The technical trend and the future of super hard material cutting tools

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]**Abstract**

Super hard materials which are PCBN (Poly Crystalline Cubic Boron Nitride) and diamond materials are applied to high speed machining and machining of some difficult to cut materials. In This paper, 3 topics about super hard materials are described. First topic, PCBN has used for high speed milling of cast iron so that it has the high hardness and thermal conductivity and also has low reactivity with ferrous materials. But thermal cracks due to thermal gap are one of the difficult issue in high speed milling. Second topic is diamond coated tools for CFRP drilling. Recently CFRP (Carbon Fiber Reinforced Plastic) are applied to aerospace body ,main structure and some parts. Carbon fiber which is contained in CRRP has high hardness, so diamond coated carbide tools are suitable for their machining. The third topic, BL-PCD (Binderless nano Poly Crystalline Diamond) which has higher hardness than single crystalline diamond. BL-PCD tools will realize direct milling of hard cemented carbide for die and mold manufacturing. In this report, these newest super hard material technologies and applications are described.

Keywords: CBN, diamond coating, nano crystalline diamond, high speed milling, CFRP

1 INTRODUCTION

Cemented carbide were developed in Germany , 1926. The cemented carbide tools have been evolved to coated carbide tools, which is one of the most important cutting tools in this 87 years. Furthermore, PCD (Poly Crystalline diamond) and PCBN (Poly Cubic Boron Nitride) which are produced by sintering diamond or CBN particles under super high pressure have been important tools, too. In this report, three newest technologies about super hard materials, which are new PCBN grade for high speed machining of cast iron, diamond coated carbide drills for CFRP (Carbon Fiber Reinforced Plastic) and BL-PCD (Binderless nano Poly Crystalline Diamond) endmills for carbide direct milling, are introduced.

2 New CBN grade applied to high speed milling of cast iron

CBN (Cubic Boron Nitride) has the highest hardness and thermal conductivity among all materials except for diamond, and also has low reactivity with ferrous materials. PCBN is produced by sintering CBN particles with ceramic binding materials, and it contributes to the shifting the machining method of hardened steel from grinding to cutting. Sumitomo Electric Hardmetal Corp. has produced PCBN cutting tools and contributed to the productivity improvement and cost reduction in finishing and semi-finishing of ferrous materials such as cast iron and ferrous powder metal with high CBN content PCBN tools[1]-[5]. On the other hands in high precision and high efficiency machining of cast iron, PCBN cutting tools are applied due to the PCBN properties of high strength and high thermal conductivity. For example, the machining surface of engine block or oil pump is often finished by milling with PCBN cutting tool for high efficiency and high precision machining. In this paper, we focused milling of cast iron by newest PCBN tools.

PCBN sintered body is divided into two types: the sintered body that has the CBN particles bound on contact with a binder material, and the sintered body that is formed by binding together the CBN particles using a small amount of binder material. The former shows excellent wear resistance and it is usually used for hardened steel cutting. On the other hand, the latter, which has high CBN content and features excellent thermal conductivity and toughness, can be used for the machining of cast iron, heat resistant alloys and PM parts. BN7000 is classified into the latter.

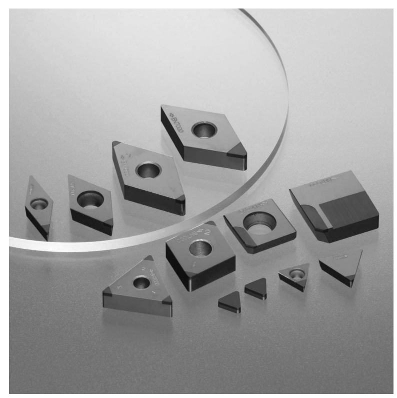


Figure 1: New PCBN grade BN7000

Figure 1 shows new PCBN grade BN7000 tools. BN7000 was realized excellent strength, toughness, high hardness and thermal conductivity by means of the highest CBN content than any other conventional grades. Figure 2 shows the observed microstructure and its properties. The shown properties are PCBN actual properties, but the shown microstructures are melted the binder by the acid treatment to make clear its structures. By using higher sintering pressure than conventional 5 GPa, the CBN content increased from 90 vol% to 93 vol% with an actual value. The amount of binder in BN7000 sintered body was 30% decreased against conventional grade in order to suppress the abrasive wear of the binder. Furthermore the binding force between CBN particles became stronger than conventional grade by improvement of binder composition due to the acceleration of the reaction between CBN particles during the sintering process. BN7000 has fewer holes made by the binder melting from acid treatment than conventional grade, and there are little inter face between CBN particles due to the increase of contact face between CBN particles for high CBN content.

The temperature of cutting edge becomes up to 1000 degrees Celsius in high speed cast iron machining, Vc = 700 m/min.[6]. In interrupted cutting like face milling, the main criteria is thermal cracks which occur at cutting edge due to the tensile stress by the cycle of expansion and shrink due to the temperature gaps of the tool surface and inside associated with the cycle of cutting and idling. In order to suppress the thermal cracks, cutting tools which have high toughness and thermal conductivity are required.

In order to compare the thermal crack resistance between BN7000 and conventional grade, milling test has been carried out using milling cutter of FMU4100R and cutting tools of SNEW1203ADTR, using two cast iron plate (150 mm in length, 100 mm width and 25mm in height, hardness = HB200 - 230) parts of FC250 (JIS) as shown in Figure 3, in the cutting condition of Vc = 1500 m/min., f = 0.2 mm/rev., ap = 0.3 mm without coolant.

Figure 4 shows the comparison of thermal cracks between BN7000 and conventional grade after 45 passes machining. There are smaller thermal cracks at cutting edge of BN7000 than the same of conventional grade and the improvement of thermal crack resistance was confirmed.

By using new PCBN grade BN7000, for cast iron, high efficient cutting and long tool life can be achieved. BN7000 has the highest CBN content, hardness and thermal conductivity and it can be used for difficult to machine material application, which requires tools with high strength. BN7000 is expected to contribute to reduction of the total cost of the cutting process, high quality and high precision cutting in future.

3 Diamond coated tools are applied to CFRP machining

Composite materials feature mechanical characteristics that can be controlled relatively freely by suitably combining their matrix with reinforcement material. Among these, CFRP (Carbon Fiber Reinforced Plastic) has recently expanded its uses as a structural material for industrial machines such as automobiles, windmills, medical equipment, and railroad vehicles owing to the material's superiority to metals in specific tensile strength, specific rigidity, and corrosion resistance. Further, CFRP has recently been adopted as a primary structural material for aircraft, thereby reducing fuselage weight and consequential fuel efficiency improvement, improving the cabin environment, and reducing maintenance costs[7]-[11].

As a solution for the above issues associated with CFRP machining, the aircraft industry is increasing the use of diamond-coated tools in place of the conventional tools.

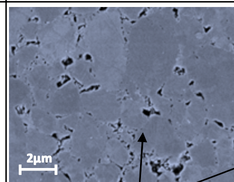
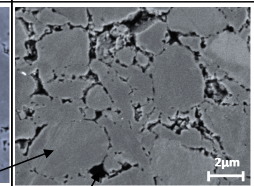
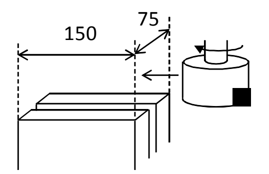
	BN7000	Conventional PCBN
Micro structure	 CBN particle	 Holes made by the binder melting from the acid treatment
CBN content	93 vol%	90 vol%
Hardness	HRA 41-44	HRA 40-43
Thermal conductivity	110-120 W/m*K	100-110 W/m*K

Figure 2: Micro structure of CBN sintered body after acid



Work material : FC250, GG25 (HB200-230)
Tools : Milling body FMU4100R
Insert SNEW1203ADTR
Cutting conditions:Vc = 1500 m/min., f = 0.2 mm/rev., ap = 0.3 mm

Figure 3: Tooling of Milling test of cast iron

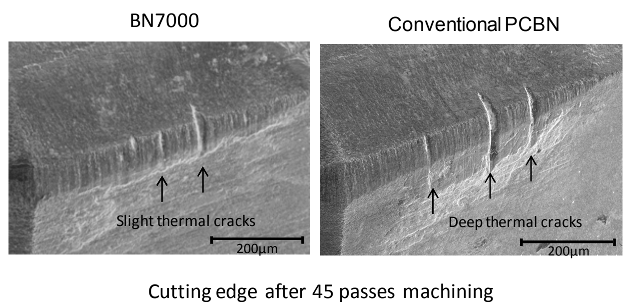


Figure 4: Comparison between BN7000 and conventional PCBN after the milling test on cast iron

Figure 5: Diamond coated drills SDC type

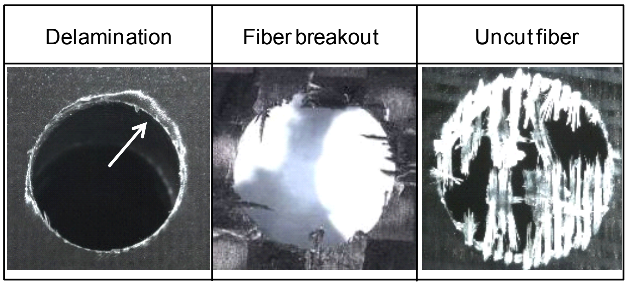


Figure 6 : Various failure modes of CFRP drilling

Sumitomo Diamond Coated drills, SDC type (Figure 5) have been developed for CFRP fine hole making. After a fundamental review of the properties required of the cemented carbide material as the substrate metal of the new tool, diamond coating pre-processing method and diamond coating technology, we established a unique diamond coating technology that ensures stable cutting of CFRP.

When drilling holes in CFRP, the material is easily delaminated since the thrust force acts in the direction to reinforce fiber sheet lamination, which are shown in Figure 6 and Figure 7. When the drilling resistance increases as cutting tool wear progresses or chips stick to the cutting edge, CFRP is extraordinarily heated and its strength deteriorates. To solve these issues, it is indispensable to use a diamond-coated drill having a configuration optimally designed for CFRP drilling.

Figure 8 shows a main feature of this drill configuration. It is that the point angle changes in three steps from the centre to the periphery of the drill, thereby reducing the thrust force when cutting holes with the drill outer edge and minimizing delamination. The shortened cutting edge length with triple point angles, combined with an optimal balance between appropriate helix angle and optimal flute groove geometry, enables the new drill to limit heat generation even when drilling deep holes.

Figure 9 shows the surface of diamond coating film. One of the most important issue in diamond coating is anti-peeling resistance. It is difficult to combine between the diamond coating film and carbide substrate so that diamond coating film has high chemical stability performance against substrate. Our diamond coating solved such issues by optimization of not only diamond microstructure but also optimum carbide grade, coating pre-treatment technologies.

An example of CFRP drilling with a newly developed drill SDC type is shown in Figure 10. It shows fine hole quality, which means no delamination and uncut fiber. In addition, the high abrasion resistance of the diamond coating helps this drill maintain long tool life and stable drilling. As this result shows, the newly developed CFRP drill SDC type ensures higher-quality drilling for a much longer period than conventional drills.

With an aim to solve the issues associated with CFRP machining, we developed new diamond coated drills. The new technology extends the service life of drills while causing them to wear more stably and gradually than conventional drills. The diamond coated drills discussed in this paper are expected to further expand their use since they can be used to machine not only aircraft CFRP but also them for general industrial use, for example automotive and machine parts.

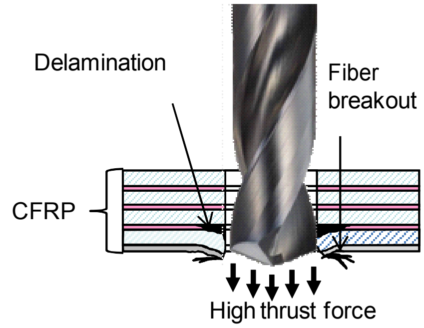


Figure 7 : Relationship between thrust force and delamination

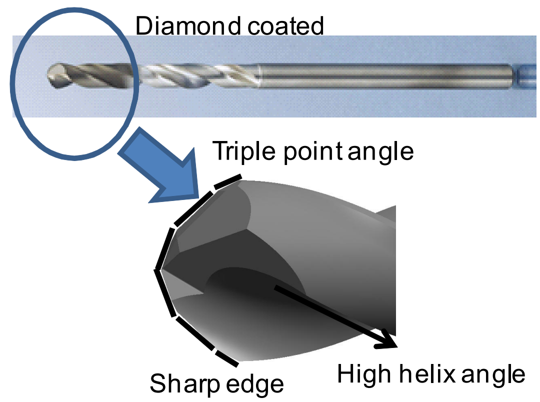


Figure 8 : Design of diamond coated drill for CFRP

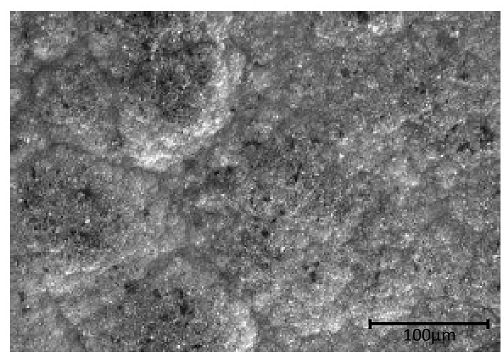


Figure 9 : Surface of Diamond coating

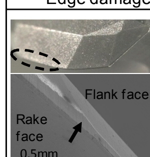
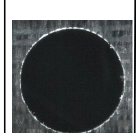
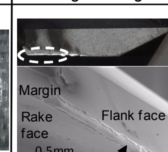
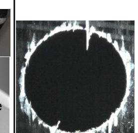
Diamond coated drill SDC type after 600 holes		Conventional drills after 50 holes	
Edge damage	CFRP exit	Edge damage	CFRP exit
			
No peeling, Slight wear on flank face	No delamination	Film peeling from edge and flank face	Delamination
Drill : Dia.6.375mm diamond coated drill, Work material: CFRP Drilling conditions : Vc=130m/min, f=0.075mm/rev, H=15mm, Dry			

Figure 10 : Cutting performance of diamond coated drills

4 Direct milling of cemented carbide

In the mold manufacturing process, to manufacture more precise die and mold, it had been increasing the demands to manufacture the die mold by direct milling using the coated carbide endmills. Recently manufacturer required harder die and mold[12], so it has been developed the PCD (Poly Crystalline Diamond) tools, diamond coated carbide tools, SCD (Single Crystal Diamond) tools for direct milling of harder materials. If it will be able to cut the cemented carbide alloy, ceramics, glass, such as brittle materials directly at low cost, It is possible to respond to new needs such as separators mold of the fuel cell and high-precision lens mold etc.

For realization of direct milling of cemented carbide mold, hardness of conventional PCD is not enough, Strength of SCD is not enough and sharpness of PCD and diamond coating tool is not enough either. So BL-PCD (Binderless nano Poly Crystalline Diamond) has been developed by ultra high pressure sintering technologies. BL-PCD has higher hardness than PCD and SCD, and higher toughness than SCD, almost same as PCD, and its sharpness is much better than PCD and diamond coating.BL-PCD has suitable performance for direct milling of cemented carbide die and molds, especially finishing process.

Figure 11 shows microstructure of BL-PCD and conventional PCD. Under an ultra-high pressure and a temperature, nano size graphite is directly converted into nano size diamond with no binder. Under these conditions, polycrystalline compacts of solidly sintered single-phase diamond are synthesized by controlling the conditions. We synthesized BL-PCD in which diamond particles with a diameter of several tens of nanometers are directly and strongly bonded to each other. This BL-PCD is a revolutionary new material.

Figure 12 shows hardness of BL-PCD. The conventional PCD contains with Co binder and hardness is about 40-60 GPa. The SCD's hardness is 60-120GPa, It has difference due to direction of crystal. BL-PCD is harder than SCD. With individual particles oriented randomly, the anisotropy and cleavage that are observed in SCD do not exit and fracture toughness is high. And also sharpness of cutting edge is better than other polycrystalline diamond.

BL-PCD's superior property for direct milling of cemented carbide are described. Then BL-PCD ballnose endmills are produced for validation of those effectiveness.

Figure 13 shows the BL-PCD ballnose endmills. BL-PCD is brazed at top of carbide shank. It has single cutting edge, Ball radius R is 0.5mm.

Figure 14 shows one of carbide direct milling test results. The purpose of this test is how fine surface roughness is obtained by BL-PCD endmill. Work material is super fine particle carbide, HRA92.5, WC particle size is about 0.5μm. BL-PCD endmill was applied for finish operation, and diamond coated endmill was applied for rough and semi-finish operations. In this cutting test, spindle speed N=40,000 min-1, feed rate Vf=120mm/min, depth of cut ap=0.003mm, half concave shape considering lens mold are machined. Total finish milling time is 150min to achieve fine surface. The roughness of work-piece obtained 8 nm at center of concave and 7 nm at 45

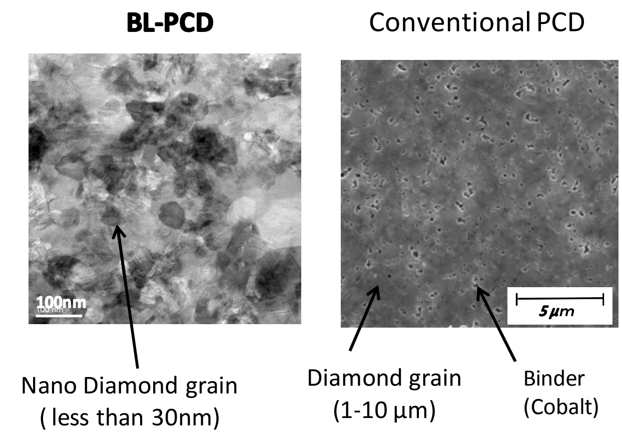


Figure 11 : Micro structure of BL-PCD and conventional PCD

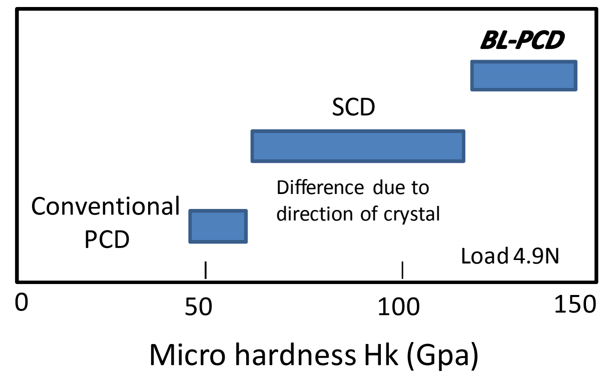


Figure 12 : Hardness of BL-PCD,SCD and PCD

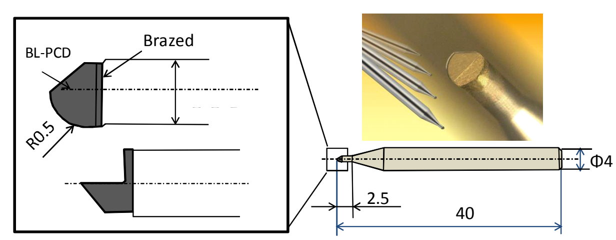


Figure 13 : Dimension of BL-PCD ballnose endmill

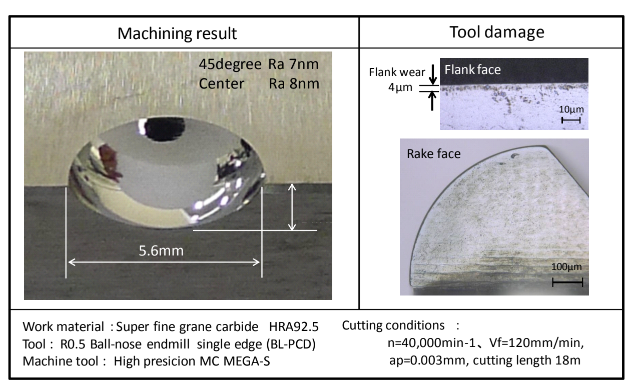


Figure 14 : Test results of direct milling by BL-PCD endmill

degree, both value is so fine to reduce or less polishing time after finish milling. And damage of cutting edge is very slight, flank wear is only 4 μm and chipping and fatal breakage were not occurred.

Figure 15 shows another direct milling test result. The purpose of this test is high efficient milling consider the actual production of carbide die and mold. In this case, work material is fine particle cemented carbide A1, that hardness is 91.4HRA and WC particle size is about 0.7μm. For realization of actual production, feed speed is increased, Vf=800mm/min. Regarding as cutting conditions for finishing after rough cutting, we adopted a method by which spindle speed of 40,000min-1, depth of cut ap= 5μm and feed speed Vf=800mm/min, total finishing time is only 38min.. In such high efficient conditions, excellent surface quality, Ra less than 15nm were obtained by BL-PCD endmill.

The possibility of applying the direct milling for carbide mold is described. BL-PCD has excellent performance for finishing operation.

5 CONCLUSIONS

In this paper 3 newest topics of super hard materials are discussed. The main conclusions are as follows.

1)New PCBN grade BN7000 which has high strength, toughness and thermal conductivity so that its CBN content increased 90 vol% to 93 vol% has been developed. That realized high speed milling of cast iron Vc=1500m/min by means of high anti thermal crack resistance.

2)Diamond coated drills SDC type has been developed for fine hole making of CFRP. In case of CFRP drilling, reduction of delamination and uncut fiber are important issues because carbon fiber has high hardness. SDC type solve these issues by means of original 3 step top angle geometry. Furthermore diamond coating, which are optimized diamond film structure, carbide grade and coating pre-treatment, realize much longer tool life than conventional tools.

3)BL-PCD(Binder-Less Poly Crystalline nano Diamond) are developed by ultra high pressure technologies. It has higher hardness and toughness than SCD and sharper cutting edge than conventional PCD. BL-PCD ballnose endmill applied to direct milling of cemented carbide for die and mold. It realized fine surface roughness, less than 10 nm.

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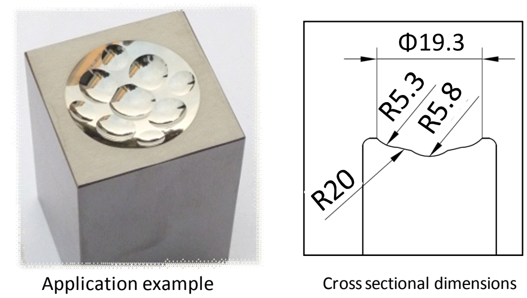

Work material : Cemented carbide A1 (91.4HRA)
Finishing tool : BL-PCD R0.5 ballnose endmill
Finishing time : 38min
Finishing conditions : n=40,000min^{-1},Vf=**800**mm/min
ap=0.005mm, wet, cutting length 29.3m

Figure 15 : Application example of direct milling of carbide