, (e) 80% cBN, and (f) 100% cBN

The curve in Fig. 7 illustrates the results of wear rate as a function of cBN content for the segments, sintered at 600°C. As illustrated, the wear rate of the segments increased together with the increase in cBN content. The wear rate for 0% cBN was 0.047 mm/m², 0.049 mm/m² for 20% cBN, 0.053 mm/m² for 40% cBN, 0.065 mm/m² for 60% cBN, 0.085 mm/m² for 80% cBN, and 0.115 mm/m² for 100% cBN.

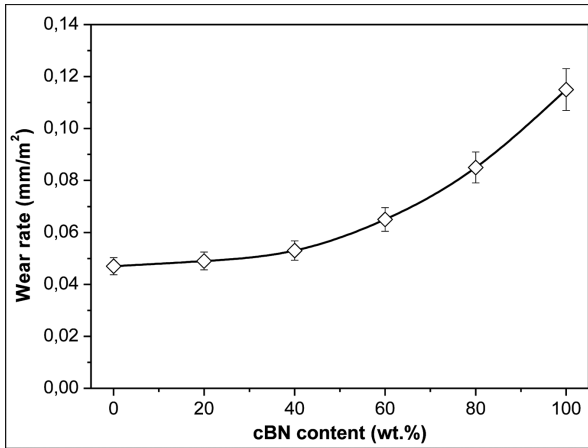


Fig. 7. The effect the cBN content has on the wear rate of the segments

During the natural stone cutting process, the cutting grain pulls out after a certain time owing to worn matrix. New diamond grains appear as the matrix continues to be worn and the cutting process maintains. This cycle, which should continue until the segment is complete, is an indicator of how productive segments perform the cutting procedure, and the compatibility between the matrix and diamond grain. In the event that new diamond grains do not appear, the cutting tool becomes blunt and loses its cutting function [18]. Figure 8a illustrates the new diamond grains that appear on the wear surface of a segment produced with 100% diamond addition.

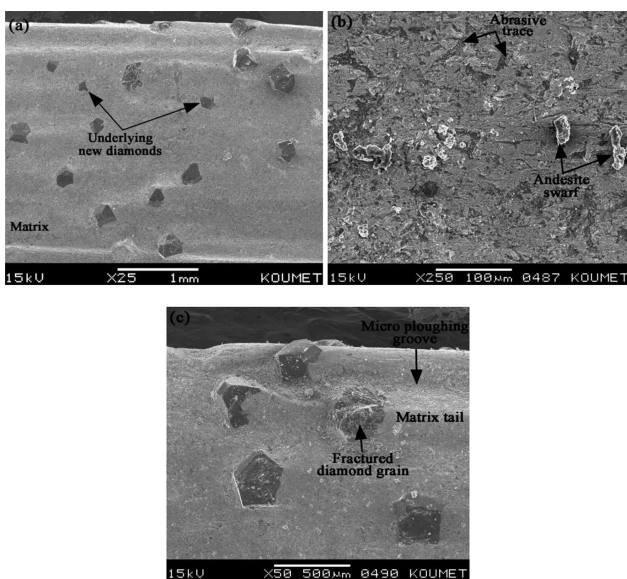


Fig. 8. The worn surface of diamond cutting segment (100wt.%): (a) underlying new diamonds, (b) abrasive traces formed in the matrix, and (c) micro ploughing groove, matrix tail and fractured diamond grain

In general, the wear mechanism of matrix in cutting tools is abrasive wear. Figure 8b illustrates the abrasive traces formed in the matrix. These traces form as a result of the friction between the natural stone and the matrix during the cutting process. Natural stone create a micro ploughing effect which establishes the grooves necessary for the swarf to flow within the matrix. The inhibition of wear by the abrasive swarf leads to the development of a matrix tail. The matrix tail supports the diamond grain to allow an effective cutting process [19,20]. It is possible that fractures occur in the diamond grain as cutting tool comes into contact with the natural stone during the cutting process. The new fracture surfaces that appear after diamond grains fracture form new cutting edges at the same time. At this point the diamond grain cuts as normal, but its resistance towards impacts decreases significantly [21]. Figure 8c illustrates the micro ploughing grooves, the matrix tail, and the state of fractured diamond grains.

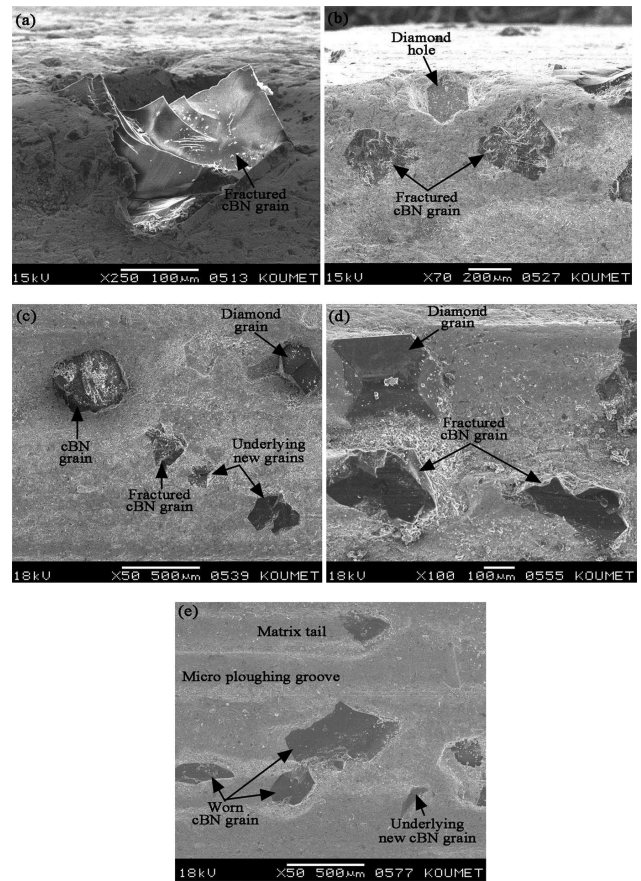


Fig. 9. The worn surfaces of the segments: (a) 20% cBN, (b) 40% cBN, (c) 60% cBN, (d) 80% cBN, and (e) 100% cBN

Figure 9 illustrates SEM images regarding the wear surfaces of cBN cutting tools after the andesite cutting process. It is obvious that the fracture grains on the wear surface are cBN (Figure 9a). There was more fracturing in cBN grains in comparison to diamond grains; the reason being that cBN has lower hardness in comparison to diamond [22]. The diamond grain holes were observed on the wear surface (Figure 9b). The similarity between the geometry of diamond grain and holes concluded that these holes belong to diamond grains. The fact that cutting grains pull out easily is related to inadequate sintering conditions. New cutting grains appeared in the

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matrix, which allowed the cutting process to continue (Figure 9c-d). Figure 9e illustrates that matrix tail formation was less in cBN cutting tools in comparison to diamond cutting tools. The matrix tail did not form clearly since the mechanical strength of cBN is lower than diamond; therefore, it wears, or fractures, quicker during the cutting process, which wears the matrix even more. As illustrated in Figure 9e, micro-ploughing grooves, required to discharge andesite swarfs from the cutting region as soon as possible, also formed in cubic boron nitride cutting tools.

4. Conclusions

1. Natural stone cutting segments were produced successfully by adding different amounts of diamond / cBN to a bronze matrix at a sintering temperature of 600°C, under a pressing pressure of 35 MPa, and for a sintering time of three minutes.
2. XRD analysis of segments concluded that α -Cu, Cu₃Sn, diamond, and cBN phases formed in the microstructure, no phases formed between the cutting grains and matrix, and accordingly that the bonding between the cutting grain and the matrix was only mechanical.
3. Three-point bending tests concluded that the 100% cBN segments had the highest TRS; the reason is that cBN forms a better mechanical bonding with the matrix in comparison to diamond. Fracture surfaces proved that the matrix had a porous structure; this was related to inadequate sintering conditions.
4. The cutting test concluded that radial wear of cutting segments increased together with the increase in the amount of cBN added. SEM images proved that there were more fractures and wear in cBN grains in comparison to diamond grains in segments; the reason is that the mechanical properties of cBN grains are lower than those of diamond grains.
5. Results concluded that as cubic boron nitride is cheaper than diamond it can be used to process softer natural stones, or can be added to matrix together with diamond.

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