SUMIBORON BINDERLESS Tools for Finishing Difficult-to-Cut Materials

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SUMIBORON BINDERLESS is a polycrystalline cubic boron nitride (CBN) that directly binds nanometer- or sub-micron-level cBN particles without binder materials (Binderless CBN: BL-CBN). BL-CBN is harder or has better thermal conductivity than conventional CBN. Therefore, it offers higher efficiency and longer tool life in the machining of difficult-to-cut materials, such as cobalt-chromium alloys, titanium alloys, nickel-based heat-resistant alloys, and hardened steel for use in the aircraft, mold, and medical industries.

Keywords: cutting tool, ultra-high-pressure, cobalt-chromium alloy, titanium alloy, nickel-based heat-resistant alloy

1. Introduction

Cutting processes are used in an extensive range of industrial sectors, including the automotive, aircraft, and electronics industries. Cutting has fulfilled the requirements of various industrial needs for high-speed, high-efficiency, and high-precision machining. Recent technical trends are toward fuel economy improvements and electrification promotion in the automotive sector and higher-density mounting in the semiconductor and electronics sectors necessitated by faster and higher-capacity wireless communication networks. Against this backdrop, machining systems are required to adapt to flexible manufacturing and digitization including the Internet of Things (IoT); cutting tools are required to adapt to the development of lightweight and high-strength workpieces and to difficult-to-cut materials emerging through the multi-material approach. Figure 1 provides a history of the development of cutting tool materials.

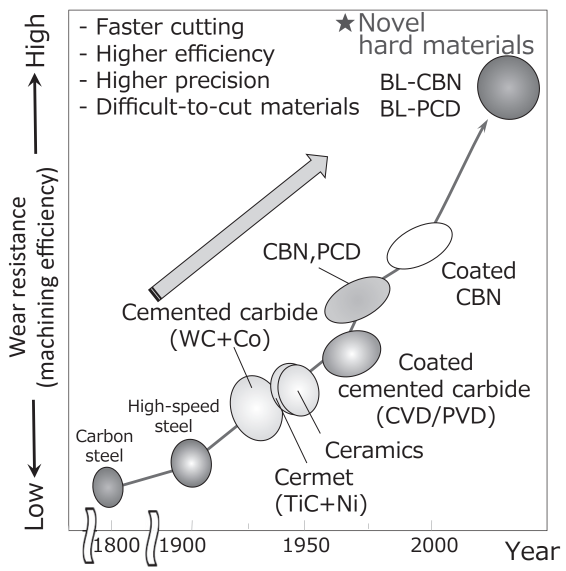


Fig. 1. History of development of cutting tool materials

Tungsten carbide-cobalt (WC-Co) cemented carbides, developed in 1923 in Germany, enable high-efficiency machining and offer superb general versatility. They are therefore still used as the primary cutting tool materials today. Nonetheless, customers desired faster and higher-precision machining capabilities. In response to their demand, tools made from polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (CBN) emerged on the market in the 1970s. Provided with a ceramic coating, such as titanium nitride (TiN), chromium nitride (CrN), and titanium aluminum nitride (TiAlN), cemented carbides and CBN, used as base materials, achieve high machining efficiency. PCD and CBN are industrially manufactured by an ultra-high-pressure technology at a pressure of between 5 and 6 GPa. In the 2000s, Sumitomo Electric Hardmetal Corporation pursued a further technology and established a mass-production technology capable of achieving ultra-super-high pressures up to 20 GPa.(1) And, binderless nano-polycrystalline diamond (BL-PCD) and nano-polycrystalline CBN (BL-CBN) were commercialized as innovative hard materials applicable to difficult-to-cut workpieces. This article describes continuous and interrupted machining using SUMIBORON BINDERLESS tools made from BL-CBN that meet recent cutting tool needs.

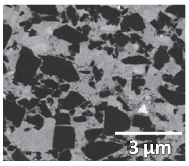
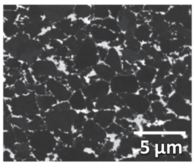
2. SUMIBORON BINDERLESS

2-1 SUMIBORON

SUMIBORON is a CBN made by blending cubic boron nitride (cBN) with binders, such as metal or ceramic powder, and sintering at a high temperature and pressure. The abbreviation CBN is used to denote sintered bodies that contain cBN.

cBN does not naturally occur. It is synthesized and is the second hardest known material after diamond. Due to its low reactivity with iron-group elements (e.g. Fe, Ni, and Co), the material is primarily used to cut iron-based difficult-to-cut materials. Table 1 presents representative CBN materials and their properties. In the cutting of hardened steel, the cutting temperature increases and thermal

Table 1. Representative CBN materials and their properties

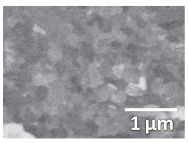
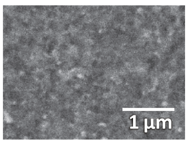
CBN	Low-cBN-content grade	High-cBN-content grade
Structure of sintered body		
cBN content (vol%)	60	85
cBN particle size (µm)	1~2	1~3
Binder	TiN (Ceramic)	WC-Co (Metal)
Sintering conditions	Approx. 5 GPa, 1,500°C	
Vickers hardness (GPa)	35	39
Thermal conductivity (W/m·K)	60	100
Principal use	Hardened steel	Cast iron Sintered alloys

wear is dominant. In such uses, low-cBN-content grades whose binder is functionally dispersed ceramics excel in wear resistance because ceramics feature lower reactivity with iron-group elements than cBN. Using a metal binder, high-hardness sintered bodies with high-cBN-content are obtained. They are used in the cutting of cast iron and sintered alloys where mechanical wear is dominant.

2-2 Binderless CBN (BL-CBN)

BL-CBN is a sintered body made from hexagonal boron nitride (h-BN), which is the normal-pressure phase of BN, and other constituents, through direct conversion to cBN under pressure and temperature conditions of 10 GPa or higher and 2,000ºC or higher, bonding the cBN particles firmly with each other.[(2),(3)] Without containing any binder such as metal or ceramic, BL-CBN is the ultimate form of high-cBN-content grades. The material has been commercialized for cutting tools under the brand name SUMIBORON BINDERLESS. Table 2 shows the properties of BL-CBN.

Table 2. Properties of SUMIBORON BINDERLSS

CBN	Ultra-fine BL-CBN (NCB100)	Ultra-super-fine BL-CBN (IX002)
Structure of sintered body		
cBN content (vol%)	100	100
cBN particle size (nm)	200~500	40~60
Vickers hardness (GPa)	~54	~54
Thermal conductivity (W/m·K)	~200	~80

BL-CBN particle sizes can be controlled by changing the proportion of h-BN, used as a constituent, and the pressure and temperature conditions used during sintering. Ultra-fine BL-CBN (NCB100) approximately 350 nm in particle size exhibits higher hardness and thermal conductivity than conventional CBN. NCB100 is used to produce indexable ISO inserts for high-speed high-precision machining and long life. It is also applied to radius end mills capable of machining difficult-to-cut materials such as heat-resistant alloys and additive manufacturing layering materials at high speeds. Meanwhile, the ultra-super-fine BL-CBN (IX002) approximately 50 nm in particle size contains a larger amount of grain boundaries than NCB100. It therefore offers superb sharpness, although its thermal conductivity is not much different from that of conventional CBN. Thus IX002 is applied to small-diameter end mills for the mirror finishing of hardened steel molds with which the edge temperature remains relatively low during cutting. Both grades are expected to be long-lived in instances where mechanical wear is the principal factor involved in service life during cutting. These SUMIBORON BINDERLESS tools are shown in Photo 1.

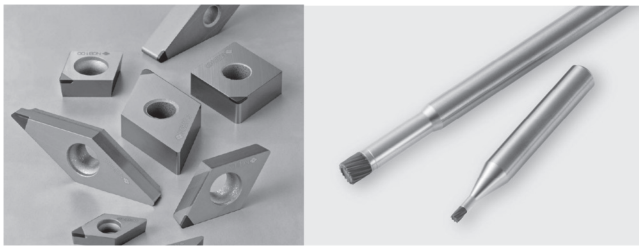


Photo 1. SUMIBORON BINDERLSS tools

3. Continuous Machining

NCB100, an ultra-fine BL-CBN with high thermal conductivity, is particularly effective in the turning of heat-resistant alloys such as difficult-to-cut cobalt-chromium alloys and titanium alloys, in which tool wear is accelerated by the increase in cutting temperature. This chapter presents the evaluation results of tool grades used to cut cobalt-chromium and titanium alloys.

3-1 Cobalt-chromium (Co-Cr) alloy

Cobalt-chromium alloys are used in aircraft engine parts. Since they are also used for medical care applica-

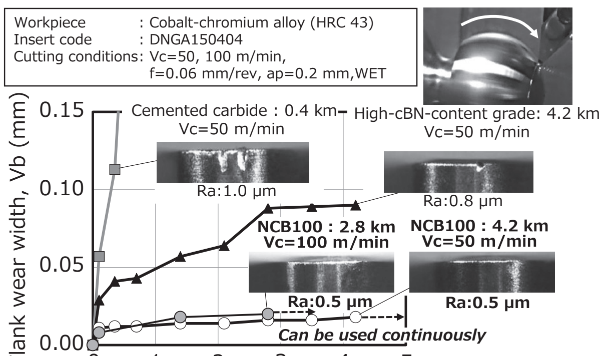


Fig. 2. Results of turning of cobalt-chromium alloy

tions, we conducted an evaluation, assuming the finishing of an artificial joint. Figure 2 illustrates the evaluation results.

Cemented carbides developed substantial boundary wear, while high-cBN-content grades exhibited reduced wear; and NCB100 showed no wear. After cutting for 4.2 km at a cutting speed of Vc = 50 m/min, the flank wear amount Vb of NCB100 was less than 0.02 mm. Even using the high-speed condition of Vc = 100 m/min, NCB100 exhibited a similar trend up to 2.8 km. Regarding machining quality, the machined workpiece was visually excellent with its surface roughness Ra being 0.5 µm. Thus NCB100 is suitable for finishing.

3-2 Titanium alloy (Ti-6Al-4V)

Titanium alloys are commonly used in aircraft engine parts. It is common to machine them with a cemented carbide tool at a low speed of less than Vc = 100 m/min. In recent years, high-pressure coolant has come into use as a means of edge cooling. We evaluated its cooling effects on an NCB100 insert. For comparison purposes, a cemented carbide and high-cBN-content grade were also used. The pressure of the high-pressure coolant was set to 7 MPa. Figure 3 plots the evaluation results. At a cutting speed of Vc = 200 m/min, the cemented carbide was worn quickly; the high-cBN-content grade was worn relatively little; and the maximum flank wear amount of NCB100 was minor at 0.06 mm after cutting for 16 km, possibly allowing the tool to cut even for 50 km. NCB100 produced the finest finished surface, achieving Rz = 1.5 µm, which was very close to theoretical surface roughness. Edge temperature measurements were conducted to verify the causes, under common coolant conditions using a two-color radiation thermometer.[4] Figure 4 outlines the test apparatus.

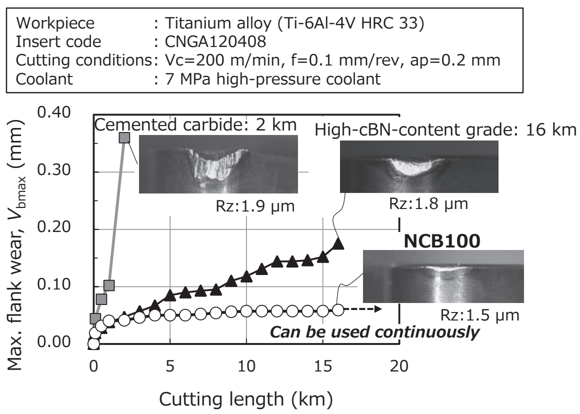


Fig. 3. Results of high-speed turning of titanium alloy with NCB100

An optical fiber was inserted into a small hole bored in a workpiece. In wet boring, infrared rays, which were radiated from the flank when the edge passes in front of the optical fiber, were received to measure the temperature. The coolant absorbed infrared rays. The small hole was purged with air during the measurement to prevent the coolant from entering the hole. The flank temperature of the NCB100 tool proved to be lower than that of the high-cBN-content grade by approximately 50°C, as shown in Fig. 5. It is surmised that the amount of wear decreased due to the improved cooling effects provided by the high-pressure coolant.

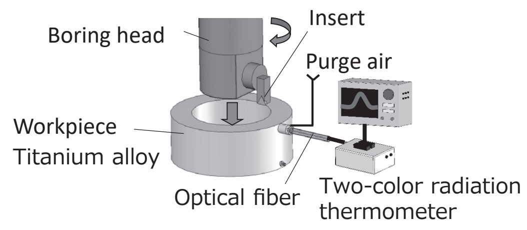


Fig. 4. Edge temperature test system (boring)

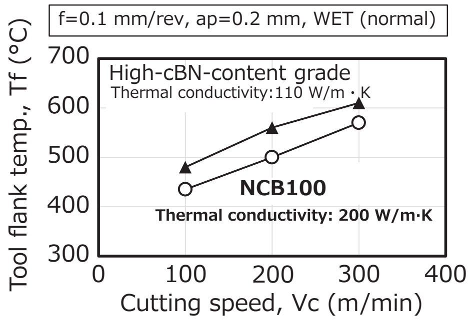


Fig. 5. Edge temperature during turning of titanium alloy

3-3 Exploring improved chip-breaking capability

In high-precision finishing, chip breaking sometimes emerges as a noticeable problem. Long chips can scratch workpieces or entangle in the machine causing it to stop. Cemented carbide inserts, which are manufactured by stamping with dies, are easy to form into a three-dimensionally shaped chip breaker to break chips and efficiently treat them. In contrast, CBN inserts, difficult to manufacture through molding, are not easily shaped. Accordingly, the use of grinding to form chip breakers on them is the mainstream. Considering that improved chip breaking capability is an important element to be studied for turning with NCB100, we formed a three-dimensionally shaped chip breaker through laser machining and evaluated it.

(1) Forming a three-dimensionally shaped chip breaker

In laser beam machining, the energy of light absorbed in an area of a workpiece surface locally heats, melts, and vaporizes the proximity of the energy absorption area. cBN is difficult to cut by laser beam machining whether a laser operates at the basic wavelength of 1,064 nm or the second harmonic wavelength of 532 nm.

The reason is that the material's absorption edge is less than 200 nm, as illustrated in Fig. 6, which shows transmittance measurement results for cBN between 200 and 800 nm wavelengths.[5] Even with wavelength transmitting materials, high-intensity light emitted from an ultra-short optical pulse laser generating picosecond or femtosecond pulses causes multiphoton absorption as a result of nonlinear optical effects, with photons directly acting on the interatomic bonds of the workpiece. Atoms with broken bonds are removed (abrasion). Applying an ultra-short pulse laser, we developed an NCB100 insert precisely with the desired chip breaker shape, as presented in Photo 2.

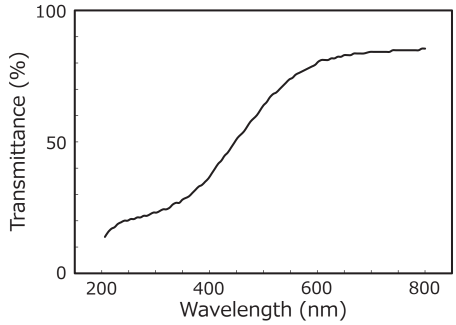


Fig. 6. cBN transmittance measurement results

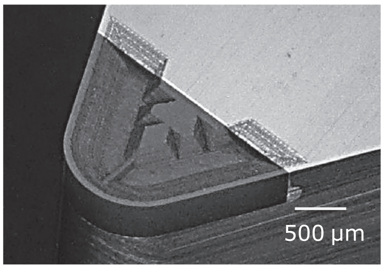


Photo 2. NCB100 insert with a three-dimensionally shaped chip breaker

(2) Chip-breaking capability

To ensure the stable cutting of titanium alloys, it is important to deal with chips efficiently, in addition to reducing the cutting temperature. Therefore, the three-dimensionally shaped chip breaker built on the NCB100 insert was evaluated. Table 3 presents the evaluation results. Using inserts provided with 0.01 mm-size round honing on the edge ridgeline, differences in the shape of chips between ground and three-dimensionally shaped chip breakers were surveyed. The ground chip breaker produced continuous spiral chips, while the three-dimensionally shaped chip breaker produced small broken chips, thereby proving its effectiveness.

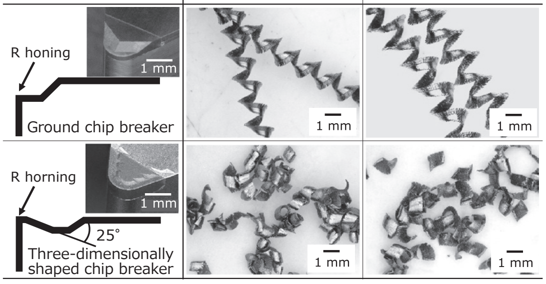
3-4 Nickel-based heat-resistant alloys

Inconel is a typical nickel-based heat-resistant alloy. Like titanium alloys, it is used as a material in aircraft engine parts. Due to its exceptionally high heat resistance, Inconel is used in high-temperature parts such as turbine blades. Expectations were high for NCB100 to be a long-lived insert due to its thermal conductivity. However, it turned out to be as short-lived as high-cBN-content grades. This is thought to be the result of increased wear due to chemical reaction attributable to the 100% cBN content,

Table 3. Evaluation of chip breakers formed on NCB100 inserts

Workpiece	: Titanium alloy (Ti-6Al-4V, Heat-treated)
Insert code	: DNGA120408
Cutting conditions	: Vc= 200 m/min
Coolant	: 7 MPa high-pressure coolant

Edge shape	Chip shape	
	f=0.15 mm/rev ap=0.3 mm	f=0.20 mm/rev ap=0.5 mm



cancelling the wear suppression effects of reduced edge temperature. Meanwhile, low-cBN-content grades can be used to cut Inconel, because they use low-reactivity ceramics as a binder, contributing to reduced wear, and heat generated by cutting softens the workpiece.

4. Interrupted Machining

The evaluations described above showed that NCB100 with higher thermal conductivity than conventional CBN suppresses increases in edge temperature and is expected to make machining faster and extend tool life. Milling tools, which cut workpieces with rotating edges, have relatively low edge temperature because of repeated cycles of heating during cutting and cooling during idle state. Consequently, NCB100 may be viable for milling nickel-based heat-resistant alloys and hardened steel that tends to cause the tool to have a higher edge temperature and wear more quickly than titanium alloys. Thus, we explored the potential of NCB100 for milling Inconel 718 and hardened steel.

4-1 Nickel-based heat-resistant alloys

It has been the predominant manufacturing method for aircraft engine turbine parts made of a nickel-based heat-resistant alloy to machine the blades and the disk separately, followed by joining them. However, for improved reliability, the technique of machining integral blisks (bladed disks) eliminating joints is coming into use. Nickel-based heat-resistant alloys are subject to high cutting temperatures. For them, conventional end mills using cemented carbides cannot use higher cutting speeds, and one notable challenge is to reduce the finishing time. Therefore, we explored the use of NCB100 to achieve faster finishing. A prototype end mill using NCB100 was built by joining a cylindrical piece of NCB100 to a cemented carbide shank and forming 45° spiral flutes similar to cemented carbide end mills. In a simulated blisk machining process, a cemented carbide end mill on a five-axis machine was used to provide coarse cutting. Subsequently, finishing was done with the NCB100 end mill and a cemented carbide end mill, followed by comparing and evaluating these two processes. Figure 7 illustrates the evaluation results in a V-T diagram.

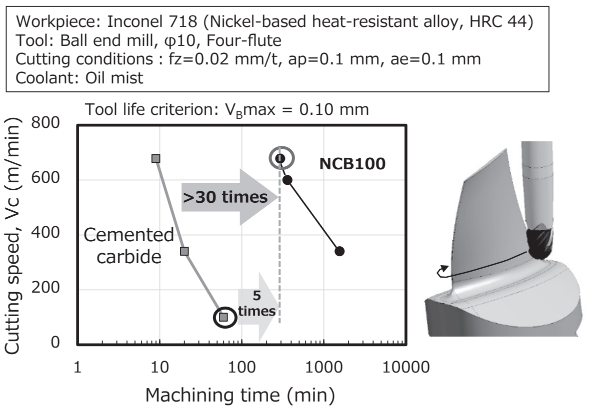


Fig. 7. V-T diagram of machining of Inconel 718 with end mills

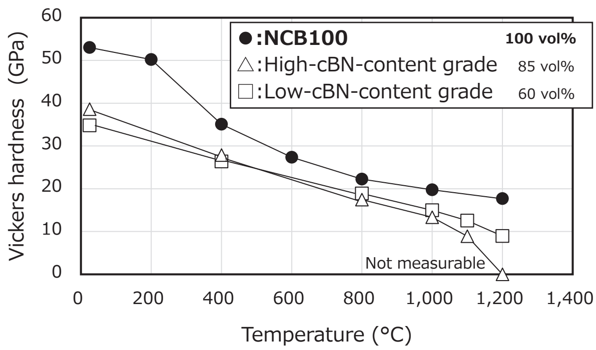


Fig. 8. High-temperature hardness of different CBNs

Cemented carbide end mills operate at an approximate cutting speed of Vc = 100 m/min at the maximum. In contrast, at Vc = 700 m/min, NCB100 exhibits 30 times or higher wear resistance than cemented carbide. Consequently, NCB100 is considered to be usable under high-speed machining conditions. Table 4 presents an example of the cross-sectional observation results for the cut surfaces.

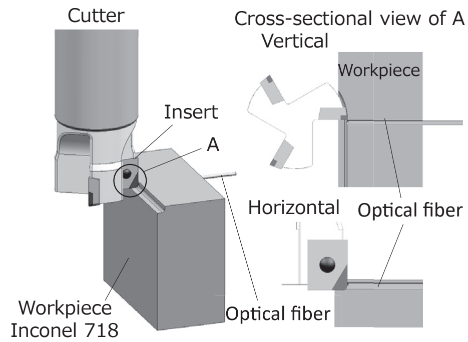
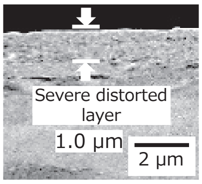
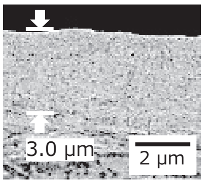
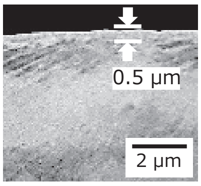
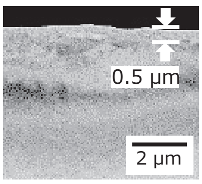


Fig. 9. Edge temperature test system (milling)

Table 4. Cross sections of finished surfaces of milled Inconel 718

Cutting conditions : fz=0.02 mm/t, ap=0.1 mm, ae=0.1 mm, Oil mist

Tool material	Early cutting phase	After progress of wear (Vbmax=60 μm)
Cemented carbide Vc=60 m/min	 Severe distorted layer; 1.0 μm; 2 μm	 3.0 μm; 2 μm
NCB100 Vc=600 m/min	 0.5 μm; 2 μm	 0.5 μm; 2 μm

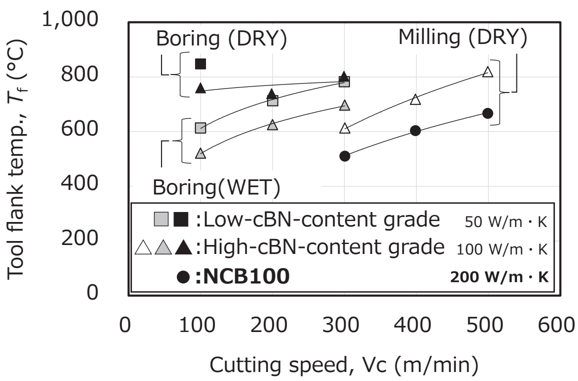


Fig. 10. Cutting speed vs. tool flank temperature

Even in the early cutting phase, cemented carbide formed a relatively thick severe distorted layer. After the progress of wear, the thickness of the severe distorted layer reached approximately 3.0 μm. In the case of NCB100, despite high-speed cutting, the thickness of the layer was as low as approximately 0.5 μm even after the progress of wear. The probable reasons for this are NCB100's high thermal conductivity and its edge temperature remaining low due to its superb high-temperature hardness contributing to the preservation of sharp edges during cutting, as shown in Fig. 8.

A fundamental evaluation of dry cutting using the test apparatus outlined in Fig. 9 was conducted to study cutting temperatures.[6] Figure 10 shows the relationships between cutting speed and tool flank temperature along with the measurement results obtained by boring Inconel 718, which were illustrated in Fig. 4.

At the cutting speed of Vc = 300 m/min, the edge temperature was higher during boring than during milling. Meanwhile, during milling at Vc = 500 m/min, the edge temperature of the high-cBN-content grade was approximately 820°C, while that of the NCB100 was approximately 670°C, with no noticeable progress of wear on the edge of the NCB100.

For coarse cutting, ceramic tools soften workpieces with heat generated by cutting. In contrast, NCB100 with high hardness and sharp edges enables high-precision machining and is therefore suitable for high-speed milling performed for the finishing of heat-resistant alloys, including Inconel 718.

4-2 Hardened steel

The IX002 (ultra-super-fine BL-CBN) contains a larger amount of cBN grain boundaries than NCB100. It therefore shows lower thermal conductivity than NCB100 and is unsuitable for high-speed machining. However, the IX002 is expected to achieve high-quality mirror finishing due to its sharp edges. Thus, we explored its use in small-diameter end mills for milling hardened steel molds, where the edge temperature remains relatively low. The results are shown in Fig. 11.

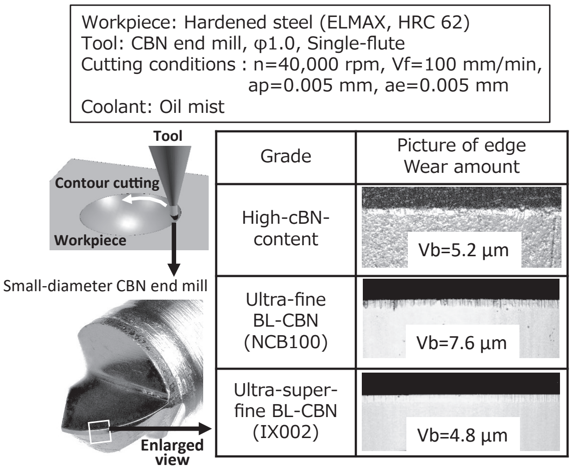


Fig. 11. Example of mold machining with SUMIBORON BINDERLESS end mill

The high-cBN-content grade exhibited substantial unevenness at the edge. NCB100 had a lower level of unevenness, but its worn flanks showed scratches. Compared with these materials, the IX002 developed smooth flank wear and the amount of wear was the lowest.

Consequently, as presented in Fig. 12, using the IX002, we developed a super-multi-flute radius end mill for high-efficiency machining and a ball end mill for mirror finishing and machined hardened steel imitating a light emitting diode (LED) mold.[7]

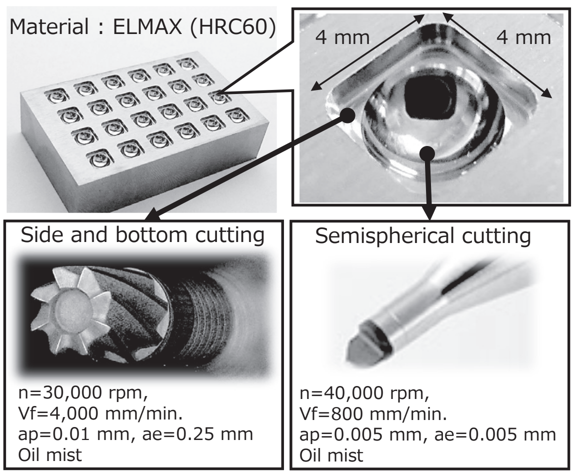


Fig. 12. Example of mold machining with SUMIBORON BINDERLSS end mill

The former eight-flute end mill with an edge diameter of 2 mm machined the workpiece under the high-efficiency conditions of a table feed rate of Vf = 4,000 mm/min. It achieved a surface roughness (Ra) of 0.1 μm. The latter single-flute end mill with an edge diameter of 1 mm machined the workpiece and achieved mirror finishing with Ra being 0.025 μm. It is highly probable that these results are attributable to the smooth edges of the ultra-super-fine BL-CBN, which produces superbly finished surfaces despite its low thermal conductivity.

5. Conclusion

Using ultra-fine BL-CBN (NCB100), we have developed SUMIBORON BINDERLESS tools, including indexable ISO inserts and end mills for machining heat-resistant alloys and other difficult-to-cut materials. We have also developed small-diameter end mills for the machining of hardened steel using ultra-super-fine BL-CBN. These materials have higher hardness and higher thermal conductivity than conventional CBN grades and therefore enable high-efficiency machining of difficult-to-cut materials, longer tool life, and mirror finishing of hardened steel molds. We intend to further develop novel and distinctive cutting tools like these in the future, helping various industrial sectors achieve growth.

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