Sumidia Binderless Ball-Nose Endmills "NPDB" for Direct Milling of Cemented Carbide

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There has been a growing demand for cutting tools that can be used for the direct milling of cemented carbide materials to create high precision mold/die parts at low costs. However, conventional tools are insufficient in chipping resistance, wear resistance, and edge sharpness. To address these challenges, the authors have developed "Sumidia Binderless NPD10," a nano-polycrystalline diamond that has extremely high hardness and strength with no anisotropic mechanical properties. Adopting the NPD10 diamond for the edge, the authors have created milling tools Sumidia Binderless ball-nose endmills "NPDB." These endmills exhibit excellent cutting performance in the direct milling of cemented carbide.

Keywords: single crystalline diamond, polycrystalline diamond, cemented carbide, direct milling

1. Introduction

As electronic components and the like parts are becoming smaller and more precise in recent years, molds / dies materials for producing them are becoming harder in order to retain high precision for a long period of time. Manufacturing such molds / dies from steel-based materials, for instance, requires micromachining of high-hardness materials of over HRC 60. Furthermore, to produce higher-precision optical components and forging dies at lower costs in the future, demand is growing for cemented-carbide molds / dies and therefore cutting tools that can direct milling of cemented carbide. Cemented carbide materials are currently machined with such tools as polycrystalline diamond (PCD) tools (sintered), electroplated grinding wheels, and diamond coated tools. However, no currently available tools feature sufficient chipping resistance, wear resistance and edge sharpness. In addition, since it is difficult to obtain a mirror-finish surface with any of currently available tools, an additional finish-polishing process is generally performed to produce higher-precision molds / dies. However, the finish-polishing makes molds / dies prone to dimensional errors. To overcome this problem, it is necessary to realize direct milling that can produce a high-precision mirror surface without the need of finish-polishing.

The Sumidia Binderless NPD10 has been developed to respond to the needs for machining such hard work materials with high efficiency, precision and quality. The NPD10 is a PCD produced without the use of any binder. It is also called nano-polycrystalline diamond (NPD)[1]. The NPD10 is extremely hard and is not easy to manufacture; by manufacturing the NPD10 using a special manufacturing process, we successfully developed the ball-nose endmill NPDB (**Photo. 1**).

This tool has excellent properties suitable for machining high-hardness materials such as cemented carbide. The present paper introduces the material properties of the Sumidia Binderless NPD10 and some examples of cemented carbide workpieces mirror-finished with the NPDB.

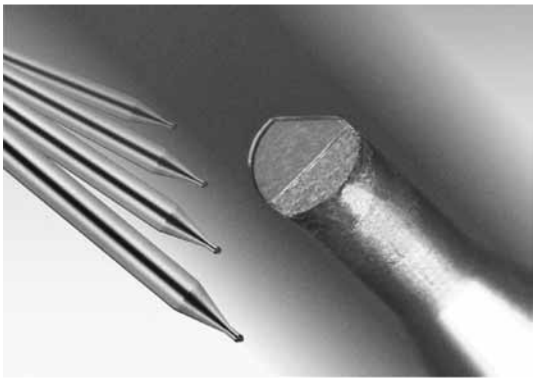

Photo. 1. Sumidia Binderless Ball-Nose Endmill NPDB

2. Properties of Sumidia Binderless NPD10

The Sumidia Binderless NPD10 is a nano-polycrystalline, single-phase diamond using graphite as the starting material. It is produced by directly converting graphite into diamond while allowing particles to be bonded together under ultrahigh-pressure and high-temperature conditions (15 GPa or higher and 2,200˚C or higher)[1].

Figure 1 is photographs showing the microscopic structure of Sumidia Binderless NPD10[1] (TEM image) and that of conventional PCD (SEM image) for comparison. For the conventional PCD in this photograph, cobalt binder has been removed by etching to enhance the visibility of the structure. While the conventional PCD uses cobalt binder to sinter 1 µm–10 µm diamond particles, the NPD10 diamond is an epoch-making new material with extra-fine diamond particles (30 nm–50 nm) bonded together directly without using any binder. The NPS10 diamond looks unevenly colored because each particle is a single crystalline diamond oriented in a different direction.

A cutting tool using this revolutionary NPD10 diamond for the edge provides the following characteristics.

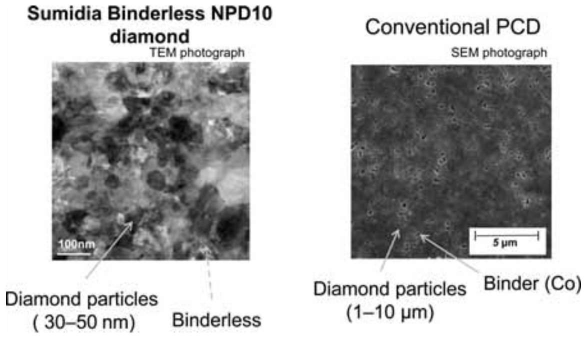

Fig. 1. Comparison between Sumidia Binderless NPD10 and Conventional PCD

(1) Harder than single crystalline diamond (**Fig. 2**), the NPD10 diamond tool is capable of machining harder material with higher precision for a longer period of time than with any conventional cutting tool.
(2) Unlike single crystalline diamond, the NPD10 diamond does not have anisotropic properties and is therefore free from uneven wear associated with crystallographic orientation, enabling high-precision profile machining for a long period of time.
(3) Unlike single crystalline diamond, the polycrystalline NPD10 diamond does not have the cleavage property and provides high chipping resistance.
(4) The NPD10 diamond is a polycrystalline sintered compact of nanometer-level ultra-fine diamond particles and is therefore superior to conventional PCD in edge sharpness, producing good surface roughness.

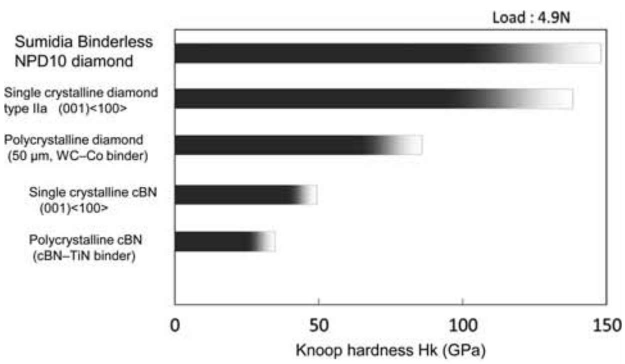

Fig. 2. Hardness Comparison among Various Hard Materials

3. Lathe-Turning of Cemented Carbide with NPD10 Diamond

Figure 3 shows the changes in the flank wear of various diamond tools used in lathe-turning of cemented carbide(1),(2). Four tools were evaluated: Sumidia Binderless NPD10, conventional fine-grain PCD (5 μm in particle size), coarse-grain PCD (30–50 μm in particle size), and single crystalline diamond (type Ib, synthesized). For evaluation, lathe-turning was conducted under the following conditions: wet turning, Vc = 20 m / min, ap = 0.05 mm, and f = 0.1mm / rev.

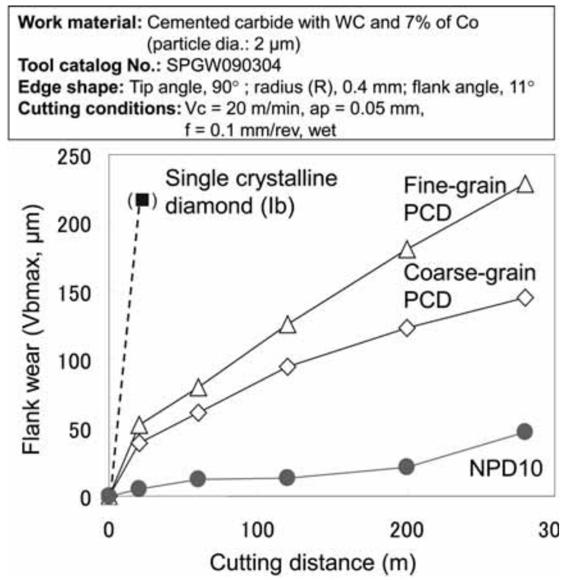

Fig. 3. Comparison among Various Diamond Materials in Cemented Carbide Machining

The single crystalline diamond was superior in wear resistance and edge sharpness, but under such high feed conditions, it chipped off as soon as it cut into the carbide, because of cleavage property. For use in lathe-turning cemented carbide, coarse-grain PCD was generally superior in wear resistance. A disadvantage of coarse-grain PCD is that, because of the grain coarseness, the unevenness of the tool's cutting edge is transferred to the work material, deteriorating the roughness of machined surface. Fine-grain PCD, which is superior in edge sharpness, was inferior in wear resistance because wear progressed as fine particles were released. Thus the evaluation revealed that it is extremely difficult for any of the conventional diamond-based tools to show superiority in all properties of edge sharpness, wear resistance and chipping resistance.

In contrast, the NPD10 diamond showed good cutting performance even under the conditions where single crystalline diamond may chip off, and was far superior in wear resistance to coarse-grain PCD. In addition, the NPD10 diamond, manufactured by directly bonding nano-order diamond particles together, has high grain boundary strength and can maintain edge sharpness, i.e., the NPD10 diamond is excellent in all of wear resistance, chipping resistance and edge sharpness.

4. Application examples for Cemented Carbide with NPDB Endmill

This section introduces an example of machining with Sumidia Binderless ball-nose endmill NPDB.

Since lathe-turning tools are simple in shape, they can be produced only by grinding for a long period of time. However, in the case of a ball-end milling tool, it is difficult to shape it by grinding. Even a micro-end-milling tool of general PCD is often shaped by electric discharge machining (EDM). The NPD10 diamond is not conductive and cannot be machined by EDM. We developed a special machining technique and applied it to successfully shape the NPD10 diamond into a ball-end milling tool. Higher-precision tools are necessary to produce higher-precision molds / dies. The NPDB endmill has adopted a single-edge design, enabling the radius shape to be finished at high precision. We performed the basic evaluation of the NPDB endmill and examined its applicability as a cemented carbide machining tool.

Various cemented carbides for molds / dies are commercially available, which are selected depending on the applications (**Table 1**). As the work materials in the present study, we used ultra-ultra-fine-grain cemented carbide grades AF1 and ultra-fine-grain cemented carbide grade A1, both of which are extremely tough and hard and widely used for punch dies precision molds / dies.

Table 1. Characteristics of Materials for Cemented Carbide Molds

■ Material characteristics and applications

Characteristics / Classification / Material type	Ultra ultrafine grain alloy	Ultrafine grain alloy	Fine grain alloy	
	AF1	A1	KH03	KH05
Particle dia. (μm)	0.5	0.7	1.0	1.0
Co amount (wt%)	12.0	13.0	10.0	13.0
Bending strength (GPa)	4.4	3.2	3.3	3.5
Hardness (HRA)	92.5	91.4	91.4	90.4
Hardness HV (GPa)	17.3	15.6	15.2	13.6
Applications	Mold punch material	Mold punch material	Mold die material	Mold die material

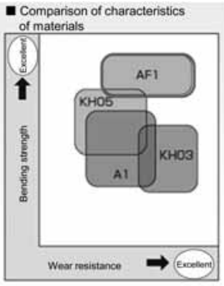

Figure 4 shows a cemented carbide workpiece (AF1) precision-machined for high quality with the NPDB R0.5 ball-nose endmill (Model NPDB1050-020). To realize a high-precision 3D shape with mirror-finished surface, rough machining with an electroplated grinding wheel was followed by finish-machining under the conditions of spindle speed at 40,000 min^{-1}; feed speed Vf at 120 mm / min; and machining stocks at 3 μm. The finish-machining was carried out in a wet condition using oil mist. while machining took as long as slightly less than six hours, the finished surface quality was single-nanometer order of 8 nm in surface roughness (Ra).

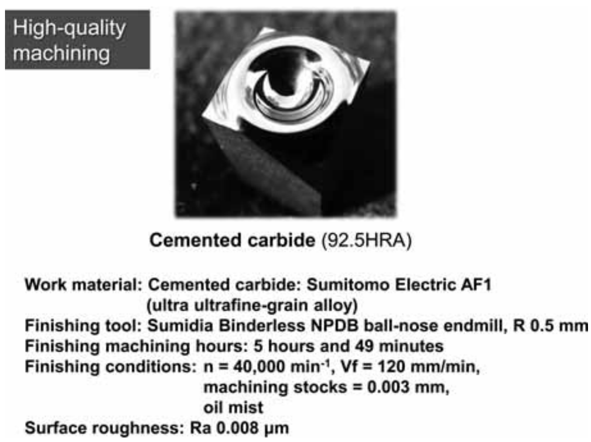

Fig. 4. Example of High Quality Machining of Cemented Carbide with NPDB

Figure 5 shows an ultrafine-grain alloy workpiece (Al) machined with high efficiency using the same NPDB1050-020 ball-nose endmill as used in the example of **Fig. 4**, at a higher feed rate, in consideration of actual machining applications. The conditions of finish-machining after rough machining were: spindle speed at 40,000 min^{-1}; Vf at 800 mm / min; machining stocks at 5 μm; and wetting with oil. The finish-machining time was 38 minutes, resulting in a surface roughness of Ra 15 nm. The tool was in a good condition with minimal wear, verifying its applicability in direct milling of cemented carbide.

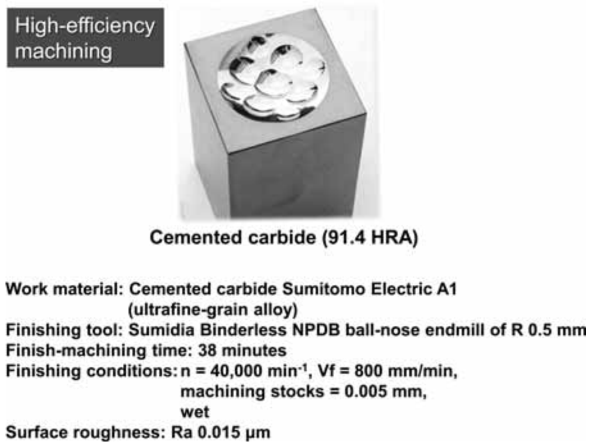

Fig. 5. Example of High-Efficiency Machining of Cemented Carbide with NPDB

In machining cemented carbide material using the ball-nose endmill NPDB with an NPD10 diamond, it is realistic to carry out rough-machining with an electroplated grinding wheel or similar before conducting semi-finishing and finish-machining with the NPDB endmill.

For basic evaluation of the NPDB R0.5 ball-nose endmill, cemented carbide AF1 was rough-machined and then finish-machined with the NPDB at three different spindle speeds of 60,000 min^{-1}, 40,000 min^{-1} and 20,000 min^{-1} under the conditions of feed amount (f) at 0.01 mm / t, machining stocks at 5 μm, and wetting with oil mist. **Figure 6** shows change in the finished surface quality. A semispherical surface was machined and the cutting distance was 234 m. After machining a distance of 234 m to finish semispherical surfaces, no difference was observed in surface roughness Ra depending on the spindle speed. However, higher spindle speed resulted in higher surface glossiness although it is difficult to quantitatively evaluate the glossiness.

Figure 7 shows SEM images of tool wear observed at

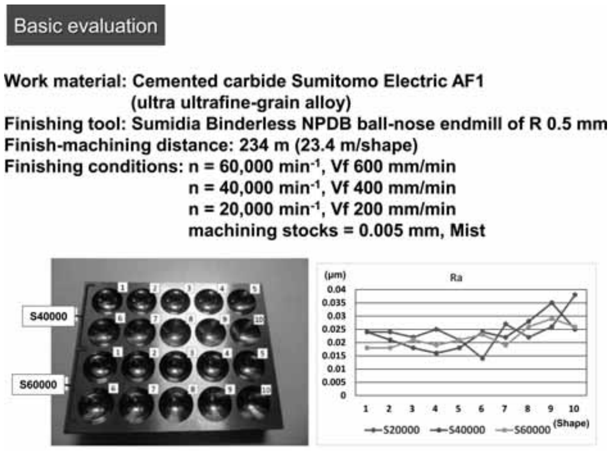

Fig. 6. Example of Basic Evaluation of NPDB Machining of Cemented Carbide With NPDB

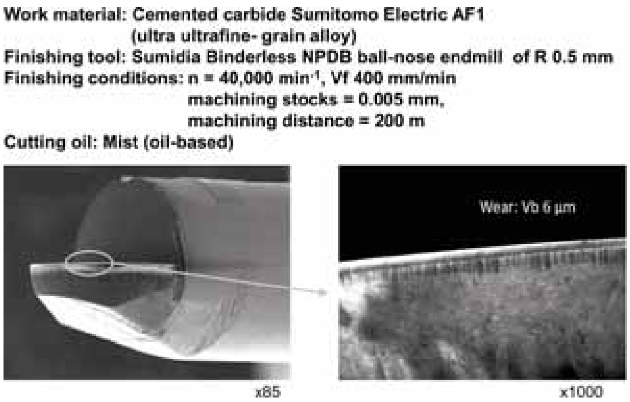

Fig. 7. Tool Wear Observation by SEM (L = 200 m)

the machining distance of 200 m in the evaluation above. The conditions were: spindle speed at 40,000 min^{-1}, Vf at 400 mm / min; machining stocks at 5 µm; and wet with oil mist. After machining a distance of 200 m, the tool wear Vb was 0.006 mm, indicating high wear resistance. The tool life of the NPDB cannot be determined definitely because it varies depending on the surface finish quality and shape precision requirements; however, it has been confirmed by the present study that the NPDB will be able to perform machining at least 300 m when used to machine a hemispherical shape on AF1 grade cemented carbide under the cutting conditions of spindle speed at 40,000 min^{-1}; Vf at 400 mm; machining stocks at 5 µm; and wet with oil mist, targeted at finished surface roughness of Ra 50 nm.

Figure 8 shows a still image captured from high-speed video that recorded cemented carbide AF1 being cut with the NPDB ball-nose endmill, along with SEM images of collected cutting chips.

The cutting conditions were: spindle speed at 40,000 min^{-1}; Vf at 120 mm / min; and machining stocks at 5 µm. Initially, the cutting chips resulting from micromachining cemented carbide, which is hard brittle material, had been expected to be powdery due to brittle mode chip formation as in grinding. Actually, however, fan-shaped cutting chips resulted. This indicates that the NPDB ball-nose endmill performs ductile mode cutting in the direct milling of cemented carbide.

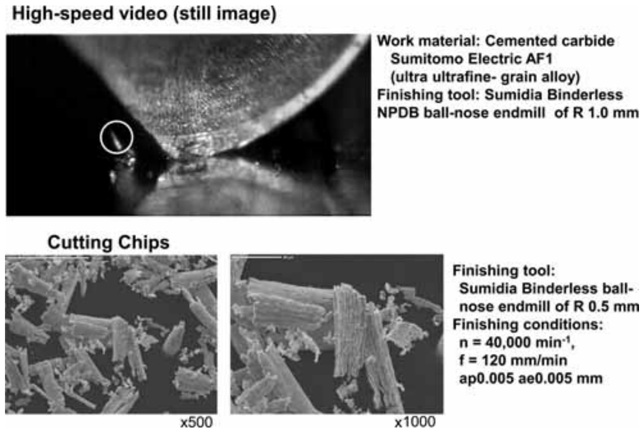

Fig. 8. Cuting chips Observation (SEM, high-speed video)

5. Conclusion

Sumidia Binderless NPD10 diamond is a revolutionary tool material superior in wear resistance, chipping resistance and edge sharpness. It can be used not only to machine extremely hard material such as cemented carbide, but also has a good potential as a material of tools to machine hard brittle materials such as ceramics. Since NPD10 is harder than diamond, shaping of NPD10 into a cutting tool with a diamond wheel would take a long time. In the present study, we developed a special machining method to successfully shape NPD10 into a machining tool, such as an endmill. This method has made NPD10 applicable as the material of tools for machining forging dies, precision press molds, and molds / dies for optical components and semiconductor components. We plan to commercialize this tool as well as various other tools using Sumidia Binderless NPD10. We also intend to determine optimal machining conditions through basic evaluation, thereby developing tools that are easier to use and more beneficial to users.

· Sumidia is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

Technical Terms

*1 PCD: Polycrystalline diamond: Sintered diamond, which is polycrystalline diamond using binders and sintering aids such as cobalt.

*2 Single crystalline diamond: Diamond that has a constant crystal orientation all over. Single crystalline diamond is the antonym to polycrystalline diamond. Single crystalline diamond has cleavage property and mechanical anisotropic properties due to crystallographic orientation, and is strong in a given direction but weak in different directions.

*3 Cemented carbide: High-hardness material produced by mixing and sintering tungsten carbide and cobalt as a binder.

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