STUDY ON THE HARDNESS AND WEAR PERFORMANCE OF LOW CONTENT POLYCRYSTALLINE CUBIC BORON NITRIDE CUTTING TOOLS

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Abstract - Low content polycrystalline cubic boron nitride (PcBN) samples were synthesized by synthesis method with cubic boron nitride (cBN) contents (wt%) of 50%, 60%, and 70%, respectively. Using titanium nitride as the ceramic adhesive and aluminum as the metal adhesive, the synthesis was carried out in a UDS-650 six sided hydraulic press with a pressure of 5.5 GPa, a temperature of 1400-1600 ° C and a sintering time of 10 minutes to obtain PcBN with a thickness of 4 millimeters. The phase composition and microstructure of PcBN were confirmed with apparatus of XRD and SEM. Results indicated that with the increasing of cBN content, the Vickers hardness value of PcBN shows same trend. The effect of ball milling time and working power on increasing the hardness of materials is not significantly. PcBN cutting tools with 50% cBN content exhibit abrasive wear and poor wear resistance. The cutting tools with 60% cBN content and 70% cBN content both have lower wear degree, but the PcBN cutting tools with 60% cBN content is significantly better than that of 70% cBN content. The PcBN cutting tools with 60% cBN content shows excellent wear resistance after mid-term turning, then the wear on the back surface slows down rapidly and exhibits a stable micro wear state.

Keywords: High temperature and high pressure; PcBN; cutting tool; XRD; SEM; Low content.

1. Introduction

Polycrystalline cubic boron nitride (PcBN) is an artificially synthesized material with the hardness that only next to diamond. Due to excellent wear resistance, corrosion resistance, heat resistance and thermal conductivity, PcBN has been widely accepted in high-speed cutting of wear-resistant non-ferrous metals, black metals, chemically active materials, high hardness and high-strength materials, etc [1,2]. PcBN with different cBN contents exhibit different properties, application fields and processing objects [3-5]. Generally, cBN with a volume content below 70% is referred to as low content PcBN, while volume content above this level is referred to as high content PcBN [6]. High content PcBN with relatively higher hardness and thermal conductivity is commonly used for processing high hardness and high temperature resistant materials such as high-temperature alloys, pure metals (pure nickel, pure tungsten) and wear-resistant cast iron. Low content PcBN with relatively higher toughness and strength is generally used for processing quenched steel [7].

The hardness of PcBN cutting tools comes from the high hardness of cBN, which can avoid the disadvantages of easy cleavage and fracture of single crystals [8]. Because of high thermal stability, PcBN cutter tools could continual work at high temperatures of 1200° C, even could be used for processing titanium alloy materials. Generally, the surface hardness (HV3000-6000) of PcBN materials has exceeds most hard alloys and carbon tool steels. Moreover, PcBN has better wear resistance than hard alloys and ceramics while machining high hardness materials [9]. PcBN cutting tools used in highly automated machining technology could reduce the auxiliary time of tool replacement, as well as reduce size dispersion and dimensional deviation [10, 11].

Currently, more researchers have focused on the manufacturing technology to improve properties of PcBN. Han Jinlong et al. prepared PcBN materials using cBN with different grain diameters and contents as raw materials through a six sided top pressing mechanism [12]. Exploring into the microstructure of PcBN material and detect bending strength and density, researchers have found that the less cBN content (below 70 wt%) and the smaller diameter of cBN grain, the greater the flexural strength and density of PcBN. While the cBN content reaches 70 wt%, there is a significant bridging phenomenon between cBN grains, resulting in a decrease in the density and bending strength of the samples.

Yang Limin et al. synthesized PcBN materials using Al and TiC as binders at 5.5 GPa and 1350° C [13]. Results proved that during the sintering process, Al reacts with cBN to form AlN and AlB2 phases, while TiC never react with cBN. With the increasing of the Al content, the strength of cBN based composite materials first decreases and then increases. AlN and AlB2 can strengthen PcBN materials to a higher extent. During the process, TiC is used as a binder, adding 10wt% TiC could obtain PcBN materials.

Liu Yinjuan et al. prepared PcBN materials by high-pressure infiltration method using Si as the melt [14]. Researchers have found that sintered PcBN materials with high hardness, high thermal stability and high cutting performance could be obtained under high-pressure infiltration of 5.5 GPa and 1500° C. The starting temperature of oxidation can reach 1300 ° C and the cutting performance is superior to common materials.

As the main phase of PcBN, cBN content might influence the performance of PcBN [15]. Once the cBN content is less than 40 wt.%, the synthesized PcBN material might exhibit lower hardness, which will lead to structural breakdown of plastic flow during cutting process. However, Once the cBN content is higher than 95 wt.%, the PcBN material will show lower wearing resistance. The low bonding degree between the binder and cBN grains might be the primary reason for above, consequently, the holding force will also be insufficient to keep structural stability.

This study selected titanium nitride as ceramic adhesive and aluminum as metal adhesive to synthesize PcBN with low cBN content under high temperature and high pressure (HTHP). The phase composition and microstructure of PcBN were studied with apparatus of XRD and SEM. The mechanical properties of PcBN samples with different cBN contents were evaluated through hardness testing and cutting testing to obtain a better ceramic metal bonding ratio.

2. Fabrication of PcBN Samples

The primary component used in this experiment is micro powder of cBN with an average particle size of 4 microns. The aluminum powder acts as metal bonding agent has a purity of 99.9%. Aluminum powder with a lower melting point can form liquid phase at high temperatures, which facilitates the flowing of cBN particles and binders, consequently promoting sintering process. Titanium nitride is an adhesive with a purity of 99.9%, which can chemically bond with cubic boron nitride at HTHP condition.

The preparation procedure of PcBN samples is shown in Figure 1 During the fabrication process, cBN micro powder was added in with content of 50%, 60% and 70%, respectively. The content of aluminum powder remains constant. The amount of titanium nitride is determined by remaining amount. After weighing above components, mix the materials in anhydrous ethanol, dry and pull into metal cups with hard alloy. After applying pre pressure, vacuum heat treatment is carried out, finally the assembly of pyrophyllite blocks is completed. Figure 2 describes the schematic diagram of assembling pyrophyllite blocks.

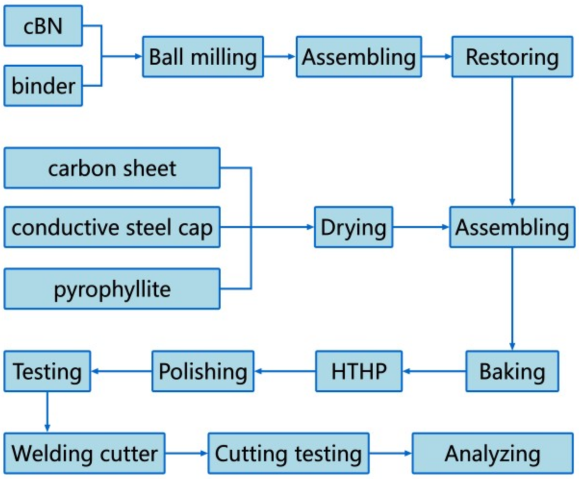


Figure 1: Preparation process of PcBN samples

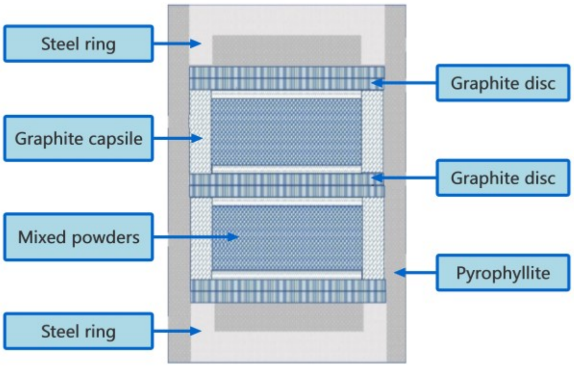


Figure 2: Schematic diagram of sample assembling

The six sided top press machine is an important equipment for synthesizing polycrystalline boron nitride. The hexahedral top press machine has 6 working oil cylinders, with a first stage pressure of up to 8GPa. A second stage pressure boosting device is directly placed in its hexahedral pressure chamber, which can form an octahedral pressure chamber with a maximum pressure of 25 GPa and a maximum temperature of 2500 ℃. The heating method can be optical waveguide heating method. In this study, PcBN synthesis was carried out on the UDS-650 six sided hydraulic press (Figure. 3), with a synthesis pressure of 5.5 GPa, a synthesis temperature of 1400-1600 ° C and a sintering process time of 10 minutes. After processing the plane and outer circle, PcBN samples with a diameter of 12.5 mm and a thickness of 4 millimeters were obtained, which can be used for hardness testing.

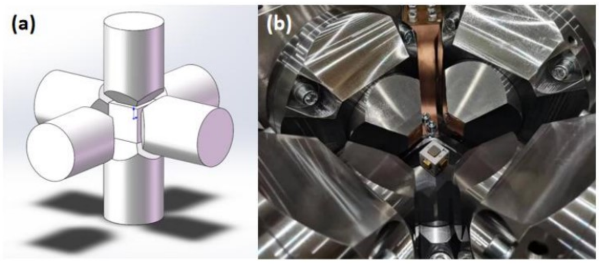


Figure3: Six-sided hydraulic press machine (a) structural diagram (b) physical image

Smartlab X-ray diffractometer (XRD) was used to characterize the phase of PcBN sintered bodies with different compositions under HTHP conditions. During the testing process, the X-ray source is a copper target and the testing angle 2θ of Kα rays ranges from 20° to 90°. After rough processing, the PcBN sample is subjected to precision grinding and polishing treatment to remove any residual pyrophyllite on surface for further testing in XRD.

By scanning electron microscopy (SEM) (JOEL, JSM-6380), the morphology and microstructure were observed. Finally, low content PcBN samples were welded onto the cutter body and made into standard blades for cutting experiments. By observing and measuring the wear width of the cutting surface with a metallographic microscope (MEIJI, MT8100), the physical properties of the material is studied.

3. Experimental Results and Discussion

3.1 Phase Analysis of Synthesized PcBN

The phase composition of PcBN, synthesized by different contents of titanium nitride and cBN micro powders with aluminum under HTHP, shows no significant differences. As is shown in Figure 4, all the phases of PcBN with different cBN contents were composed of cBN, TiN, TiB2 and AlN. The differences in the phase diagram are reflected in the fact that the relative intensity of the reactant diffraction peaks changes with the addition of raw material content. The constant phase composition is closely related to the synthesis temperature. As to the high content PcBN sintering, no AlB2 phase was found. During HTHP sintering, molten Al easily flows into the gaps between cBN grains, resulting in the direct formation of AlN phases around cBN grains, while most of the boron atoms generated by the reaction dissolve in AlN. From the figure, it can be seen that the AlN diffraction peak has high intensity and sharp shape, without the characteristic peak of AlB2, which may be due to the small amount of added Al being the reason for the absence of AlB2 generation. All molten Al reacted on the surface of cBN grains, indicating that all Al in the PcBN sample sintered under high temperature and high pressure conditions was transformed into AlN phase.

The sintering temperature of low content PcBN is lower, which may be related to the relatively low content of AlB2 products, which has not reached the lower limit of XRD detection. In addition, according to previous research, the determined aluminum content may also be one of the reasons for the consistency of PcBN products with 50%, 60%, and 70% cBN content.

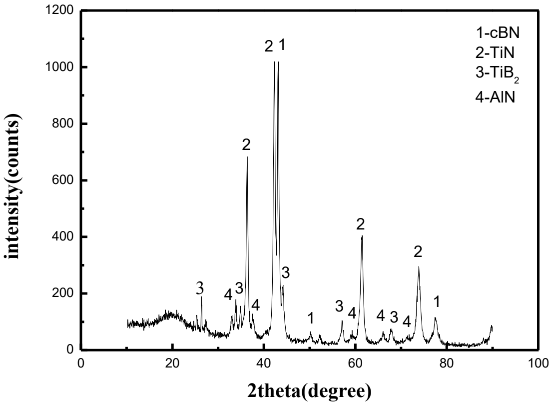


Figure 4: XRD pattern of low content PcBN with Al and 30 wt% TiN as the binder

3.2 SEM Analysis of PcBN Samples

Figure 5 shows the SEM image of PcBN samples with cBN contents of 50%, 60%, and 70% (wt), respectively. It can concluded that the microstructure of PcBN sintered body is related to the content of binders, where the regions covered in black is distributed by cBN particles and the area covered in gray areas is distributed by binders. The cBN particles are evenly distributed among the binders, indicating that the microstructure of the PcBN sintered body is less dense with some gaps.

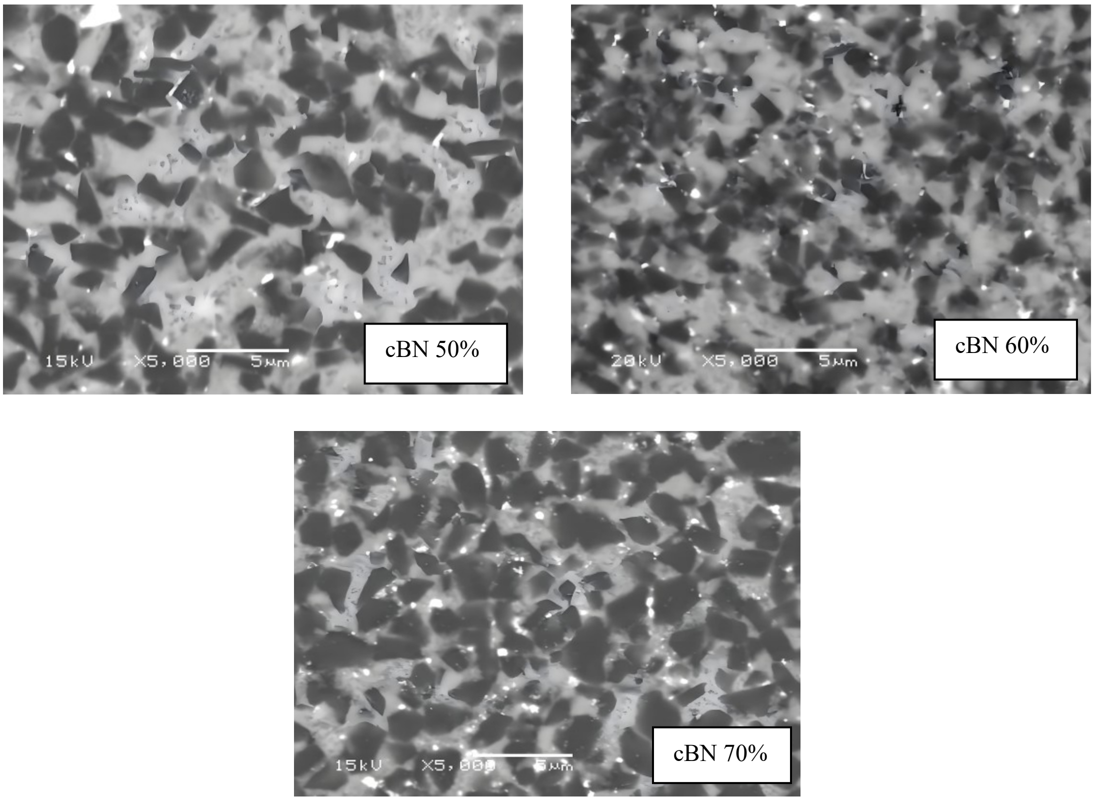


Figure 5: SEM micrographs of PcBN with different cBN content

A low amount of adhesive might result in insufficient bonding effect of cBN particles. With the relative increasing of binder content, the microstructure of the sintered material continuously becomes denser. However, due to the presence of gaps and pores among the cBN particles, the mechanical properties of PcBN will be reduced. The cBN in low content PcBN is surrounded and solidified by adhesive, which is different from the diamond bonding in diamond composites. The cBN is connected to the adhesive through chemical bonds formed by synthesis process. The uniformity of the microstructure of low content PcBN is the main factor that affecting its performance. At the same time, the adhesive also participates in the cutting process, therefore, the selection and preparation of the adhesive are equally crucial.

The adequate black regions distributed with dense particles means the cBN particles are tightly wrapped by the binders, indicating that the formed sample material is relatively compact. The binders can evenly fill into the cBN gaps, but there are still trace amounts of pores. It can be observed that some cBN particles are layered, indicating that the fracture mode of the sintered body is intergranular fracture.

3.3 Vickers Hardness Test of PcBN Samples

High energy ball milling has become one of the effective ways to prepare ultrafine inorganic powders. After high-energy ball milling, the grain size of inorganic powders can be refined to the nanometer level. The decrease in grain size is accompanied by an increase in surface energy and reaction activity, which can improve sintering driving force and reduce sintering temperature. Research has shown that the finer the grain size of ceramic structural materials, the better the mechanical properties of their sintered bodies.

The ball milling process parameters might affect the performance of the final synthesized material. In the ball milling process, the mixing time of materials is confined as 3h, 5h, 7h, 9h and 11h respectively. The working power is selected as 7.8KW, 8.0KW, 8.2KW, 8.4KW, 8.6KW and 8.8KW respectively. After completing the ball milling process task, the synthesis of PcBN samples were carried out. A batch of circular PcBN samples with a diameter of 12.5mm and a thickness of 4mm were obtained for hardness testing. The actual samples used for testing hardness by hardness tester is shown in Figure 6.

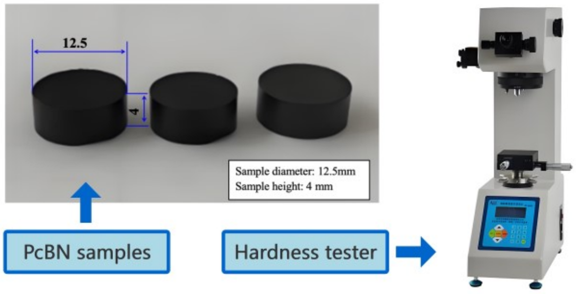
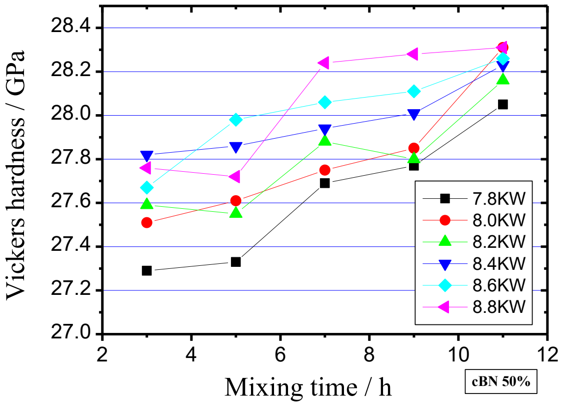


Figure 6: Physical image of PcBN samples used for hardness testing by hardness tester

Surface hardness of material is a major performance indicator of PcBN, referring to the ability of PcBN materials to resist elastic deformation and plastic deformation under external loads. Study the Vickers hardness of PcBN materials with three different cBN contents. Use HV-30Z hardness tester to measure the surface hardness of PcBN, with an external load of 5 kg and a holding time of 20 s. Conduct tests at five positions on the surface of the sample to determine the average hardness values.

Figure 7 shows the hardness values of synthesized samples obtained at different mixing time and working power for ball mixing process. Obviously, with the increasing of cBN content, the hardness value of PcBN samples shows a significant trend of improving. While the cBN content is 50%, the average hardness value of the sample ranges from 27.2 to 28.3 GPa. While the cBN content is 60%, the average hardness value of the sample ranges from 28.3 to 29.4 GPa. As the cBN content reaches 70%, the average hardness value of the sample ranges from 30.7 to 32.4GPa.

The relationship between the hardness of materials and cBN content is not a monotonically increasing linear relationship, but being influenced by various factors of working conditions. In other words, different ball milling processes might leads to different results. Overall, with the increasing of ball milling time, the Vickers hardness of the sample never show a significant or sustained increase. For example, during some special periods, the Vickers hardness of the sample remains essentially unchanged and sometimes even decrease slightly. For example, while the cBN content is 50% and the working powers are 8.2KW and 8.8KW, at the time of 3-hour point, the hardness values are 27.59GPa and 27.76GPa, respectively. However, there was only a slightly decreasing at the time of 5-hour point, which are 27.55GPa and 27.72GPa, respectively. For three different cBN contents of PcBN, it can be seen that the ball milling power shows no significant effect on the hardness value of the sample material.



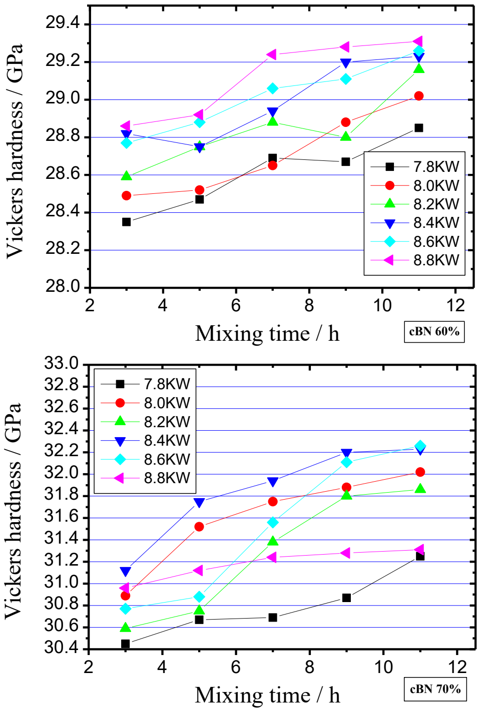


Figure 7: Hardness values obtained at different ball milling times and powers

PcBN cutting tools with 50% cBN content exhibit abrasive wear type and poor wear resistance. For example, while the cBN content is 50% and the working power is 7.8KW, 8.0KW and 8.2KW, the hardness value of the material tends to increase. However, during the continuous increase of working power from 8.4KW to 8.8KW, the hardness value of the material never show definite increasing trend, sometimes even decreased slightly. The same irregular phenomenon also occurs in samples with cBN content of 60% and 70%. In summary, among the three different content conditions, the average hardness value of PcBN samples reaches the highest at a cBN content of 70%, ranging from 30.7 to 32.4 GPa. It can be considered that with the increasing of cBN content, the reaction between Al and cBN becomes more tightly, and the sintered body becomes denser, resulting in a significant increasing of the hardness. From above analysis, it also can concluded that increasing the ball milling time and working power to improve the hardness value of materials is not an optimal solution for the reason of weak effects derived from milling time and working power.

3.4 Wear Performance Test of PcBN Cutting Tools

In order to obtain the desired tool shape for PcBN samples, wire electrical discharge machining (EDM) cutting is a preferred process.

The machining path of WEDM follows along the diameter direction and takes 10 minutes to complete. The shape of the PcBN sample is suitable for the structure of cutter body and a precision surface will be beneficial for welding together.

As is shown in Figure 8, three turning cutters were prepared by welding the PcBN sample onto the cutter body for testing the actual mechanical properties of PcBN tools. Processing tests were conducted on the CAK5085nj CNC lathe of Shenyang Machine Tool Co., Ltd. The object being machined is a forged bainitic steel rod with a hardness of HRC55~60, which had slightly intermittent impact on the cutting tool during cutting.

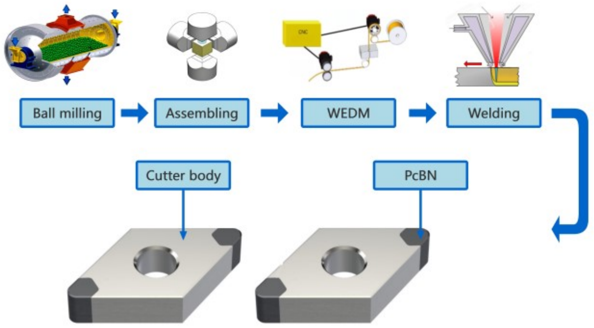


Figure 8: Physical image of assembling PcBN after WEDM and welding onto the cutter body

During the mechanical processing, a steel rod with a size of Φ 40mm×300mm is machined through dry cutting method with a cutting line speed of 120m/min, a cutting depth of 0.1mm and a tool feed of 0.2mm. After completing a turning distance of 1.1Km, measure the degree of wear on the cutter surface. The relationship between the wear value and the machining length is shown in Figure 9.

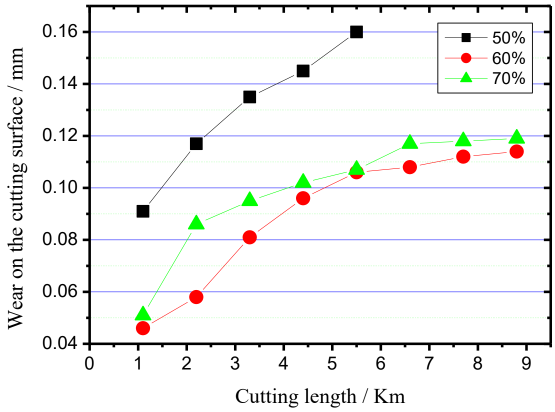


Figure 9: The relationship between the wear degree of the front cutting surface and the cutting length

From Figure 9, it can be seen that the cutter wears out quickly in the early stage of turning. While the wearing width of cutting edge reaches a certain level, then the wearing degree of the rear cutting surface no longer increases with the machining length and enters into stable cutting state. The three types of cutting tools never fall into material breakage during the machining process, indicating that a low content PcBN tends to have good toughness. The wear rate of cutter with 50% cBN content is relatively higher and approximately straight. At the machining distance of 5.5Km, the workpiece begins to show coarse turning patterns and there is a phenomenon of tool vibration. This phenomenon indicates that the ratio of ceramic and metal in the adhesive needing a properial adjustment. Accordingly, the synthesis process should be adjusted, otherwise subsequent turning tasks will be canceled. The wearing degree of turning tools with 60% cBN content and 70% cBN content is similar, both completing a turning task of 8.8Km. After turning 5.5Km, the edge wear is relatively slower, showing a stable micro wear state. Obviously, the PcBN tool with 60% cBN content is significantly better than that of 70% cBN content.

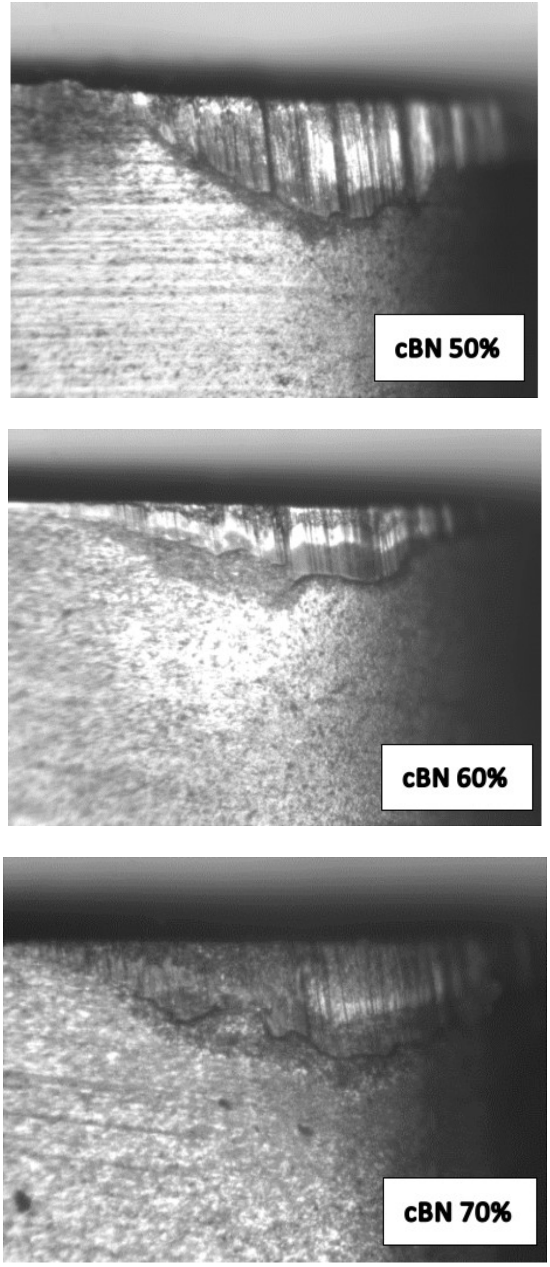


Figure 10: Wearing condition of the back surface of PcBN cutter

The main forms of wearing for PcBN cutting tools is wearing on the back cutter surface. While the cutting speed increases to a certain extent, wearing mark might also appears on the front cutter surface. Different cutting speeds can also change the wearing mechanism of the tools, unlike the front cutter surface, the rear cutting surface of PcBN tools has the less wear degree in the early stages of cutting. As cutting is progressesing, the wearing of the back cutter surface gradually increases and the main form of wearing on the back cutting surface is groove type wear.

Figure 10 shows the wearing condition of the back cutter surface recorded by metallographic microscope (MEIJI, MT8100). In this figure, the wear maps of the back surface of the cutter tools with 50%, 60% and 70% cBN content are demonstrated, respectively. The magnification is 20 times and the wear width of the cutting tool is measured by the equipment's built-in software.

Among them, the PcBN tools with 50% cBN content has a wearing width of 0.16mm on the back surface after 5.5Km processing and the wearing form is abrasive wear, manifested as plow like grooves and surface marks after erosion. The reason lies in the presence of hard particles in the workpiece being processed and the continuous friction between the workpiece and the cutting tools during the cutting process. The high pressure and temperature between the cutting tools and the workpiece should be the main reasons of stress concentration and thermal stress cracks in the contatction area, which will result in groove wearing on the back surface of the tool.

For PcBN cutting tools with 60% and 70% cBN content, after 8.8Km processing, the wearing widths of the back cutter surface are 0.114mm and 0.119mm, respectively. For PcBN cutting tools with 60% cBN content, the wearing condition on the back cutter surface is shown in figure. It can concluded that the adhesion and diffusion are also major inducing factors. Observing the rear cutter surface, a layer of coating appeared at the cutter edge, which was formed by the bonding process between the tools material and the workpiece material. Under HTHP, the tools substrate material is carried away by the chips along with the binder. As cutting is progressesing, more tools materials are torn and scratches become deeper, ultimately causing groove wear and abrasive wear on the back cutting surface. By inspecting PcBN cutting tools with 70% cBN content, it is believed that the adhesive wearing is the main reasons of early groove wearing, while diffusion wearing is the main reasons of later groove wearing. Groove wearing might reduce the strength of the tools, lead to micro chipping and consequently shorten cutter lifespan.

In conclusion, except for the PcBN cutting tools with 70% cBN content having a slightly brittle fracture, there was no significant brittle fracture at the cutter edge. Among them, PcBN with 60% cBN content had the best effect of anti chipping.

4. Conclusions

PcBN samples with cBN contents of 50%, 60%, and 70% were synthesized under HTHP conditions taking titanium nitride and aluminum as adhesives. All samples have the same phase composition, consisting of cBN, TiN, TiB2 and AlN, with uniform and dense microstructure and good conductivity. While the content of metal binder remains constant, the wear resistance of PcBN will decrease with the increasing of TiN content.

Research proved that with the increasing of the cBN content, the Vickers hardness value of PcBN tends to increase. Increasing the ball milling time and working power to improve the hardness value of materials is not an optimal solution, because the effect of ball milling technology on hardness is minor.

PcBN cutting tools with 50% cBN content exhibit abrasive wearing and poor wear resistance. The cutting tools with 60% cBN content and 70% cBN content both have lower wearing degree. For PcBN with 60% cBN content, the wear of the cutting edge slows down after turning 5.5Km, showing a stable micro wear state and the turning performance keeps in best condition at subsequently stage. After undergoing 8.8Km turning, the wearing value of the rear cutting surface is only 0.114mm. The wearing form is an abrasive wearing type, manifested as grooves resembling plows. The above research shows that cutting tools machined by PcBN samples with 60% cBN content exhibit better mechanical properties.

Acknowledgments

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